UIUC-ZJU PARTNERSHIP

University of Illinois at Urbana-Champaign - Zhejiang University Partnership

ME 270
Design for Manufacturability

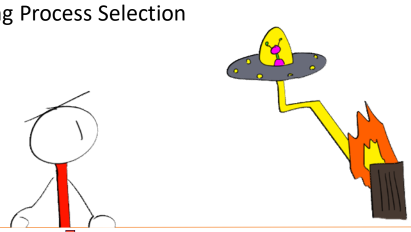
Timothy H. Lee, PhD

Fall 2021

Lecture 02 – Design Process and DtC

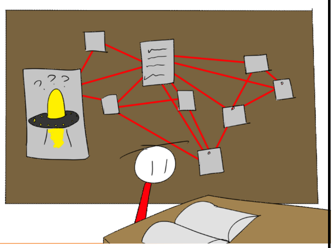
Design Process and DtC

- Design Process
- What is a “Product Design Specification” (PDS)?
- Concurrent Engineering
- aPriori
- Cost Analysis
- Manufacturing Process Selection



Four-Stages of Creative Thinking Processes

1. Preparation (stage 1):
   - The elements of the problem are examined and their interrelations are studied. Tradeoffs? Boundaries? Organize knowledge.

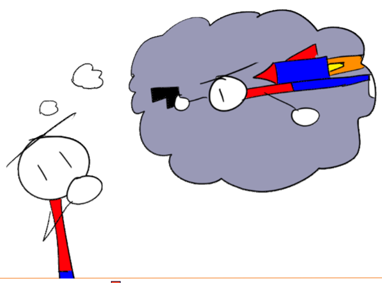


Four-Stages of Creative Thinking Process

2. Incubation (stage 2):
   - “Sleep on the problem.” Sleep disengages your conscious mind, allowing the unconscious mind to work on a problem freely.

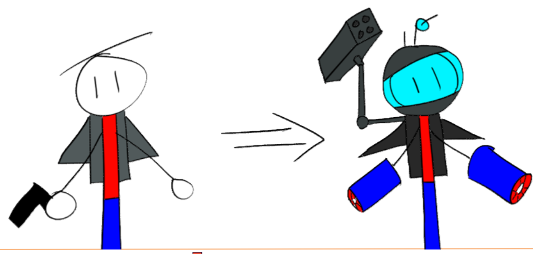
Four-Stages of Creative Thinking Process

3. Inspiration (stage 3):
   - A (vague?) solution or a path toward the solution emerges.



Four-Stages of Creative Thinking Process

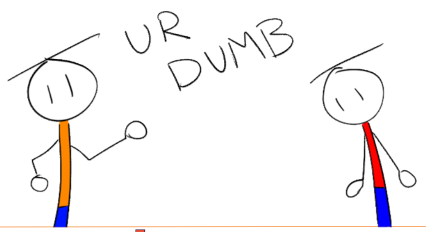
4. Verification (stage 4):
   - Solution is checked then modified for improved again and again



Four-Stages of Creative Thinking Process

Suspend your judgment!

- Nothing inhibits the creative process more than critical judgment of an emerging idea.



Types of Mental Blocks

Perceptual Blocks:

Assuming a solution must come from the same "category" of previous solutions.

Assuming a new solution must look like previous solutions.

Emotional or Environmental Blocks:

Fear of taking risks or an unease with unstructured tasks.

Fear of criticism.

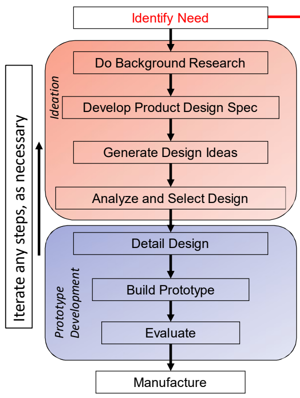
Intellectual Blocks:

Poor choice of the problem-solving strategy or having inadequate background and knowledge.

A broad definition of the problem helps keep the mind open to a wider range of ideas.

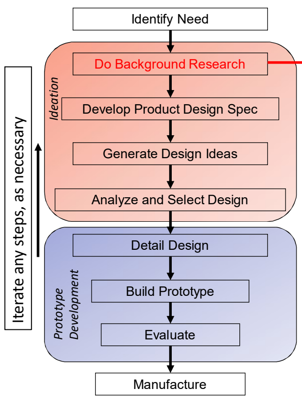
MechSE Design-Related Courses

- ME170: Computer-Aided Design
- ME199 DES/SAE: Competition Design Projects
- TAM252: Solid Mechanics Design
- ME270: Design for Manufacturability
- TAM302: Engineering Design Principles
- ME370: Mechanical Design I
- ME371: Mechanical Design II
- ME470: Senior Design Project



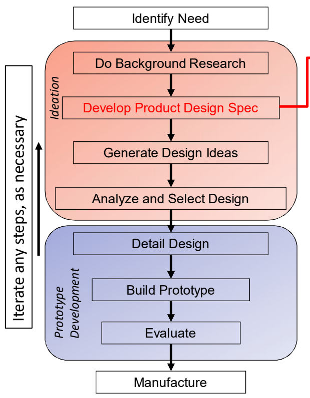
Identify Need

Need: driven by marketing or business plan, customer request, cost reduction, or desired design improvement



Do Background Research

Background: What is currently available? What is the competition? Perform benchmarking, patent search.



Develop Product Design Spec

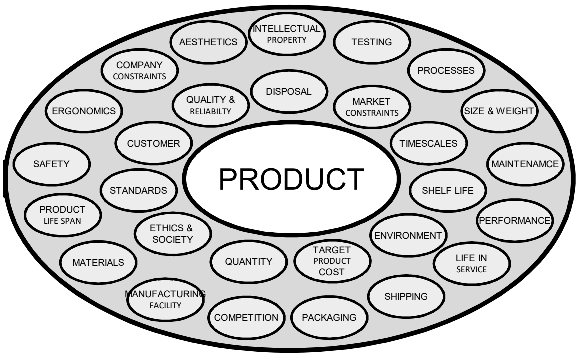
Product Design Specification (PDS)

- Identify product/design requirements
- Review all 28 Primary Elements from performance through cost, to disposal/recycling requirements
- Objective/measurable - with units (metrics)

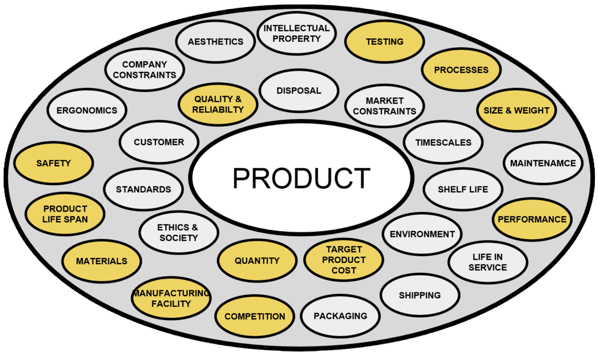
For example:

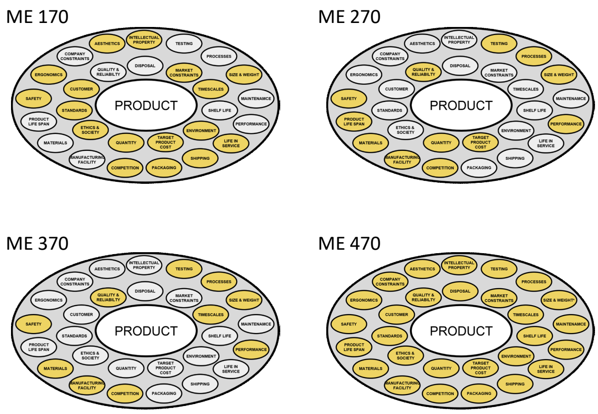
- Able to support 500 N of vertical force
- Produce flow rate of 200 gal/min
- Maintain operating temperature of 32°
- Requires no tools for assembly

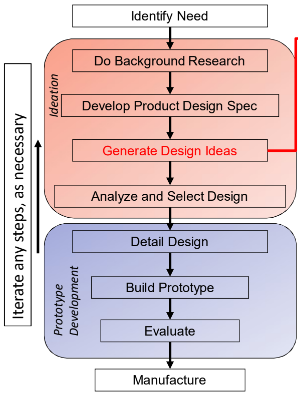
Primary Elements of PDS



Primary Elements of PDS – ME 270



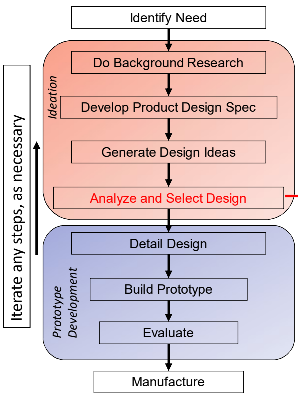




Generate Design Ideas

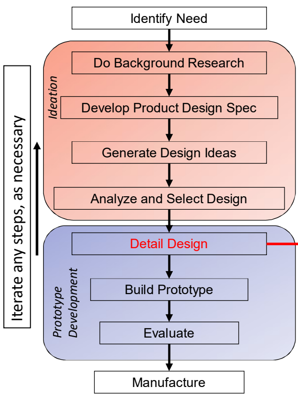
Idea generation:
- BRAINSTORMING – use mult. tools
- SKETCH IDEAS – initial simple 2D, then Refine to 3D
- Rough Prototyping with expendable materials (e.g. paper, card board, foam),

Rules of Ideation
- No criticism or ridicule
- Free flow of ideas
- Record ALL suggestions
- Do not prejudge idea



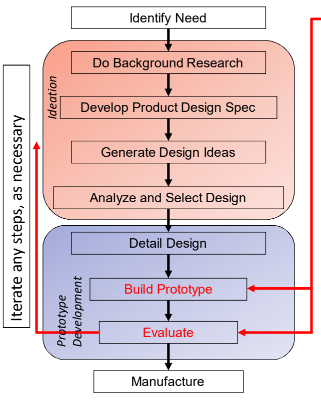
Analyze and Select Design

- Preliminary design evaluation and calculations
- Use structured concept selection process (e.g. Pugh chart/matrix)
- Present to client and explain/defend decision



Detail Design

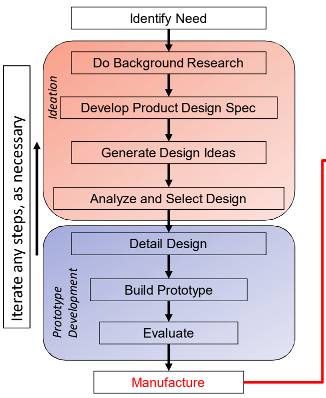
- CAD (Detailed engineering drawings)
- Analysis: Use analytical and computational tools
- Bill of Materials



Build Prototype

Evaluate

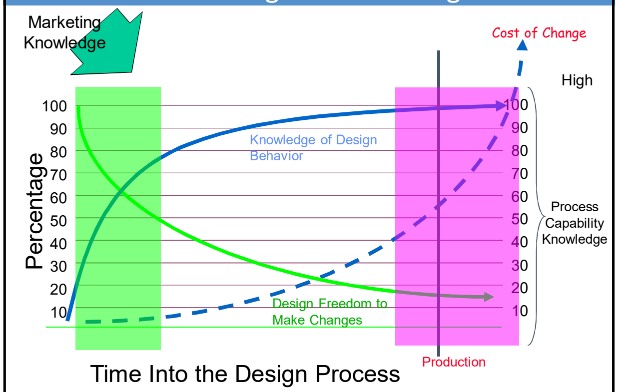
Prototyping and Evaluation:
- Measure performance
- Does it work as predicted?
- Compare against design specs & pre-set metrics
- Redesign prototype as necessary
- Debug prototype and manufacturing processes.
- Determine prototype vs. production cost … is it scalable?



Manufacture

- ME 170/270: Mass Production
- ME 470: Production for Client Needs

Knowledge and Learning



Why DtC?

Prior to the early 90's

Marketing → Design → Manufacturing → Cost Calculation

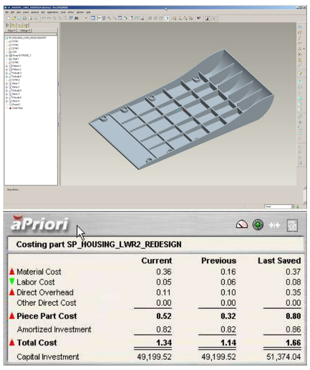
Cost as a design factor starting to surface

Marketing → Conceptual Design → Detailed design → Process Selection → Cost Estimate

70% product cost is committed at early stages of design, only 6% of development cost is spent on design itself…

Design to Cost - Implementation

Goals:
- Estimating cost directly from a part model's geometric features
- In real-time during CAD modeling with little to no extra time and without expert manufacturing knowledge
- In an integrated environment with direct access to enterprise cost data (e.g. updated material cost, machine parameters, labor rates, overhead rates etc.)
- This week's homework will use aPriori software



Cost Analysis

- Variable Cost
- Fixed Cost

- If your company is a bakery, which are fixed costs:

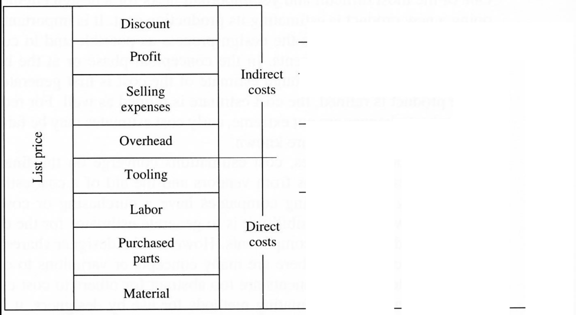
flour light bulbs oven energy boss' salary

cupcake holders capital depreciation building rent

- Fully Burdened Cost

Product Cost Components

Cost breakdown of a bicycle



Cost Factors

Why is die casting more costly than sand casting?

EXHIBIT 1.2.1 Sand-Mold Casting versus Die Casting
Part: New model pump housing *Annual quantity: 10,000 pieces*
Expected product life: 5 years *Normal lot size: 2500 pieces*

Process	Gray-iron casting			Aluminum die casting		
Cost item	Cost of item	Frequency per piece	Unit cost	Cost of item	Frequency per piece	Unit cost
1. Tooling (jigs, fixtures, etc.)	$5000 (patterns)	1/50,000	$0.10	$35,000 (die)	1/50,000	$0.70
2. Material	$0.20/lb	6 lb	$1.20	$0.70/lb	2 lb	$1.40
3. Casting: setup	0.30 h at $8/h	1/2500	$0.00	4.0 h at $8/h	1/2500	$0.01
4. Casting: direct labor	0.08 h at $8/h	1	$0.64	0.04 h at $8/h	1	$0.32
5. Machining:setup	$50 (for 5 operations)	1/2500	$0.02	$25 (for 3 operations)	1/2500	$0.01
6. Machining:direct labor	0.05 h at $8/h (for 5 operations	1	$0.40	0.03 h at $8/h (for 3 operations)	1	$0.24
7. Total unit cost			$2.36			$2.68

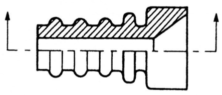
Tooling is a lot more expensive and labor costs are roughly double

Cost Factors

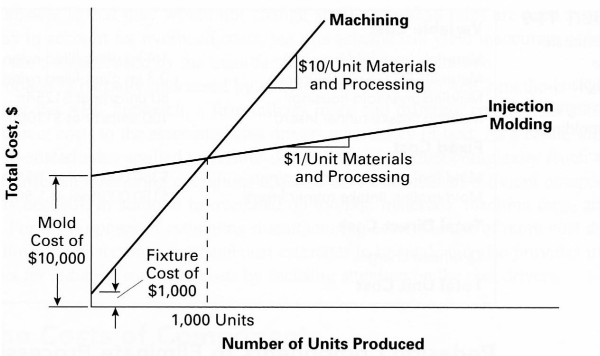
When to choose automated machining?

EXHIBIT 1.2.2 Turret Lathe versus Single-Spindle and Multispindle Automatic Screw Machines (Excluding Secondary Operations)
Part: High-pressure hose fitting *Annual quantity: 500 pieces*
Expected product life: 2 years *Normal lot size: 500 pieces*

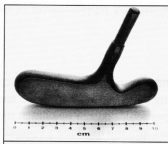
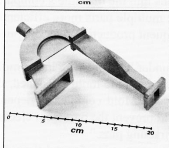
Cost item (machine)	Turret lathe	Per unit	Automatic single-spindle	Per unit	Automatic multispindle	Per unit
1. Tooling (chuck jaws, cams, form tools, other cutters	$350	$0.35	$680	$0.68	$1000	$1.00
2. Setup at $14/h	1 h ÷ 500 pieces	$0.03	2 h÷500 pieces	$0.06	3 h ÷ 500 pieces	$0.08
3. Direct labor and other overhead at $20/h	2 min (1 machine per operator)	$0.67	0.60 min (4 machines per operator)	$0.05	0.20 min (2 machines per operator)	$0.03
4. Total unit cost		$1.05		$0.79		$1.11



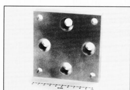
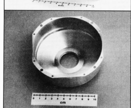
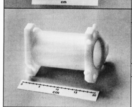
Manufacturing Process Selection



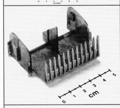
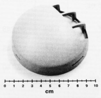
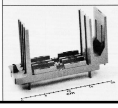
Examples of Costs: Sand Casting

	Fixed Costs	Variable Costs	Volume	Total Unit Cost
	Setup:	Material: $0.713 ea. 260 g of yellow brass	10	$163.21
			100	$28.21
	Tooling: $1.5K no cores	Processing: 4 pcs/hr. at $50/hr.	1000	$14.71
	Setup:	Material: $0.395 ea. 180 g of 712 aluminum	10	$750.40
			100	$120.40
	Tooling: $7K 3 cores	Processing: 1 pc/hr. at $50/hr.	1000	$57.40

Examples of Costs: Machining

	Fixed Costs	Variable Costs	Volume	Total Unit Cost
	Setup: 0.75 hr. at $60/hr.	Material: $9 ea. stock: 1.11 kg of 6061 aluminum	1	$75.00
			10	$21.00
	Tooling: programming: 0.25 hr. at $60/hr.	Processing: 6 min./unit at $60/hr.	100	$15.50
	Setup: 1.75 hr. at $60/hr.	Material: $16 ea. stock: 1.96 kg of 6061 aluminum	1	$386.00
			10	$102.50
	Tooling: programming: 1.0 hr. at $60/hr. Fixtures: $150	Processing: 55 min./unit at $60/hr.	100	$74.15
	Setup: 5.5 hr. at $60/hr.	Material: $25 ea. stock: 4.60 kg of ultra-high molecular weight polyethylene	1	$646.00
			10	$241.00
	Tooling: programming: 2.0 hr. at $60/hr.	Processing: 2.85 hr./unit at $60/hr.	100	$200.50
	Setup: 2.0 hr. at $60/hr.	Material: $12 ea. stock: 1.50 kg of 6061 aluminum	1	$612.00
			10	$396.00
	Tooling: programming: 2.0 hr. at $60/hr.	Processing: 6 hr./unit at $60/hr.	100	$374.40

Examples of Costs: Injection Molding

	Fixed Costs	Variable Costs	Volume	Total Unit Cost
	Setup: Tooling: $18K 8 cavities/mold no actions	Material: $0.075 ea. 45 g of linear low density polyethylene (LLDPF) Processing: 1000 pcs/hr. on an 1800 KN press at $40/hr.	10K 100K 1M	$1.915 $0.295 $0.133
	Setup: Tooling: $10K 1 cavity/mold no actions	Material: $0.244 ea. 10 g of steel-filled polycarbonate (PC) Processing: 160 pcs/hr. on a 900 KN press at $42/hr.	10K 100K 1M	$1.507 $0.607 $0.517
	Setup: Tooling: $18K 2 cavities/mold no actions 3 retracting pins	Material: $0.15 ea. 22 g of modified polyphenylene oxide (PPO) Processing: 240 pcs/hr. on an 800 KN press at $42/hr.	10K 100K 1M	$2.125 $0.505 $0.343
	Setup: Tooling: $80K 1 cavity/mold 1 action 4 retracting pins	Material: $2.58 ea. 227 g of polycarbonate (PC) with 8 brass inserts Processing: 95 pcs/hr. on a 2700 KN press at $48/hr.	10K 100K 1M	$11.085 $3.885 $3.165

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ME 270
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Lecture 3: 3D Printing

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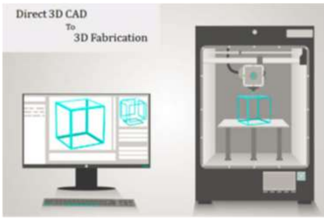
Concurrent Engineering

Product Idea

- Marketing Knowledge
- Material Choice
- Detailed Design Dev.
- Mfg. Process Selection
- Cost Knowledge

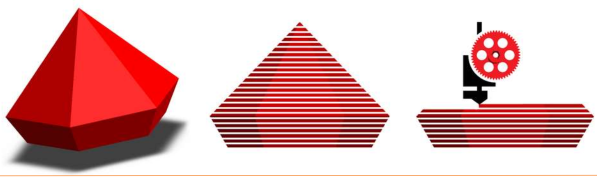
ME 270 – Lecture 3 – Ch. 9 3D Printing

- 3D Printing is an additive manufacturing method
- 3D CAD is "sliced" into 2D cross-sections that are then "printed" on top of each other
- Print size is limited by build volume of the machine



3D CAD is converted into STL "slices"

How these "slices" are fabricated depends upon the method or tool used.



History and Major Technologies

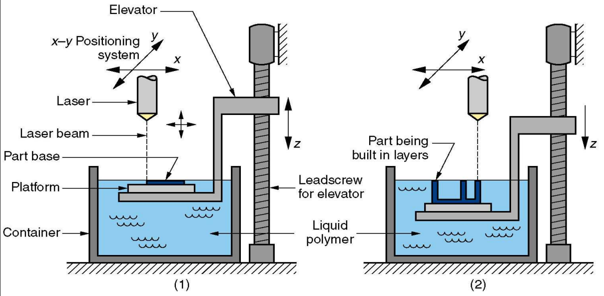
1986	1989	1992	1996
SLA	**SLS**	**FDM**	**MJP**
Stereolithography (apparatus)	Selective Laser Sintering	Fused Deposition Modeling	Multi-Jet Printing
Uses a laser to "cure" an ultraviolet light curable photopolymer (resin) layer	Uses an laser to melt a polymer powder layer	A heated nozzle melts an extruded polymer filament	Uses droplets of UV curable plastic

Stereolithography Apparatus (SLA)

Starts with a vat of photosensitive liquid polymer with the stage at top.

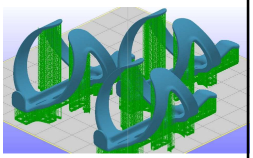
Prints a "porous" staring layer to separate the part from the stage.

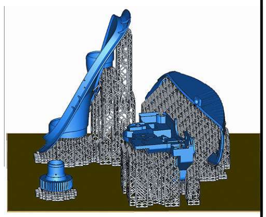
The stage is lower, then the BOTTOM most layer is printed, etc.



SLA Support Structures – "Scaffolding"

- Needed because the density of the cured resin is greater than that of the uncured.
- Only needed when the overhang angle is greater than some nominal θ, roughly 45°

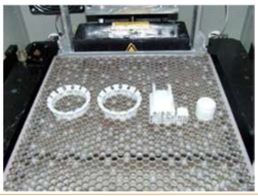




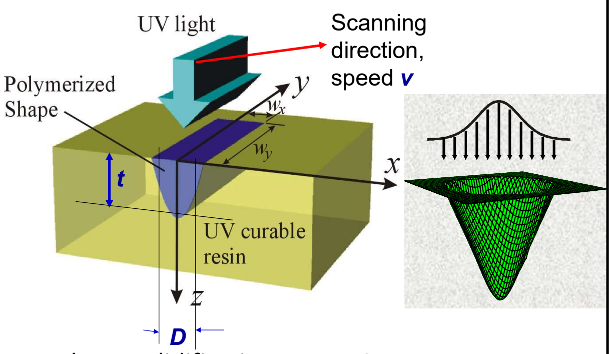
Stereolithography (SLA) Advancements:

- Layers are generally each 0.05-0.15 mm thick
- Support "pillars" (~100 μm dia.) needed every 2-3 mm for some "overhanding" or "bridging" structures.
- Recent material improvements: 1) material less brittle, 2) flexibility improved, and 3) less material shrinkage during UV post cure. (now <1% when before it was 1-2%)

Video:
http://featurebasedcosting.com/DFMeBook/eBook_mp4s/sla.mp4



Laser Scanning Profile



Volume solidification rate: $Q \approx D \cdot t \cdot v$

Part Build Time in SLA

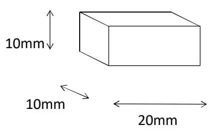
Time to complete a single layer :

$$T_i = \frac{A_i}{vD} + t_d \qquad T_{total} = \sum_{i=1}^{j} T_i$$

where T_i = time to complete layer i; A_i = area of layer i; v = average scanning speed of the laser beam at the surface; D = diameter of the "spot size;" t_d = delay time between layers to reposition the worktable; t = layer thickness; and n = number of layers *(height / t).*

$$T_{total} = \sum_{i=1}^{j}\left(\frac{A_i}{vD} + t_d\right) = \frac{V_{part}}{Q} + n \cdot t_d = \frac{V_{part}}{D \cdot t \cdot v} + n \cdot t_d$$

SLA Example:



Stage movement: **0.2mm/step**, **10s**/step
Laser: **1m/s** (velocity) **0.2mm** (dia.)

Number of layers?

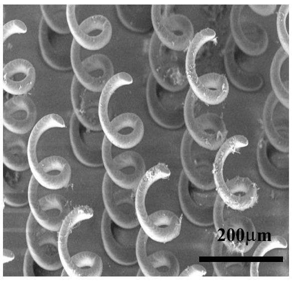
Time to "write" one layer (including one stage movement in z-direction)?

Total time to fabricate?

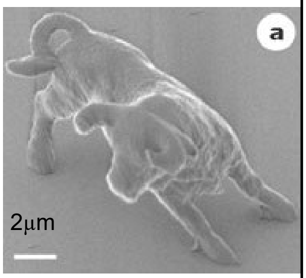
Volumetric method for approximating time to fabricate?

SLA – resolution pushed to the extreme

Spiral Lattice
(Zhang, Berkeley)



The Nanobull
(Kawata, Japan)



Resolution down to 75 nanometers are feasible!

SLA: Pros and Cons

Pros:
- Uses less support structures than some other methods
- Can achieve the highest resolution & smoothest top surface compared to other RP methods
- Can make clear rigid polymers (polycarbonate like).

Cons:
- No easy way to remove support scaffolding → must cut
- Messy to clean – resin can be trapped in small features
- Material is generally hard and brittle – easy to crack
- Final cure required – generally in UV oven for 30-60 min
- Thin parts can warp easily

Selective Laser Sintering (SLS)

- Moving laser beam sinters heat-fusible powders
- After each layer, a new layer of loose powders is spread across the surface. Typically 50 µm thick.
- In areas not sintered, the powders are loose and can be poured out of completed part

SLS Machines and Parts

SLS Powder Management

- After each layer is scanned, the powder bed is lowered by one layer thickness, typically 0.05mm
- SLS machines preheat bulk powder in the powder bed to just below its melting point. Why?

Faster because it is less work for the laser to melt.
Higher tolerance because *absorbed water* is released prior to laser sintering.

- No support structures, but powder in a *10 mm* thick shell around the part is *thermally damaged*.
  - Only a portion of this can be reused.
  - Reused powder must be *"filtered"* before re-use.
- One problem with powders:

SLS: Pros and Cons

Pros:
- No need for: 不需要支撐
- Material is strong and can be machined later.
- More chemically inert than most RP methods
- Higher melt temp than most RP methods.

Cons:
- Only 1 color – usually white, nothing "clear"
- Surface is generally not very smooth (often porous)
- "Dust" continues to come off surfaces even after brushing
- Often ovens are needed for parts to achieve full strength.
- Thin parts may warp

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ME 270
Design for Manufacturability

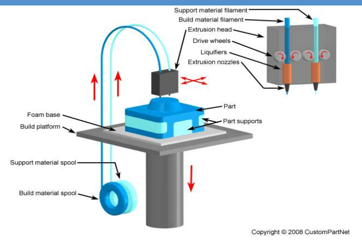
Timothy H. Lee, PhD
Fall 2021
Lecture 4: 3D Printing

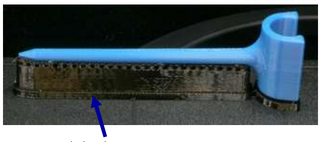
Fused Deposition Modeling (FDM)

- Continuous filament of molten wax or thermoplastic is printed from a heated needle extruder
- Extrudate is "*cold welded*" to the previous material
- Support structures are water soluble material, but slight overhangs can be tolerated, i.e. a tapered slope.
- Unlike SLA or SLS, FDM can print multiple colors using multiple extruder heads.
- Surface finish is generally not a good as other methods

Video:
http://featurebasedcosting.com/DFMeBook/eBook_mp4s/FDM.mp4
https://www.youtube.com/watch?v=WHO6G67GJbM

FDM Fabrication of Models





support structure

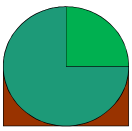
FDM: Pros and Cons

Pros:
- Typically the largest volumes and fastest fabrication

Cons:
- Overhanging structures need a lot of
- High resolution → small filament →
- Difficult to achieve surface
- No clear or elastomeric materials available.
- Warpage of thin parts

FDM Example:

The 2 color ball below is to be fabricated using FDM. Assume a layer thickness of **0.3 mm**, width of **0.8 mm**, at a rate of **3 cm/s**. The stage movement time is **1 s** per layer, but takes **8 s** to switch between any two materials.



Where do we need support material?
How often do we need to switch on the bottom half?
How often do we need to switch on the top half?
Part volume?
Number of layers?

4 cm diameter

Multi-Jet Printing

- MJP is similar to inkjet printing, but instead of jetting drops of ink onto paper, the 3D printer jets and UV-cures *tiny droplets* of liquid
- Where overhangs or complex shapes require support, the printer jets a removable water-soluble gel-like support material.
- Unlike SLA, models are ready to handle and use right out of the printer, with no post-curing needed.

Video:
http://featurebasedcosting.com/DFMeBook/eBook_mp4s/polyjet3Dprinter.mp4

MJP: Pros and Cons

Pro:

- Color !
- One of the few methods that can make flexible
-
- Thin layers (20 µm typical)

Con:

- Brittle material often cracks or breaks, elastomers easily rip or crumble when compressed
- Support material, requires 100% volume, is often time consuming to remove, and if you need a lot, can be expensive.

Ford Lab RP Machines

MEL has 4 high resolution 3D Printing machines:

1. **SLA**: Liquid photopolymer bath cured by UV laser. Too brittle to use as structural material. High temperature, high resolution.
2. **FDM**: melted thermoplastic filament. Strong enough for usable parts. ABS & PC material 40 x 35 x 40 cm volume. $0.32 / g.
3. **SLS**: powders that are bonded thermally by a laser. Slow but durable parts (Nylon like). 18 x 22 x 30 cm volume. $0.36 / g.
4. **MJP**: photopolymer ink jet printing with UV light hardening of each layer. Can make elastomers & translucent material. Too brittle

Information: https://www-s.mechse.uiuc.edu/rplab/

Self Assembly

- Unique advantage of some 3D Printing methods is the possibility of multiple parts created that are already assembled.
- 3D Printing methods where this is possible:

  FDM, SLS, MJP
- Where it is not:

  SLA

Advantages of 3D Printing

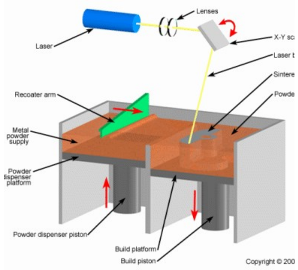
- Easy and quick to change part design and produce a new version.
- Limited skills or training needed to make parts
- Cost of producing one part, or a few unique parts, is relatively low.
- Some parts can be made already assembled.

Problems with 3D Printing

- *Part tolerance and/or surface smoothness*
  - Staircase appearance for a sloping part surface (due to slicing and layer thickness)
  - Shrinkage and distortion of RP parts
  - Part dimensions: *holes are smaller and posts bigger*
- Limited variety of materials in RP
  - Mechanical performance of the fabricated parts is limited by the materials
- Cost/removal of support material *(when needed)*
- Per part cost for large quantities is generally higher
- Part size is generally limited.

Metal 3D Printing

Direct Metal Laser Sintering (DMLS) Direct Metal Deposition (DMD)



Selective laser sintering of metal powders – like SLS

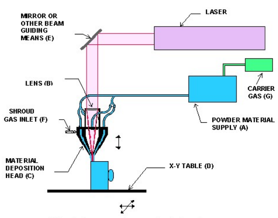
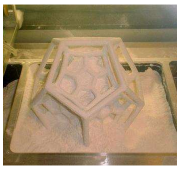


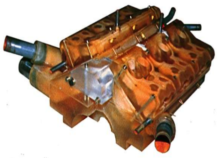
Fig. 8. Laser engineered net shaping.

Laser-induced metal deposition of powder stream – like FDM

3D Printing Applications

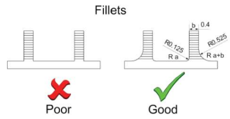
1. *Prototypes* – to visualize your idea, for wind tunnel testing, or for small batches
2. *Pattern* for casting mold
3. *Assembly* testing
4. To make parts with *intricate internal* geometries
5. *Medical Apps* - one-of-a-kind parts



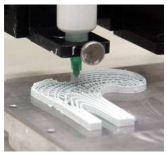


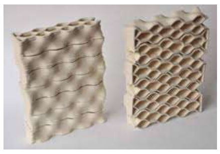
3D Printing Design Guides

- Add fillets to stress points (i.e. radius ~ wall thickness).



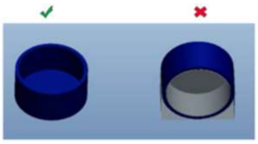
- Remove all non-structural material (no extra cost!) ***cost driver is model volume*** not volume features.





3D Printing Design Guides

- Use SLS and FDM **only** for mechanical parts. They are strong and flexible enough for mechanical prototypes
- Threads in general cannot be reliably made (or cleaned) or have sufficient strength.
- Use orientation that minimizes use of support material.



- For FDM vertical orientation is generally the weakest (cold fusion direction of material).

Doodler & Concrete 3D Printing?

3D Writing Pen?

Print a House?

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ME 270
Design for Manufacturability

Timothy H. Lee, PhD

Fall 2021

Lecture 5: Machining

ME 270 – Lecture 5 – Ch 7 Machining

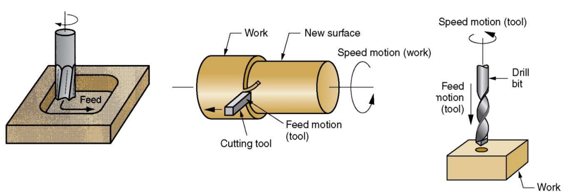
THEORY OF METAL MACHINING:

- Milling
- Turning, Taylor Tool Life Calculation
- Drilling, tapping, and grinding
- Tolerance and surface roughness
- Design Advisor
- Machining Economics - Cost calculations

Types of Machining

Where 3D Printing is an ***additive*** process, machining is:

- material is removed until the desired shape is reached
- done using a sharp cutting tool or abrasive medium



Advantages of Machining

- Used on almost any material: metals and plastics
  - *except*:
- Low cost for part revision
  - Small changes to part geometry is inexpensive
  - Good for *product development* or early production
- Good dimensional accuracy and surface finish
  - Tolerance of up to +/- 0.001 inch [0.04mm]
- *Lower investment cost* than most other fabrication methods (except 3D Printing)
  - Non automated tooling is generally less expensive

Disadvantages of Machining

- Wasteful
  - Because it is *subtractive* it inherently produces scrap
  - Waste can be
- Does not
  - *Slower* than almost any other production method
  - *Tool wear* higher if you increase production rate
- Does not do well
  - Material needs *room to be clamped* (held down)
  - Tool needs room for *access* to remove material
  - *Sharp corners* are not easy with round tools

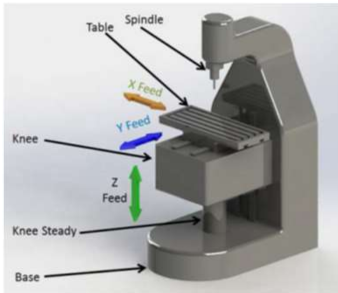
Milling

Slow Motion Milling

- The Mill is a standard tool of machine shop
- Fixed spindle with material clamped to precision gantry 3-Axis

Computer Numerical Control (CNC)

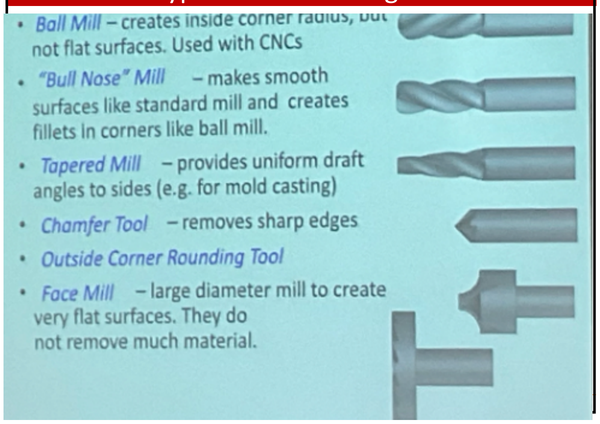
- Computer control of machining axes enable rounded parts



End Mill – standard mill cutting tool

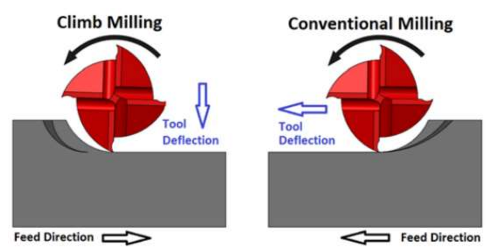
- Some have 2-flutes others have 4-flutes?
  - More flutes are *stiffer* and provide *better surface finish*,
  - Less flutes *increase material removal* rate of soft materials and are *less expensive*.
- Cuts in *any direction* - can plunge straight into the material or cut laterally

Types of Mill Cutting Bits



Milling Direction and Feed

- In Climb milling the tool is "pulled" into the work material, deflecting and gantry table must be
- Conventional milling is safer and typically used on less expensive non-production environments.

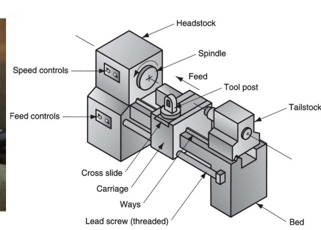


Turning using a "Lathe"

Slow Motion Lathe Cutting

- Tool is stationary and workpiece is rotated.
- Ideal for cylindrical geometries.
- Single point cutting tool is mounted in the tool post

LAYOUT OF STANDARD 2 AXIS LATHE

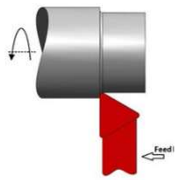


Roughing vs. Finishing

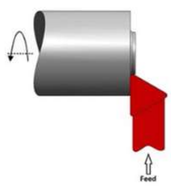
- Roughing - removes large amounts of material from starting workpart
  - Close to desired geometry (*not to full depth*)
  - Feeds and depths: large
  - Cutting speeds: slow
- Finishing - completes part geometry
  - Final dimensions, tolerances, and finish
  - Feeds and depths: Small
  - Cutting speeds: fast

Lathe Operations

- – cutting tool is fed parallel to the rotating axis reducing the outside diameter of the part

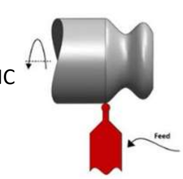


- – cutting tool is fed radially inward to create a flat face on the part end.

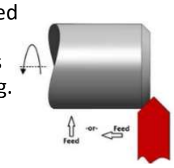


Lathe Operations

- – cutting tool is fed along a part or “profile” to obtained the desired geometry. CNC control is required.

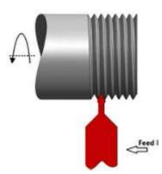


- – cutting tool is fed into an edge to break the sharp edge. If large amount of material is removed it becomes profile turning.

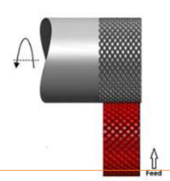


Lathe Operations

- – feed of cutting tool matches the rotational speed.

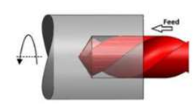


- – does not removed material but does create a rough, diamond, or square patterned surface for better grip.

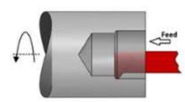


Lathe Operations

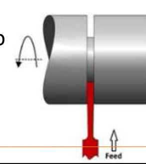
- – drill bit is stationary, mounted to the tailstock not toolpost. Must be concentric.



- – cutting tool removes material from an existing hole.

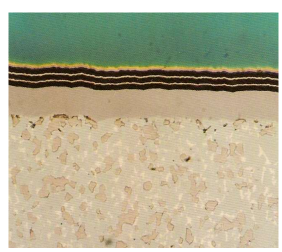


- – a thin cutting tool is fed radially inward to remove a finished part.

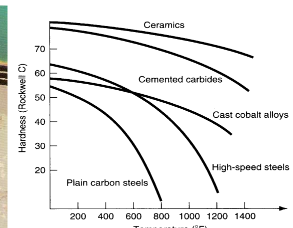


Types of Cutting Tools

Coated Carbide Tool



Photomicrograph of cross section of multiple coatings on cemented carbide tool (photo courtesy of Kennametal Inc.)



Plain carbon steel shows a rapid loss of hardness as temperature increases. High speed steel is substantially better, while cemented carbides and ceramics are significantly harder at elevated temperatures.

Cutting Conditions in Machining

Lathe Chip Formation

- Material removal rate:

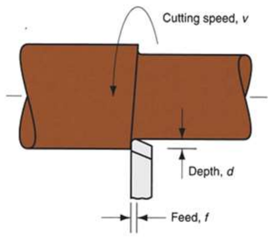
  $M_{RR} = v \bullet f \bullet d$

  where v = *cutting speed*;
  f = *feed*;
  d = *depth of cut*

- Cutting Power:

  $P_c = F_c \bullet v$

  where F_c = *cutting force down on tool*
  v = *cutting speed*;



Power Requirement

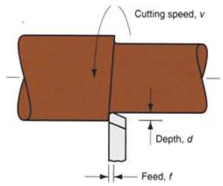
The *specific energy:*

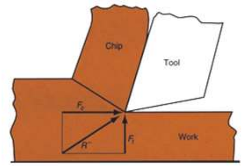
Cutting power per unit volume removal rate

$$U = \frac{P_c}{M_{RR}} = \frac{F_c v}{v f d} = \frac{F_c}{f d}$$

Energy converted to:

Approximation: U ~hardness H





Specific Energy (U) For Cutting

Approximate specific-energy requirements

MATERIAL	SPECIFIC ENERGY*	
	J/mm^3	hp-min/in^3
Al alloys	0.4-1.1	0.15-0.4
Cast irons	1.6-5.5	0.6-2.0
Copper alloys	1.4-3.3	0.5-1.2
High-Temp alloys	3.3-8.5	1.2-3.1
Mg alloys	0.4-0.6	0.15-0.2
Ni alloys	4.9-6.8	1.8-2.5
Refractory alloys	3.8-9.6	1.1-3.5
Stainless steels	3.0-5.2	1.1-1.9
Steels	2.7-9.3	1.0-3.4
Titanium alloys	3.0-4.1	1.1-1.5

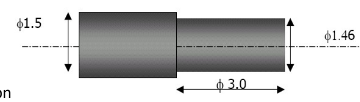
* At drive motor, corrected for 80% efficiency;

1 hp = 550 ft·lbs/s = 396,000 in·lbf/min

In-class exercise – Cutting force estimation

Parameters:

- cutting speed v = 1860 in./min,
- *feed* = 0.03 in/rev.
- *cut depth* = 0.02 in.
- U = 1.47 hp.min/in^3
- reduce dia of 3 in. section



Find:

M_{RR} (in^3/min) =

Power (hp) =

Cutting force (lbf) =

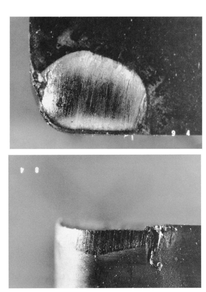
Cutting Time (min) =

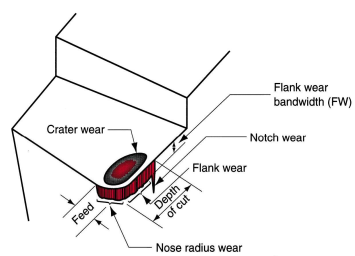
Three Modes of Tool Failure

1. Cutting force is excessive and/or dynamic, leading to brittle fracture:
2. Cutting temperature is too high for the tool material:
3. Preferred wearing of the cutting tool:

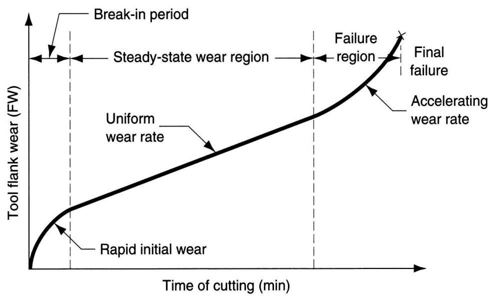
Preferred Mode: Gradual Wear

- Longest possible tool life, wear locations:
  - Crater wear location:
  - Flank wear location:



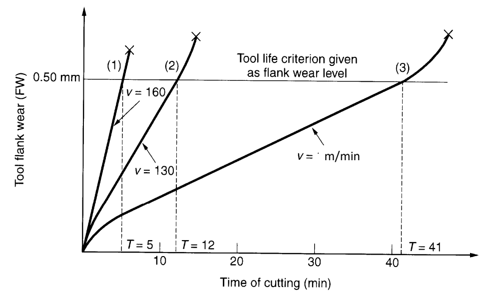


Tool Wear vs. Time



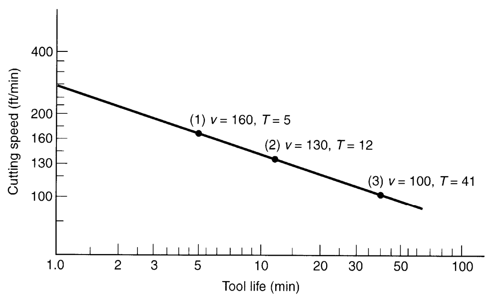
Tool wear as a function of cutting time. Flank wear (FW) is used here as the measure of tool wear. Crater wear follows a similar growth curve.

Effect of Cutting Speed



Effect of cutting speed on tool flank wear (FW) for three cutting speeds, using a tool life criterion of 0.50 mm flank wear.

Tool Life vs. Cutting Speed



Log-log plot of cutting speed vs tool life.

Taylor Tool Life Equation

where v = cutting speed;

T = tool life; and

n and C are parameters that depend on feed, depth of cut, work material, and tooling material, but mostly on material (work and tool).

- n is the *slope of the plot*
- C is the *intercept* on the speed axis at one minute tool life

Example Problem

A tool run at 160m/min lasts for 5 min. If the tool is run at 100m/min it lasts for an average of 41 min.

What is C and n?

Typical Values of n and C

Tool material	n	C (m/min)	C (ft/min)
High speed steel:			
Non-steel work	0.125	120	350
Steel work	0.125	70	200
Cemented carbide			
Non-steel work	0.25	900	2700
Steel work	0.25	500	1500
Ceramic			
Steel work	0.6	3000	10,000

Cutting Fluids (Lubricants and Coolants)

Function is to improve cutting performance:

1. Improve chip
2. Reduce
3. Improve surface

Types of cutting fluids:

1. Generally water based:
   – more effective at cutting speeds that are:
2. Generally oil based:
   – more effective at cutting speeds that are:

Mechanical Science & Engineering

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ME 270
Design for Manufacturability

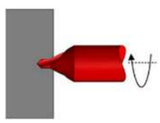
Timothy H. Lee, PhD
Fall 2021
Lecture 6: Machining

Drilling

- Tool usually has 2 flutes and cuts only along the *rotational* axis.
- Can be performed on a mill or drill press (*toolbit* rotates) or a lathe (*workpart* rotates).
- – hole that goes all the way through
- – hole that does not go completely through

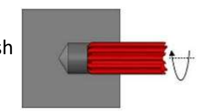
Drilling Operations

- – used to start a hole. Bits are short and rigid to avoid deflection or “walking” along surface. Few sizes.
- – center does not cut but “chisels” material toward cutting edge. Many sizes

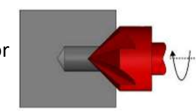


Drilling Operations

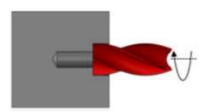
- – enlarges a hole slightly to create a fine surface finish at a precise diameter.



- – forms a chamfer along the leading edge of an existing hole. Can be for safety or to guide parts into hole.

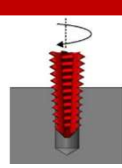


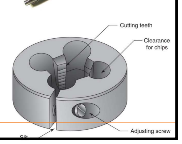
- – adds a blind flat bottomed. Often to hide the heads of screws.



Tap and Die

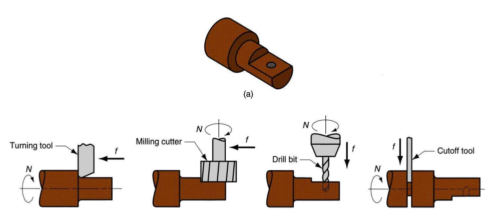
- Tap is a tapered spiral cutting tool (over 3-5 treads), use to create *internal* threads in a *existing hole*.
- A Die is a tapered cutting tool to create *external* threads on a shaft..
- Tool is rotated *forward and backward* to break cutting chips.
- Through holes are preferred to *prevent clogging* with chips.
- Large driving force (up to 20 chips are created simultaneously), so cutting or *tapping fluid* is required.





Mill-Turn Centers

Highly automated machine tool that can perform the operations:

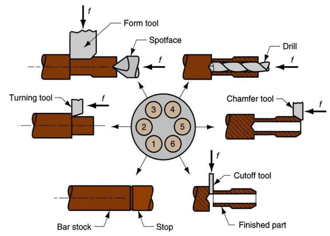


Video: http://featurebasedcosting.com/DFMeBook/eBook_mp4s/5axisMilling.mp4

Video: http://featurebasedcosting.com/DFMeBook/eBook_mp4s/cncLathe.mp4

Multiple Spindle Bar Machines

- More than one spindle, so multiple parts machined simultaneously by multiple tools. Example:



After one machining cycle, spindles are indexed (rotated) to next position

Grinding

- Most machining uses sharp cutting tools, grinding uses an abrasive media to remove material.
- More precise abrasive processes include: *honing*, *polishing*, *buffing*, and *lapping*.
- Material removal rate is usually *low*.
- Typically a *secondary process* after final part shape is nearly achieved.
- Main advantages: high *quality surface,* can hold *tight tolerances*, and be used on *most materials*.

Tolerance and Surface Roughness

Process	Dimensional Accuracy **		Surface Roughness	
	in	mm	µin	µm
Milling	0.005	0.127	63	1.6
Turning	0.005	0.127	63	1.6
Rough Grinding	>.020	>0.5	> 300	>8
Finish Grinding	0.0002	0.005	8 - 16	0.2 - 0.4
Honing	0.0002	0.005	4 - 16	0.1 - 0.4
Lapping	0.00005	.001	1 - 8	.025 - .2
Buffing	n/a	n/a	1 - 8	.025 - .2
Polishing	n/a	n/a	1 - 8	.025 - .2

** Accuracy is highly dependent on setup specifics. Average values given.

Material, Holding & Tolerances affect Costs

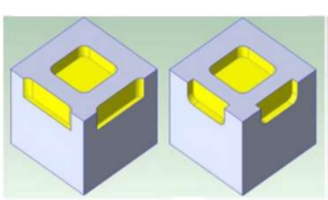
- *Machinability* is a normalized scale on how quickly and easily it is to remove a certain amount of material (standard = 1212 steel).
- *Material* choice determines costs
  - Different materials cut at different feeds and speeds
  - Harder materials increase tool wear, and slow process
- Some part designs are difficult to *hold* requiring *fixtures*
- Allowable *tolerances* effect costs both in tooling and fixtures

Material Machinability

1018 Steel	78%
1030 Steel	70%
1050 Steel	454%
1212 Steel *	100%
4140 Alloy Steel	66%
4340 Alloy Steel	57%
303 Stainless Steel	78%
304 Stainless Steel	45%
410 Stainless Steel	54%
6061 Aluminum	360%
Cast Aluminum	450%
Cast Magnesium	480%

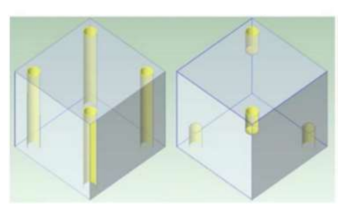
Design Advisor – Limit Setup Changes

- Design for fewest number of part setup changes
  - Tool change and part setup can dominate part cost
  - Features created in the same setup will have dimensional accuracy better than using multiple setups



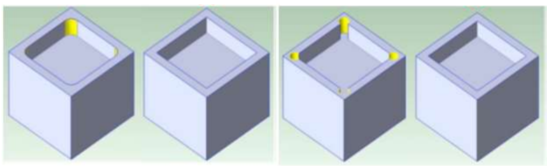
Design Advisor – Holes

- Using through holes rather than blind holes limits setups
- Longer machining time, but often lower cost and improves tolerance alignment



Design Advisor – Corners & Edges

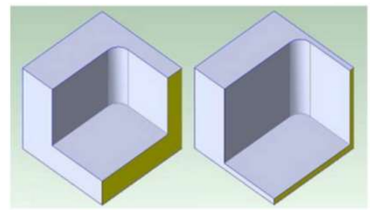
- Sharp 3-point corners *cannot be machined*
- Use *fillet* on inside corner *parallel to cutting axis*
- Set fillet to slightly larger than tool radius (e.g. for 0.25” end mill, set fillet radius to *0.125”*)
- To mate to a rectangular part, *overcut corners*



Design Advisor – Limit Thin Sections

- Parts with narrow features, thin walls, or long protrusions should be avoided. Why?

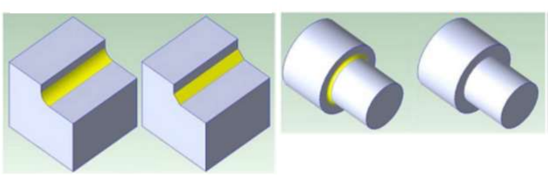
Part must be rigid enough to withstand cutting forces



Design Advisor – Corner Rounding

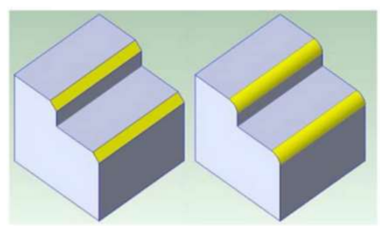
- Use corner radii that match machining tool geometry – reduces tool changes
- Sharp inside corners concentrate stress

Milling Lathe



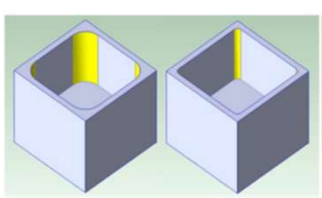
Design Advisor – Chamfer Outside Corners

- Unlike inside corners it is easier and less expensive to chamfer outside corners.



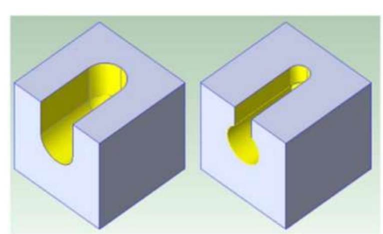
Design Advisor – Tool Size and Reach

- Design part so that largest tool can be used.
- *Larger* tools are *more expensive*, but *wear longer* and are stiff enough to create *deep features fast*.



Design Advisor – Undercut Features

- Undercut features require special tools or multiple setups. Avoid if at all possible.



Design Advisor – Volume & Tolerances

- Machining time is largely based on *volume* of material that needs to be removed.
  - Select *blanks just larger* than part volume (raw material is usually rectangular or cylindrical).
  - If a large amount of material needs to be removed, can the design be changed to *multiple parts* with each needing much less machining?
- Standard machining tolerance is 5 thou *(0.005”),* requiring higher tolerance gets very expensive
- Requiring *smoother interior surfaces* increases cost.

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Maximizing Production Rate

- Maximizing production rate = minimizing cutting time per unit
- In turning, total production cycle time for one part consists of:
  1. Part handling time per part = T_h
  2. Machining time per part = T_m
  3. Tool change time per part = T_t/n_p, where n_p = number of pieces cut in one tool life (round down)
- Total time per unit product for operation:

T_c =

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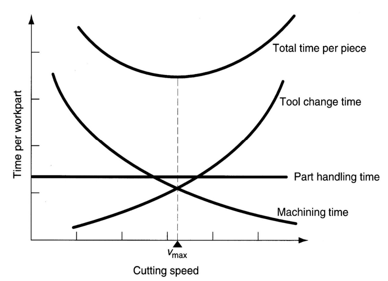
Cycle Time vs. Cutting Speed



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Minimizing Cost per Unit

- In turning, total production cycle cost for one part consists of:
  1. Cost of part handling time = C_oT_h , where C_o = cost rate for operator and machine
  2. Cost of machining time = C_oT_m
  3. Cost of tool change time = C_oT_t/n_p
  4. Tooling cost = C_t/n_p , where C_t = cost per cutting edge
- Total cost per unit product for operation:

C_c =

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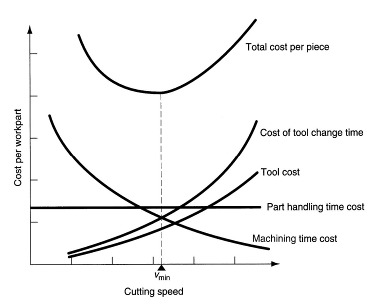
Unit Cost vs. Cutting Speed



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Comments on Machining Economics

- As *C* and *n* increase in Taylor tool life equation, optimum cutting speed
  - Cemented carbides and ceramic tools, compared to HSS, can be used at speeds:
- v_{max} (production) is always than v_{min} (cost)
  - Reason: C_t/n_p term in unit cost equation pushes optimum speed to left in the plot
- As tool change time T_t and/or tooling cost C_t increase, cutting speed should be
  - Disposable inserts have an advantage over regrindable tools if tool change time is significant

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ME 270
Design for Manufacturability

Timothy H. Lee, PhD

Fall 2021

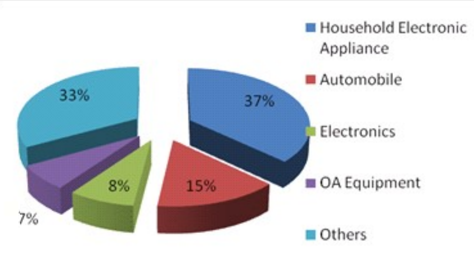
Lecture 7: Plastic Molding

ME 270 – Ch 2 Plastic Molding

- Types of polymers & typical properties
- Polymerization & molecular weight
- Crystallization & density
- Extrusion & injection molding
- Calendaring, fiber, and filament processing
- Thermoset processes & polymer casting
- RIM, SFM, and Rotomolding Processes
- Blow molding and Injection blow molding
- Thermoforming
- Design Advisor
- Molds, cores and lifters

Applications of Plastics


HDPE (replaces cast iron, Cu**)**

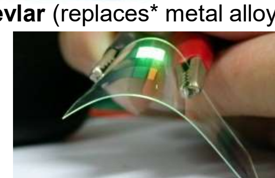


PVC

Kevlar (replaces* metal alloys)

Nylon (replaces silk)

Natural Rubber



Flexible Electronics

Polymer Categories

Three categories:

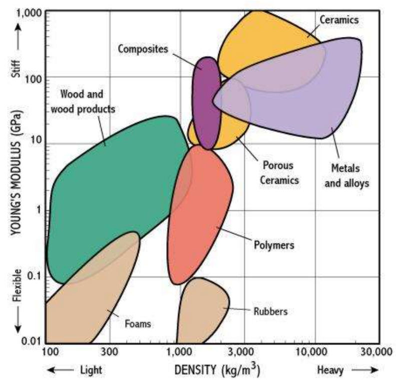
1. 热塑性（加热时会熔化粘性viscous liquid，冷却后会硬化成固）聚乙烯（PE）、聚丙烯（PP）、聚氯乙烯（PVC）、聚苯乙烯（PS
2. 热固性（在加热和固化后，不会在加热时熔化）环氧树脂、酚醛树脂
3. 弹性体（高弹性，可以在受到外力后恢复原状）丁苯橡胶（SBR）、丁腈橡胶（NBR）

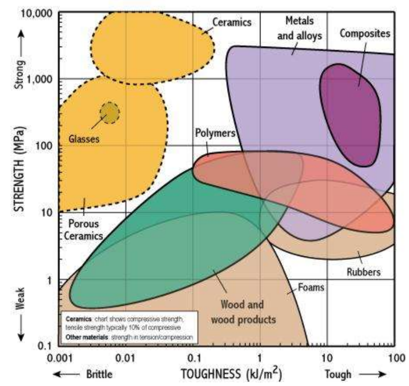
Which can be called “plastic”?12

Which can be called “rubber”?3

Which can be recycled?1

Mechanical Properties





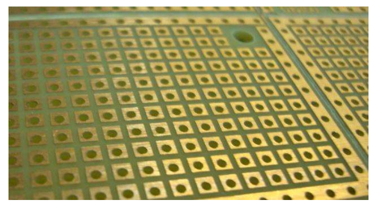
Thermoplastic Polymers - Thermoplastics

Solid materials at room temperature but viscous liquids when heated:

- Can be easily and economically shaped into products
- Melting can be done?
- Typical Examples: ABS, PMMA, PTFE, Nylons, PET, PC, PE, PP, PS, PVC

Thermosetting Polymers - Thermosets

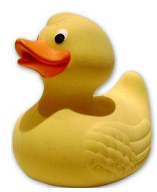
- Cannot be repeatedly melted
  - When initially heated, they soften and flow for molding
  - Elevated temperatures activates **cross linking** that hardens the material into an infusible solid
  - If reheated, rather than soften, thermosets?
- Typical Examples: Phenolic, Epoxy, PU, Polyimides
- *The Statue of Liberty has a polyurethane top coat to provide graffiti protection.*

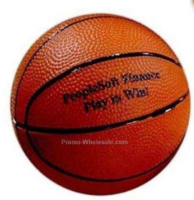


Elastomers, also called?

Polymers that exhibit extreme elastic extensibility

- Some elastomers can be stretched by a factor of 10 and remain elastic.
- Share a similar ***molecular structure*** with?
- Typical Examples: Isoprene, natural rubber, Silicone rubber, Fluoroelastomers



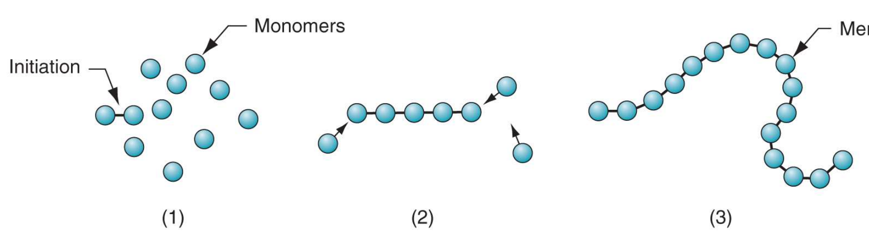


Polymer Notation

Polymer	Monomer	Repeating mer	Chemical formula
Polypropylene	H H C = C H CH_3	$[$ H H – C – C – H CH_3 $]_n$	$(C_3H_6)_n$
Polyvinyl chloride	H H C = C H Cl	$[$ H H – C – C – H Cl $]_n$	$(C_2H_3Cl)_n$
Polystyrene	H H C = C H C_6H_5	$[$ H H – C – C – H C_6H_5 $]_n$	$(C_8H_8)_n$
Polytetrafluoroethylene (Teflon)	F F C = C F F	$[$ F F – C – C – F F $]_n$	$(C_2F_4)_n$
Polyisoprene (natural rubber)	H H H C – C = C – C H CH_3 H	$[$ H H H – C – C = C – C – H CH_3 H $]_n$	$(C_5H_8)_n$

Polymerization

- Addition polymerization
  - Model of addition (chain) polymerization: (1) initiation, (2) rapid addition of monomers, and (3) resulting long chain polymer molecule with *n* mers at termination of reaction



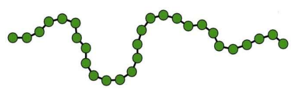
Degree of Polymerization - n

- Since molecules in a given batch of polymerized material vary in length, *n* for the batch is an:
- The mean value of *n* is called the *degree of polymerization* (DP) for the batch
- DP affects properties of the polymer
  - Higher DP effects mechanical strength:
  - Higher DP in the fluid state effects viscosity:

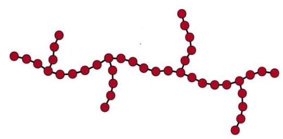
Typical Values of DP and MW

Polymer	DP(*n*)	MW
Polyethylene	10,000	300,000
Polyvinylchloride	1,500	100,000
Nylon	120	15,000
Polycarbonate	200	40,000

Polymer Molecular Structures

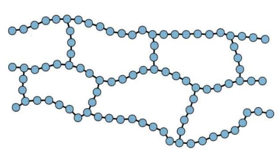


- Linear structure
  - Which polymer type(s):

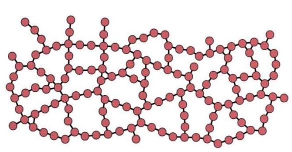


- Branched structure
  - Which polymer type(s):

Polymer Molecular Structures



- Loosely cross-linked
  - Which polymer type(s):



- Tightly cross-linked
  - Which polymer type(s):

Crystallinity in Polymers

- Both amorphous and crystalline structures are possible, although the tendency to crystallize is much less than for metals
-
- For those that can, the *degree of crystallinity* (the proportion of crystallized material in the mass) is always less than 100%

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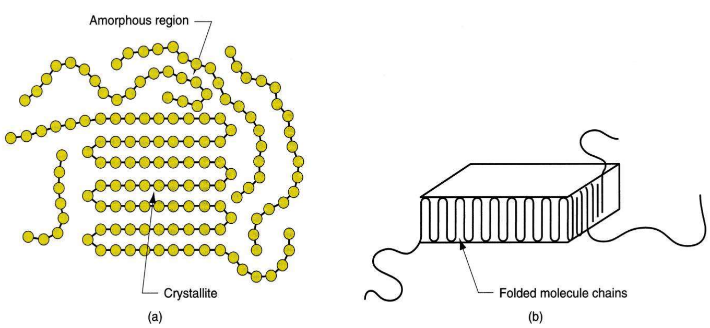
Crystalline Polymer Structure



Crystallized regions in a polymer: (a) long molecules forming crystals randomly mixed in with the amorphous material; and (b) folded chain lamella, the typical form of a crystallized region.

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Crystallinity and Properties

- As crystallinity is increased in a polymer
  - Density: ↑
  - Stiffness, strength, and toughness: ↑
  - Heat resistance: ↑
  - If the polymer is nearly transparent in the amorphous state, when partially crystallized it becomes:
    opaque

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Low Density & High Density Polyethylene

Polyethylene type	Low density	High density
Degree of crystallinity		
Specific gravity	0.92	0.96
Modulus of elasticity		
Melting temperature		

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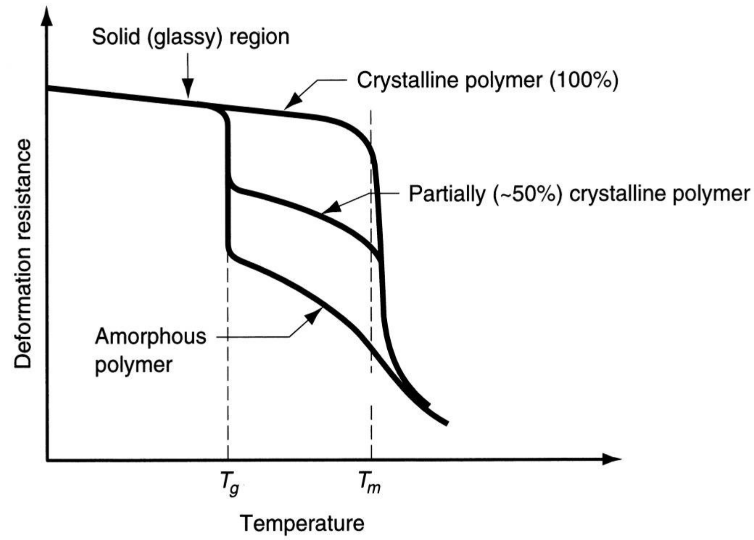
Strength vs. Temperature



Additives

Either alter the molecular structure or add a second phase, in effect transforming the polymer into a composite, types:

- Fillers – to strengthen polymer or reduce cost
- Plasticizers – to soften polymer and improve flow
- Colorants – pigments or dyes
- Lubricants – to reduce friction and improve flow
- Flame retardants – to reduce flammability of polymer
- Cross-linking agents – for thermosets and elastomers
- Ultraviolet light absorbers – reduce sunlight degradation
- Antioxidants – to reduce oxidation damage

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ME 270
Design for Manufacturability

Timothy H. Lee, PhD

Fall 2021

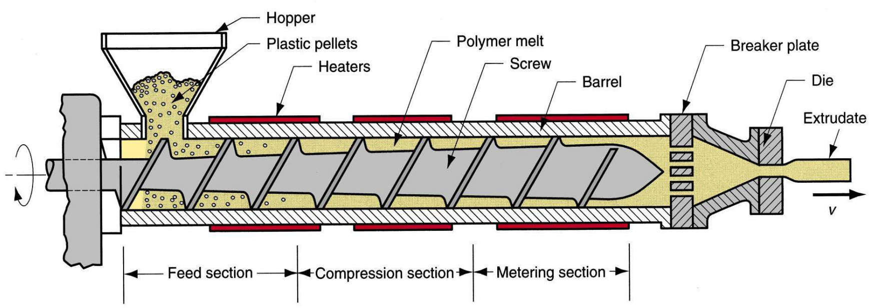
Lecture 8: Plastic Molding

Processing of Polymers

- Polymers are nearly always shaped in a heated, highly plastic state
- Common operations are extrusion and molding
- Molding of thermosets is more complicated because of cross-linking
- Thermoplastics are easier to mold and a greater variety of molding operations are available
- Rubber processing has a longer history than plastics, and rubber industries are traditionally separated from plastics industry, even though processing is similar

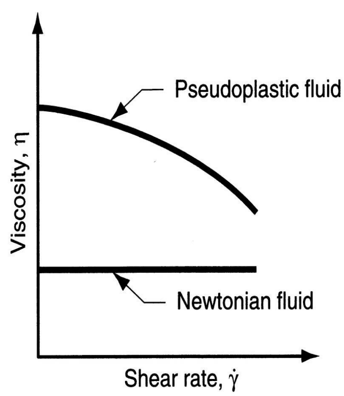
Extrusion

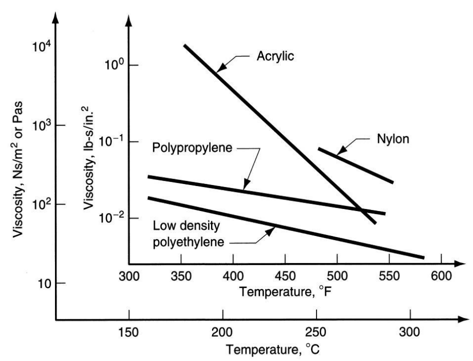
Heated plastic is forced to flow through a die orifice to provide a long continuous product (tube, sheet, etc.) whose cross-sectional shape is determined by the die orifice. The *extrudate* is then cut into desired lengths.



Three zones in an extruder:

Polymer Melt - Viscosity



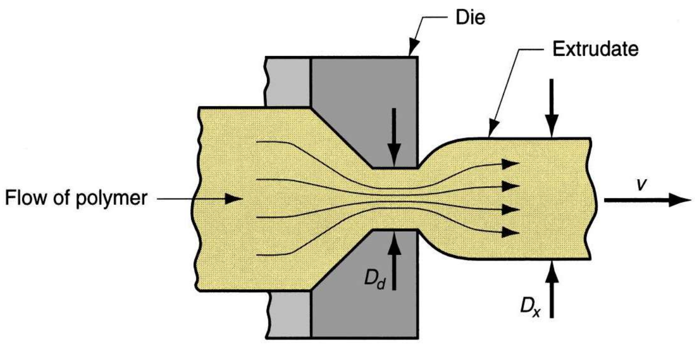


Shear rate and viscosity:

Temperature & viscosity:

Die Swell, aka:

Extruded polymer "remembers" its previous shape when in the larger cross section of the extruder, tries to return to it after leaving the die orifice



Swell ratio:

$r_s = D_x / D_d$

Die swell, a manifestation of viscoelasticity in polymer melts.

• Before the die, the melt passes through a series of wire meshes supported by a stiff plate containing small axial holes called a:
screen pack
• Functions:
1. Filter(remove contaminants and any hard lumps)
2. Build pressure in the metering section
3. Straighten flow - remove "memory" of circular motion from screw

Die End of Extruder

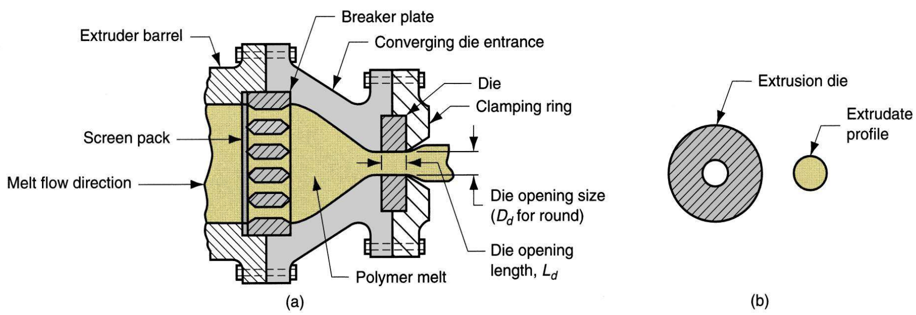
- Before the die, the melt passes through a series of wire meshes supported by a stiff plate containing small axial holes called a:

  screen pack

- Functions:
  1. Filter(remove contaminants and any hard lumps)
  2. Build pressure in the metering section
  3. Straighten flow - remove "memory" of circular motion from screw

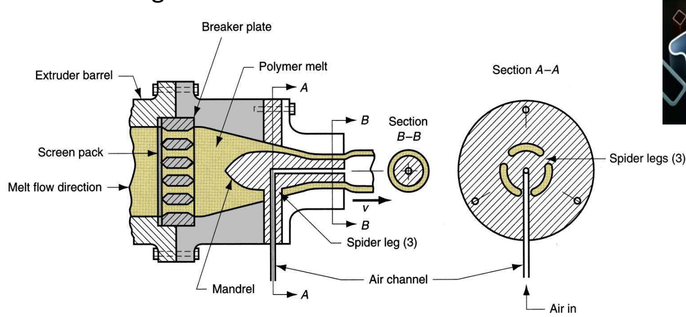
Extrusion Die for Solid Cross Sections

- The shape of the die orifice determines the cross sectional shape of the extrudate.
- Solid shapes: rods, beams, bars, plates, sheets, etc.



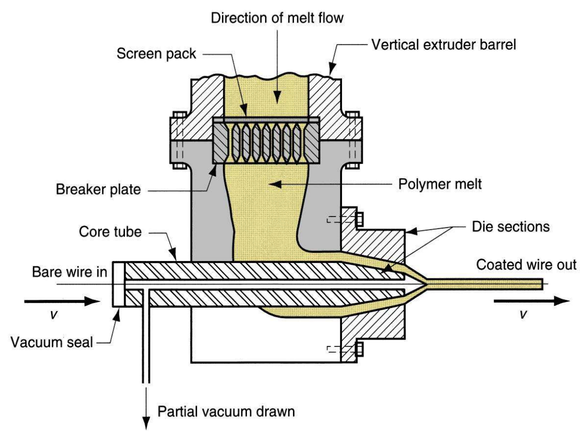
Extrusion Die for Hollow Shapes

- Hollow profiles require a “*spider*” mandrel:
  - Polymer melt flows around legs supporting the mandrel to reunite into a monolithic tube wall due to:
  - Mandrel includes an air channel through which air is blown to maintain hollow form of extrudate during hardening



Extrusion Die for Coating Wire

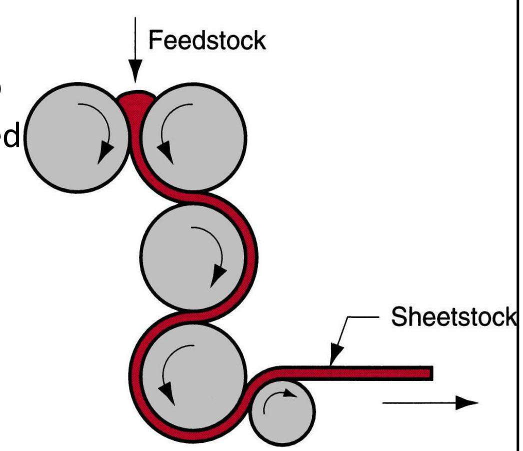
- Polymer melt is applied to bare wire as it is pulled at high speed through a die
  - A slight vacuum is drawn between wire and polymer to promote adhesion of coating



Sheet and Film Production via:

Feedstock is passed through a series of rolls to reduce thickness to desired gage

- Process is noted for good surface finish and high gage accuracy
- Products: PVC floor covering, shower curtains, vinyl table cloths, pool liners, etc.



Fiber and Filament Products

- Definitions:
  - *Fiber* - a long, thin strand whose length is at least 100 times its cross-section
  - *Filament* - a fiber of continuous length
- Applications:
  - Fibers and filaments for textiles
  - Reinforcing materials in polymer composites
- Synthetic fibers constitute ~ 75% of fiber market
  - Polyester is the most important
  - Others: nylon, acrylics, and rayon

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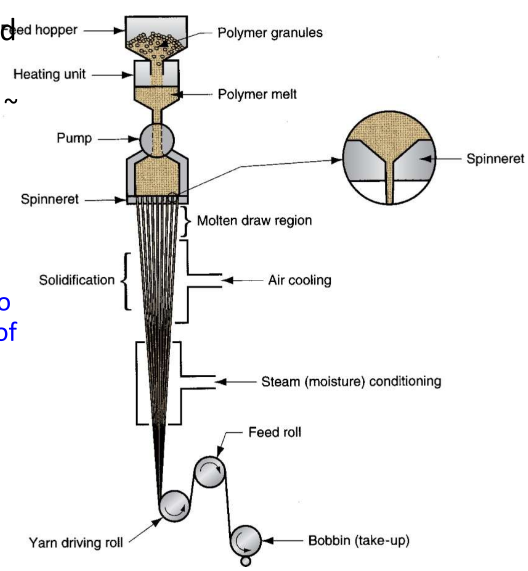
Melt Spinning

- Molten polymer is pumped through spinneret
  - Typical spinneret contains ~ 50 holes of diameter 0.25 mm (0.010 in)
  - Filaments are drawn and air cooled before being spooled onto bobbin
  - Final diameter wound onto bobbin may be only 1/10 of extruded size
  - Used for polyester and nylon filaments



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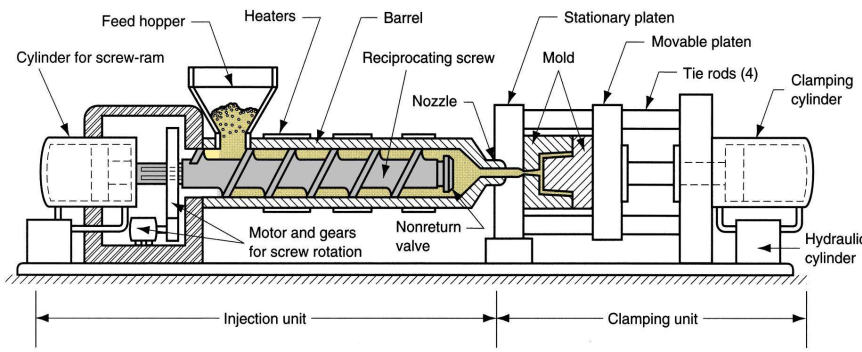
Injection Molding Machine

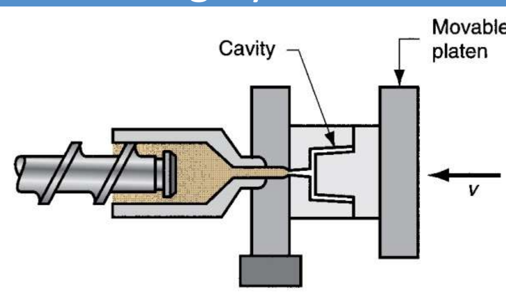


Two principal components:

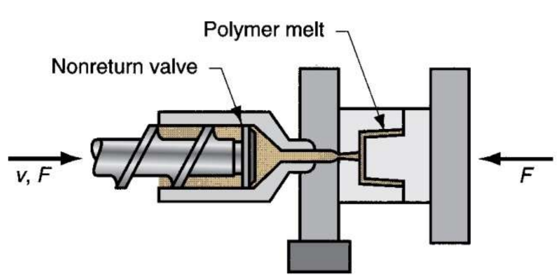
1. Injection unit (operates *similar* to an extruder)
   - Melts and delivers polymer melt (*plunger for injection*)
2. Clamping unit
   - Opens and closes mold each injection cycle

Injection Molding Cycle

1. Mold is closed

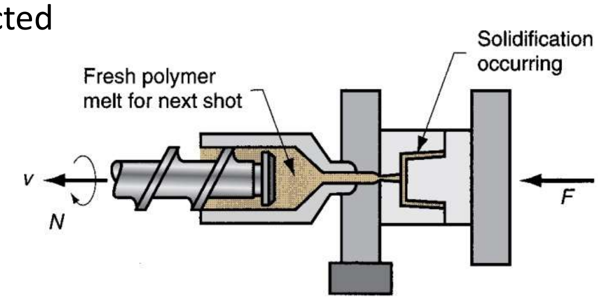


2. Melt is injected into cavity

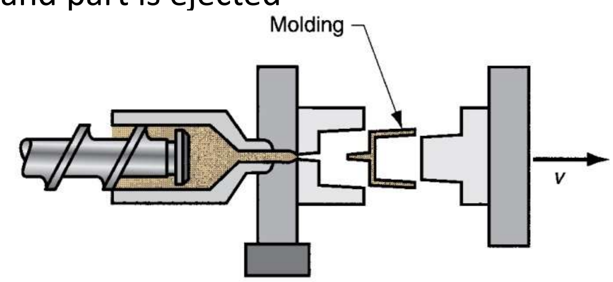


Injection Molding Cycle

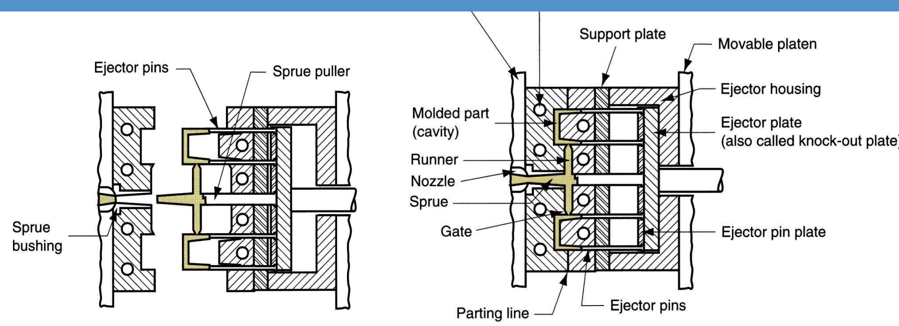
3. Screw is retracted



4. Mold is opened and part is ejected

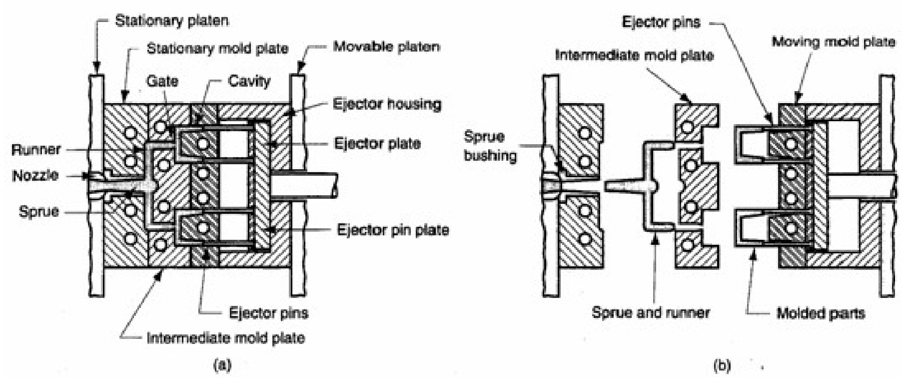


Two-Plate Mold



- Cavity – slightly oversized to allow for shrinkage
- Distribution channel
  - Sprue - leads from nozzle into mold
  - Runners - lead from sprue to cavity (or cavities)
  - Gates - constricts flow in order to:
- Ejection system – pins built into moving half of mold
- Cooling system – typically water
- Air vents – at end of flow path or at parting line

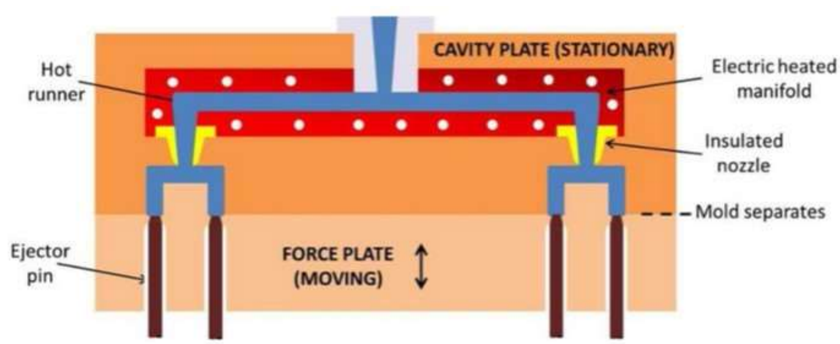
Three-Plate Mold



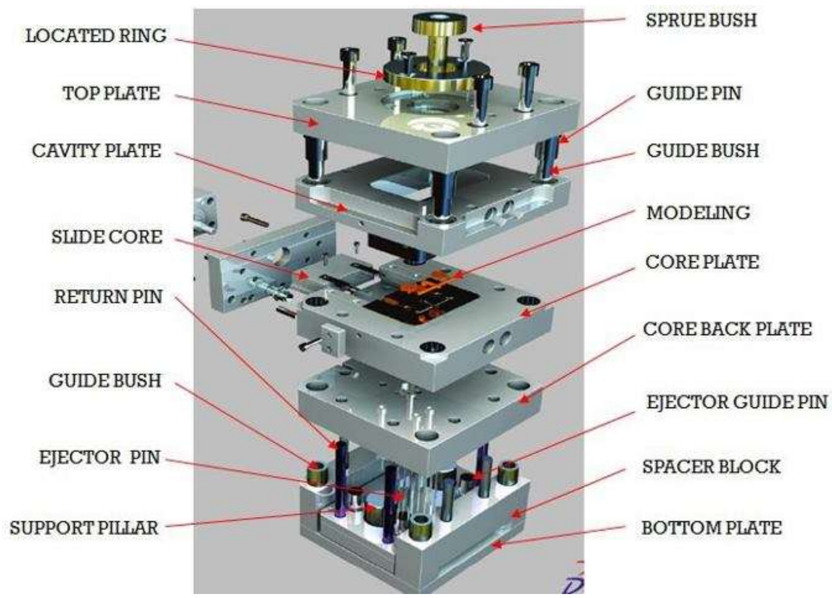
- Advantages over two-plate mold:
  - As mold opens, runner and parts disconnect and drop into *two separate* bins
  - Allows material to be injected at the mold *base or middle*, rather than side injection, which a two-plate mold must do

Hot Runner Mold – "Runner-less Mold"

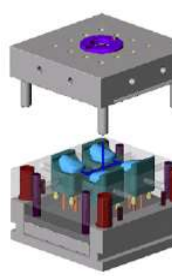
- Eliminates solidification of sprue and runner by adding manifold heaters
  - Saves material that otherwise would be scrap in the unit operation

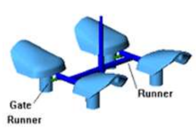


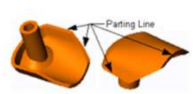
Actual mold

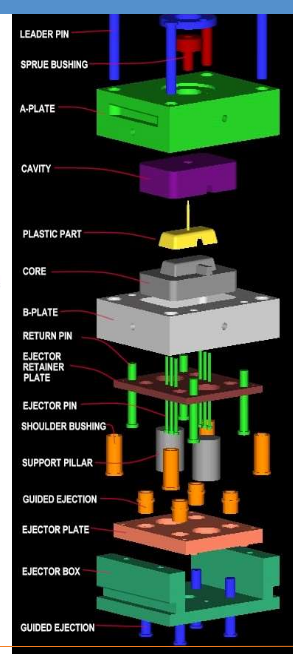


The Mold



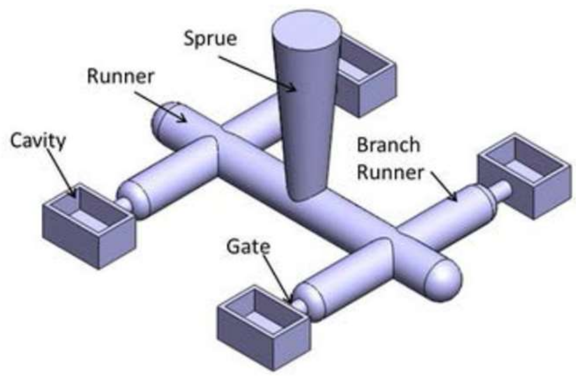






Injection Molding Material Feed

- Similar to casting there is a material feed system to deliver the melt to the part cavities.



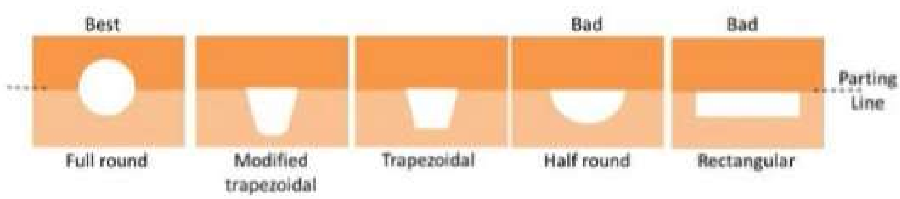
Sprue

- Usually starts with a larger diameter at the nozzle and tapers to a diameter matching the runner.

Designing a Mold

Runner System & Gate

-
-
-
- Runner shapes: (based on volume to surface area)



- Gate has a smaller cross section than the runner so the mold can be easily from the runner, and the material will be lower before entering

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ME 270
Design for Manufacturability

Timothy H. Lee, PhD

Fall 2021

Lecture 9: Plastic Molding

Injection Molding of Thermosets

- Temperatures in the injector are generally: lower
- The barrel length of the injection unit is generally: shorter
- Melt is injected into a *heated* mold, where cross-linking occurs to cure the plastic
  - The most time-consuming step in the cycle: curing in the mold

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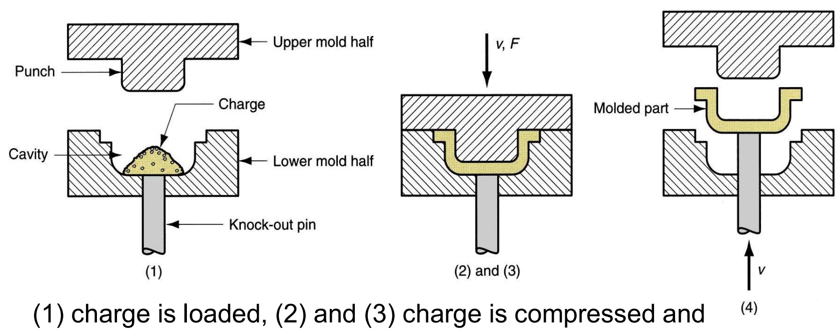
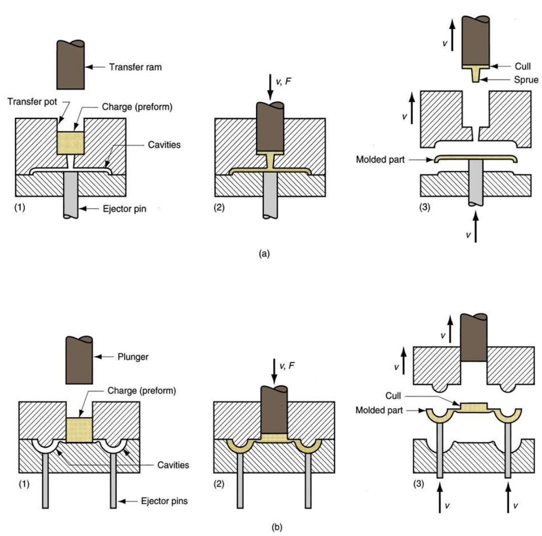
Compression Molding

- A widely used molding process for thermosets
- Also used for rubber tires and polymer composites
- Molding compound available in several forms: powders or pellets, liquid, or preform
- Amount of *charge* must be precisely controlled



(1) charge is loaded, (2) and (3) charge is compressed and cured, and (4) part is ejected and removed.

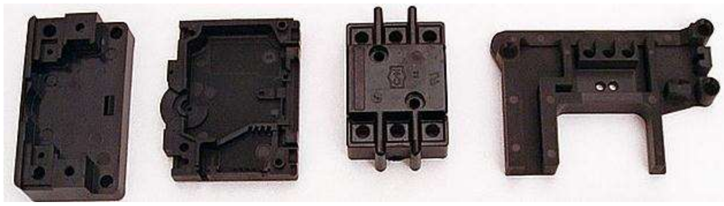
Transfer Molding



Pot transfer molding: charge is injected from a "pot" through a vertical sprue channel into cavity

Plunger transfer molding: plunger injects charge from a heated well through channels into cavity

Typical compression/transfer molding parts



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Insert Molding

- A wide variety of materials can be placed inside an injection mold to be encapsulated by the material
- No final assembly is required
- Examples:
  - Screwdrivers
  - Disposable razors
  - Product labels

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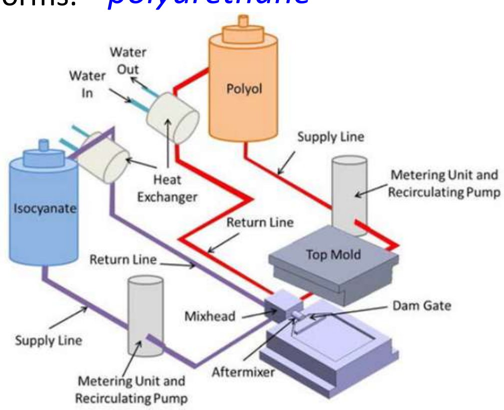
Reaction Injection Molding (RIM)

- Used to mold thermosetting materials
- Chemical reaction occurs within the mold
- Examples: automotive bumpers and steering wheels.

RIM Process Examples

- After mixhead, nozzle injects mixture at very high velocity.
- Inside mold, material undergoes exothermic chemical reaction, from Polyol and Isocyanate forms: *polyurethane*
- Mixing additives can be added: flow modifiers, blowing agents, catalysts, pigments, release agents, etc.



Adv. and Disadv. of RIM

Advantages:

1. *Varied wall thickness* – 0.25”-1” are possible in the same part; not achievable with thermoplastic molding
2. Greater *detail* – higher flowability of thermosets
3. *Larger* parts – >100 lbs due to more even distribution of liquid material and lower mold pressures needed.
4. Less *floor space* – RIM press is 1/5 to 1/6 the size of typical injection molding machine

Disadvantages:

1. Cost
2. Time – cycle time can be 1-7 minutes; 2-100 seconds for injection molding
3. Waste – runner and/or part scrap can not be recycled.

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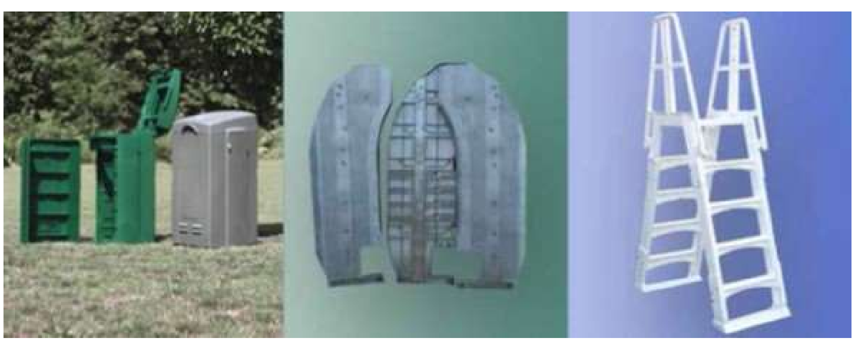
Structural Foam Molding (SFM)

- SFM relies on a foaming action of a blowing agent to expand the plastic inside the mold cavity.
- Foam in contact with cold mold surface collapses to form dense skin, while core retains cellular structure
- Used for larger objects like that require a solid external skin surrounding a inner cellular (or foam) core.



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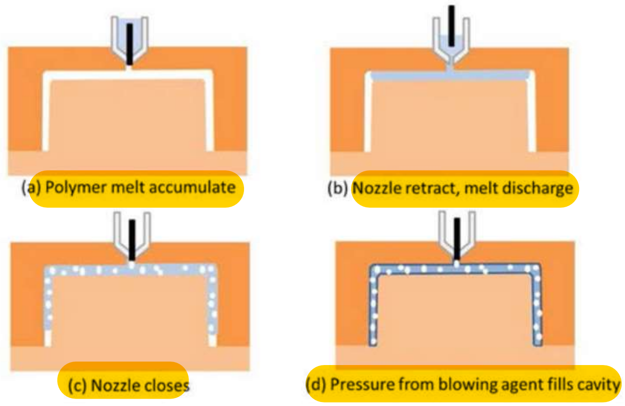
SFM Process

1. *Inert blowing agent* requires a high pressure polymer melt to prevent it from coming out of solution (e.g. nitrogen),
2. A *chemically activated blowing agent* uses heat inside the mold to activate (e.g. azodicarbonamide).



Adv. and Disadv. of SFM

Advantages:

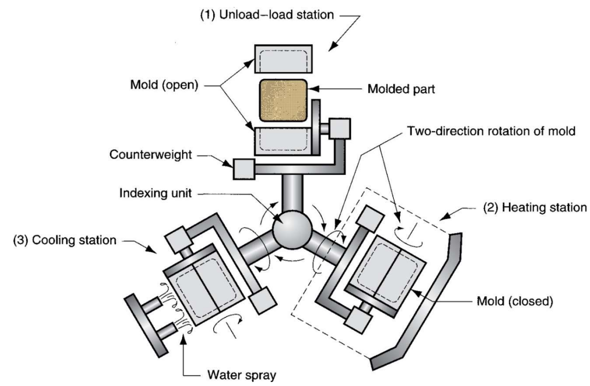
1. Light weight – significantly less material used (40-80%)
2. *Large* parts with thick wall sections
3. Low pressure means *molds* can be *lighter* and less expensive
4. High stiffness to weight ratio – 0.5-3 times greater rigidity than solid injection molded parts. A part 50% less dense, but twice as thick (i.e. same weight) could have 8 time greater stiffness.

Disadvantages:

1. *Surface finish* worse ("blushed") than injection molding
2. Long cycle *time* – lower production speed.

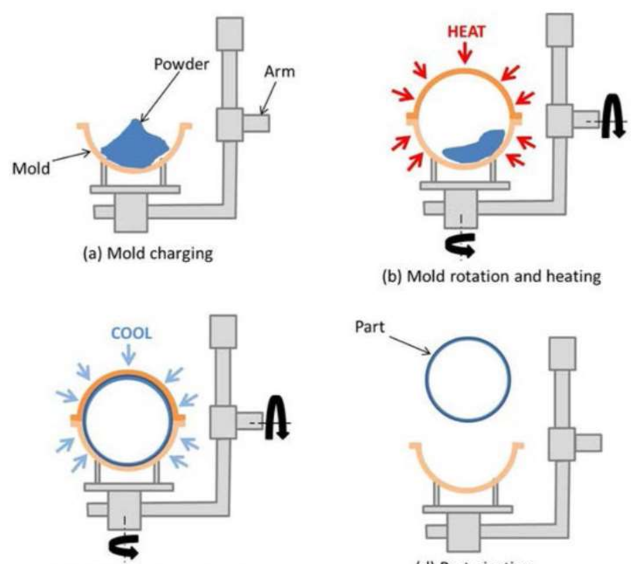
Rotomolding

- Cavity is filled with thermoplastic powder, and simultaneously heated and rotated (on 2-axis)
- Polyethylene powders are most widely used.
- Unique: heating and shaping all take place inside the mold without the application of pressure.
- Produces a hollow part



Video: http://featurebasedcosting.com/DFMeBook/eBook_mp4s/rotomolding.mp4

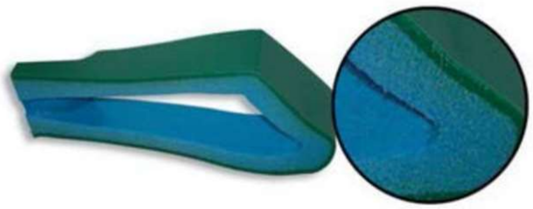
Rotomolding Process

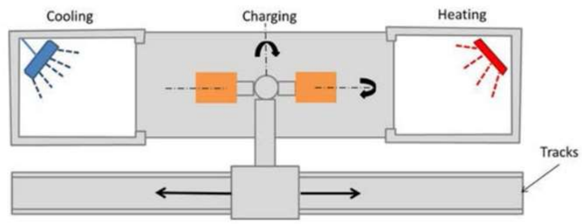


(a) Mold charging
(b) Mold rotation and heating
(c) Mold rotation and cooling
(d) Part ejection

Multiple layers in Rotomolding

- "Drop Boxes" can be used to add different material during the molding cycle.
- First powder forms the outer layer, then a different material (or foam) can be added for the next layer.





Adv. and Disadv. of Rotomolding

Advantages:

1. Very **large** parts – e.g. playground equipment, chemical storage tanks
2. Low residual **stress**
3. Wall thickness is uniform with tolerance between 10-20%. Non-uniform thickness can be achieved by altering mold temperature or using mold shielding.

Disadvantages:

1. Very *slow* process – typically 8-20 minutes
2. Difficult to achieve a *large flat* surface – better suited for curved products
3. *Sharp corners* are often not coated uniformly.

Blow Molding

- Molding process in which air pressure is used to inflate soft plastic inside a mold cavity
- Material limited to: thermoplastics
- Accomplished in two steps:
  1. Fabrication of a starting tube, called a: parison
  2. Inflation of the tube to desired final shape
- Two methods:
  1. For larger parts: Extrusion blow molding
  2. For smaller parts: Injection blow molding

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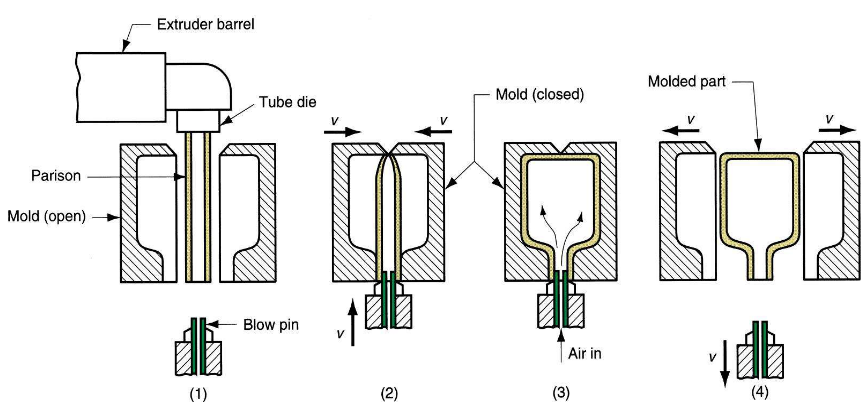
Extrusion Blow Molding

(1) extrusion of parison; (2) parison is pinched at the top and sealed at the bottom around a metal blow pin as the two halves of the mold come together; (3) the parison is inflated; and (4) mold is opened to remove the solidified part.



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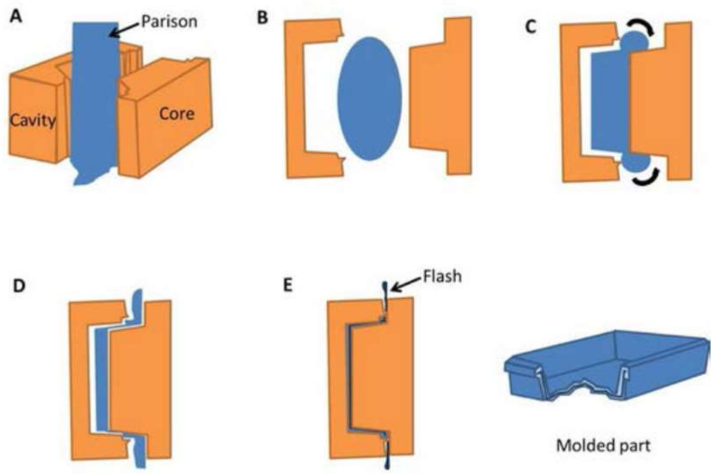
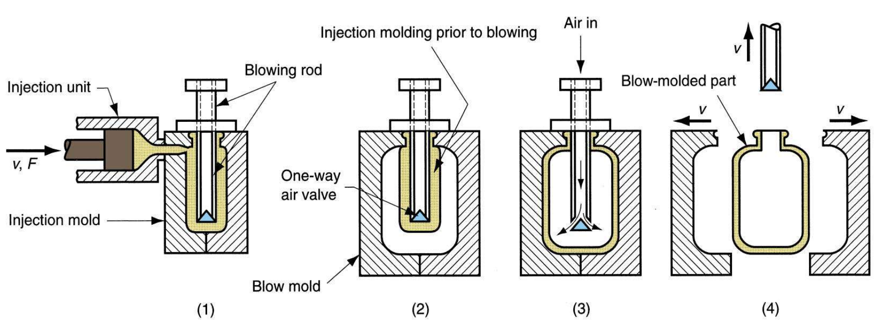
Double Wall Blow Molding

- Walls of hollow parison do not collapse, but air is trapped inside adding rigidity to the part.



Injection Blow Molding

(1) parison is *injection* molded around a blowing rod; (2) injection mold is opened and parison is transferred to a blow mold; (3) parison is inflated; and (4) blow mold is opened and product removed.



Video:
http://featurebasedcosting.com/DFMeBook/eBook_mp4s/blowMolding.mp4

Adv. and Disadv. of Blow Molding

Advantages:

1. Large volume parts – vehicle fuel tanks, etc.
2. Very *fast* process – fast production rate & high volume.
3. Wall thickness can vary by 2:1 – thicker screw threads and thinner bottle wall thickness.

Disadvantages:

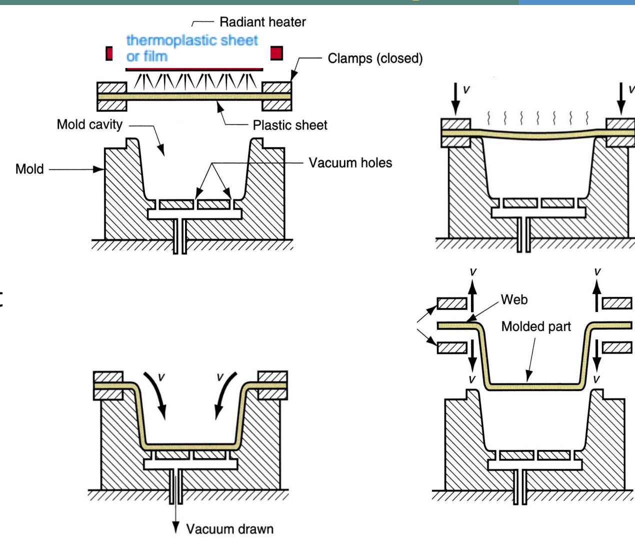
1. Only thermoplastics can be used.
2. Not suitable for small productions runs.
3. Stretching to achieve sharp corners often results in ripping.

Vacuum Thermoforming

- Starting material:

  thermoplastic sheet or film

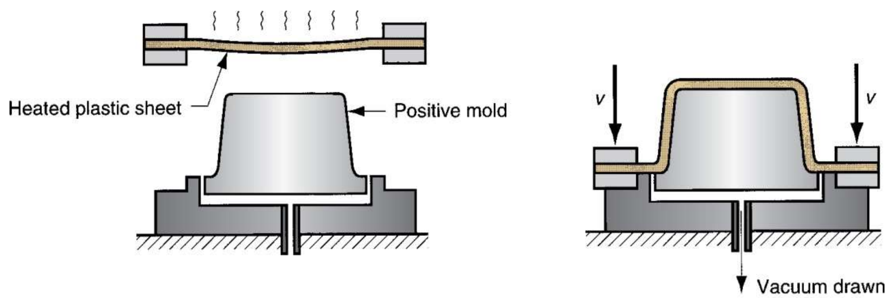
- To soften, heat is supplied by radiant electric heaters located on one or both sides



Products: bathtubs, contoured skylights, door liners for refrigerators, boat hulls, shower stalls, advertising displays and signs, etc.

Vacuum Forming – Positive Mold

- Previous example was a negative mold



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ME 270
Design for Manufacturability

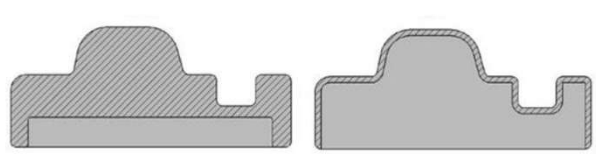
Timothy H. Lee, PhD

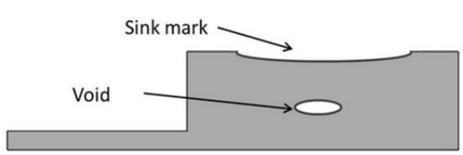
Fall 2021

Lecture 10: Plastic Molding

Design Advisor – Wall Thickness

- Maintain constant wall thickness to avoid stress and warpage (or transition gradually).
- RIM is better suited for varying wall thickness

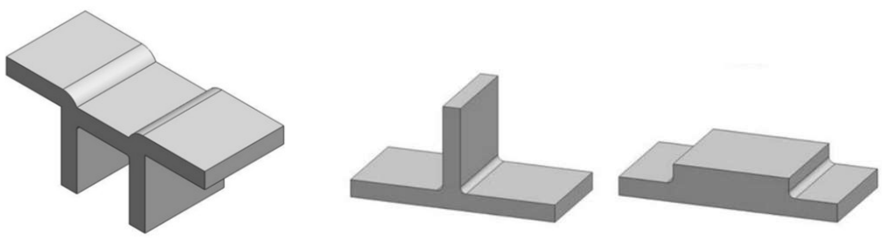




Wall Thickness (in)	Cycles/hr
0.125 - 0.187	25 - 40
0.187 - 0.275	18 - 25
0.275 - 0.393	5 - 18

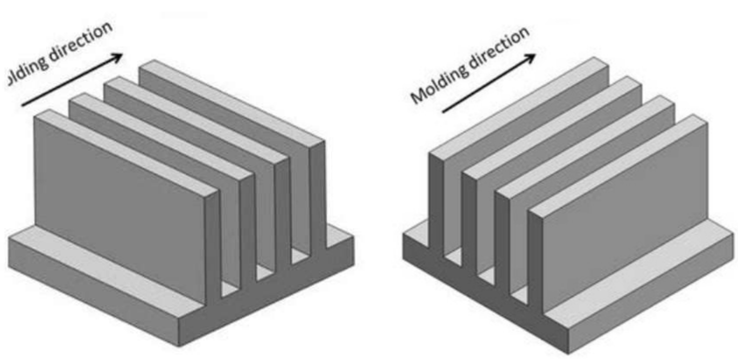
Design Advisor - Reinforcements

- An alternative to having thicker walls.
- Use ribs, bosses, and gussets that are ~½ thickness of walls
- Taller ribs are more effective than shorter, wider ribs



Design Advisor - Reinforcements

- Ribs should be oriented in direction of the material flow.

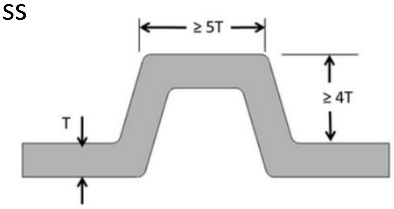


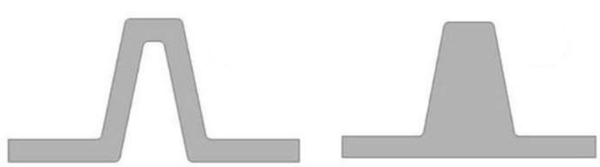
Design Advisor - Reinforcements

- Bosses can be treated like cylindrical ribs and connected to outer walls to prevent air entrapment.
- Bosses can be incorporated into the wall to avoid thickness variations.

Design Advisor – Strengthening Ribs

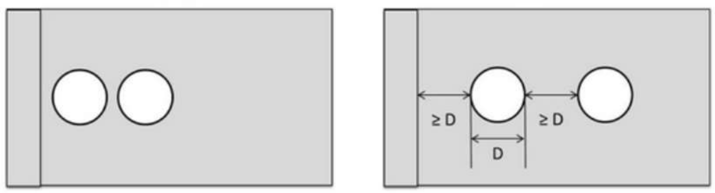
- Rib depth should be at least 4 times the wall thickness and 5 times as wide as wall thickness
- A large number of short ribs is preferred to a single large one.
- Ribs should be hollow, not solid, and curved at the corners.





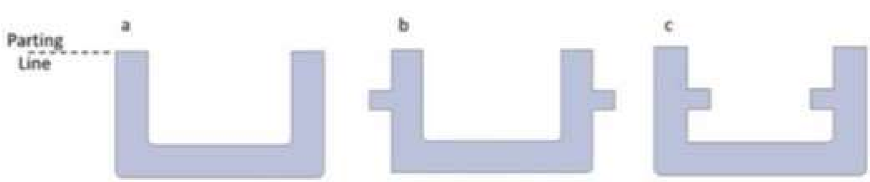
Design Advisor - Holes

- Holes can greatly effect part integrity
- Minimum of 1 diameter spacing between 2 holes or a hole and a side wall – for part strength and material flow
- Through holes preferred over blind holes and depth should not exceed 2 times its diameter



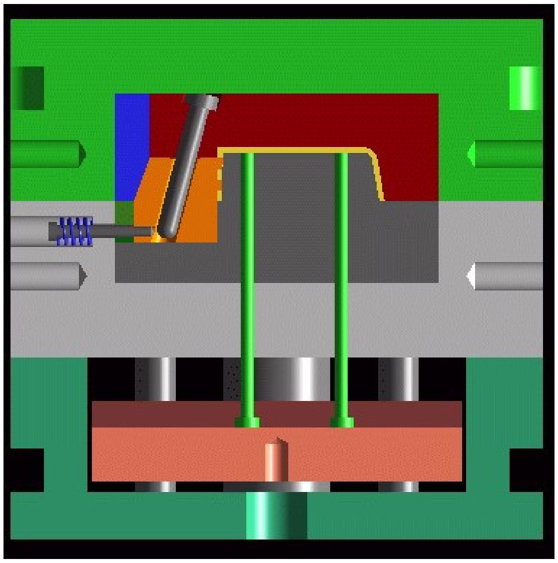
Design Advisor - Undercuts

- External undercuts sometimes require mechanical slides or side cores
- Internal undercuts generally require lifters - avoid if at all possible

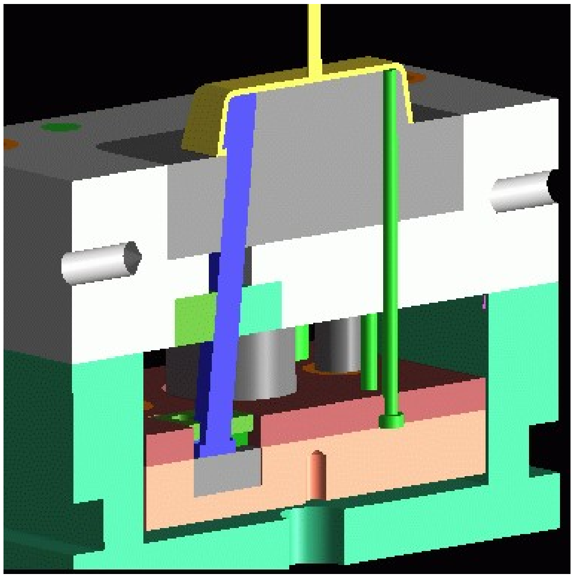


(a) No undercut (b) External undercut (c) internal undercut

Moving Side Cores or 'Slides'

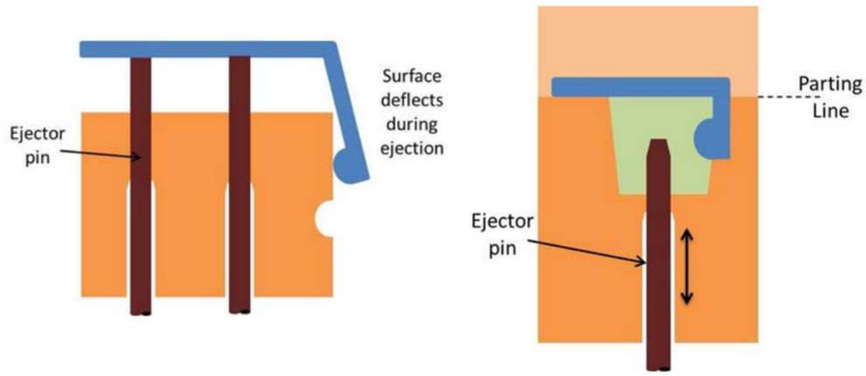


Moving Internal Cores or 'Lifters'



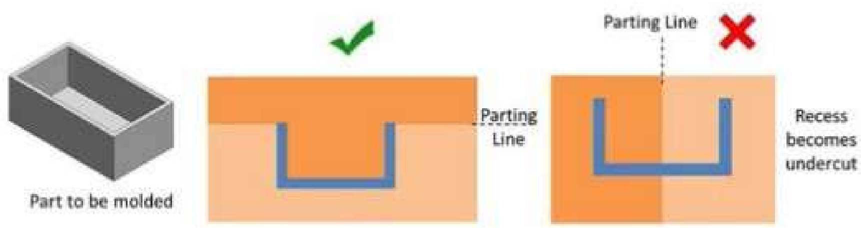
Internal Undercut without Lifters

- Depending upon part flexibility, part can be ejected without lifters.
- Or, core rod can be added to ejector pins



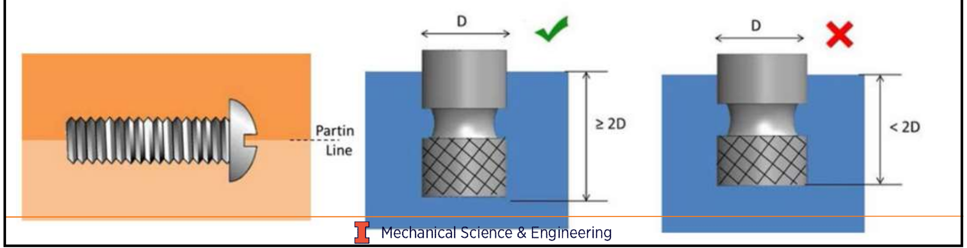
Design Advisor – Parting Line Choice

- Chose parting line to simplify mold



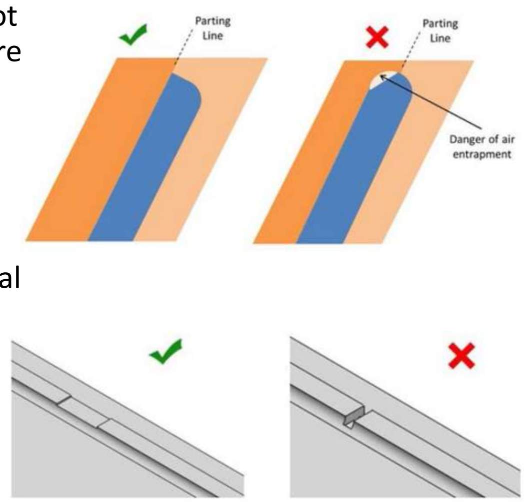
Design Advisor – Screw Threads

- Screw threads generally need to be *coarse*, or added later by *tapping* after molding.
- *Inserts* can be used for fine or *stronger threads*.
- Insert's embedded length should be at least twice its diameter and its surface roughened
- Threads and inserts should be located at the parting line. Inserts not aligned to the parting line require unscrewing mechanisms to release after molding.



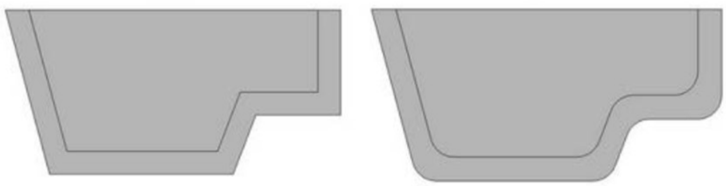
Design Advisor – Venting at Parting Line

- Air venting typically is done at the parting line. Try not to have protrusions where gas can get trapped.
- For increased venting at a parting line, make vents wide and shallow, not narrow and deep to keep material from exiting. Place near corners



Design Advisor - Corners

- Sharp corners cause stress concentrations.
- Rounding corners give the least chance of air entrapment.
- Maintain a uniform wall thickness through corners.
- Inner radius should be >25% of the wall thickness.



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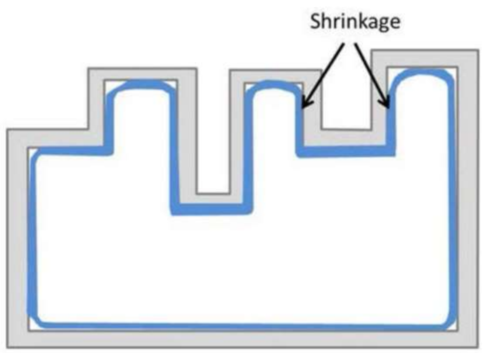
Design Advisor – Part Ejections

- Upon cooling, plastic cools and “locks” around any internal protrusions.
- Important to include draft angles on protrusions



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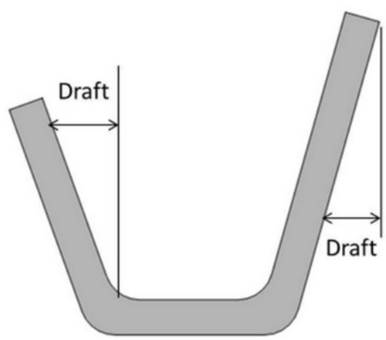
Design Advisor – Part Ejection

- To make part ejection easier, include draft or taper (minimum 0.5 degrees) to the walls.
- Locate gate and ejector pins to the underside of the part if at all possible since they adversely effect surface finish.



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Design Advisor - Texturing

- Texturing applies a surface pattern in the mold
- Texturing can hide defects and improve grip handling
- To prevent scraping, increase draft to 1-1.5° per 0.001” in depth of texture to all surfaces perpendicular to the parting plane.

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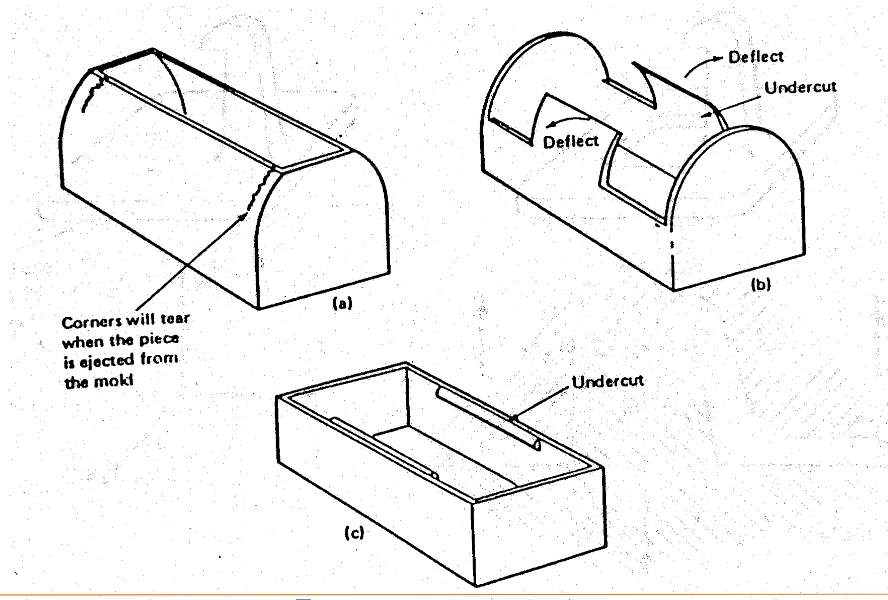
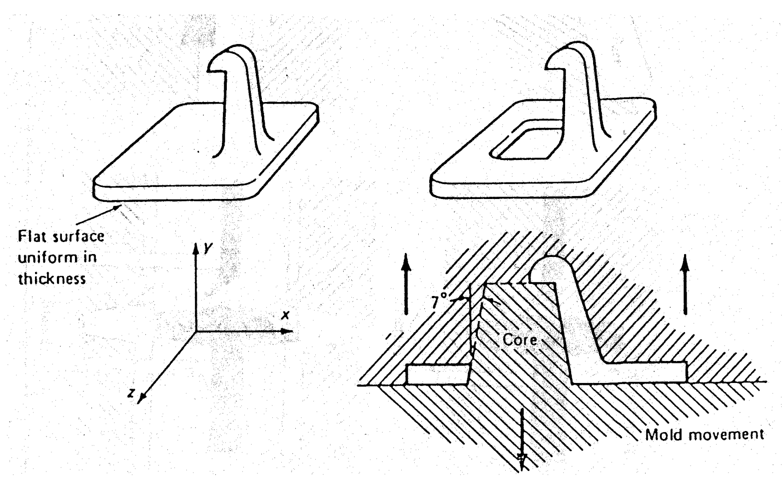
Avoiding Moving Side Cores and Lifters (1)



Avoiding Moving Side Cores and Lifters (2)



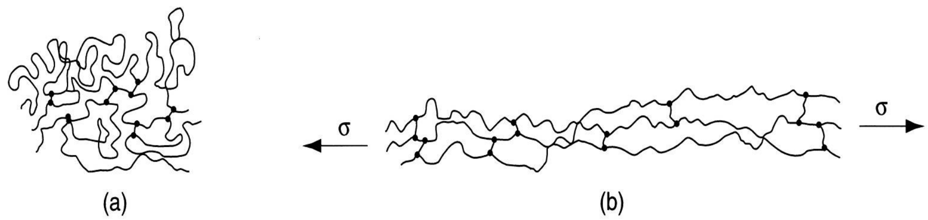
Plastic Product Design Guidelines:

- Strength and stiffness – generally not as good as metals
- Creep – problem for thermoplastics, not for thermosets
- Strength-to-weight ratio – competitive with metals
- Impact resistance – plastics absorb impact well
- Use temperature – limited relative to metals and ceramics
- CTE – ΔT dimensional changes usually more significant
- UV protection – needed to prevent sunlight degradation
- Solvents – often soluble
- Acids, Bases –resistant to most

Cost Drivers

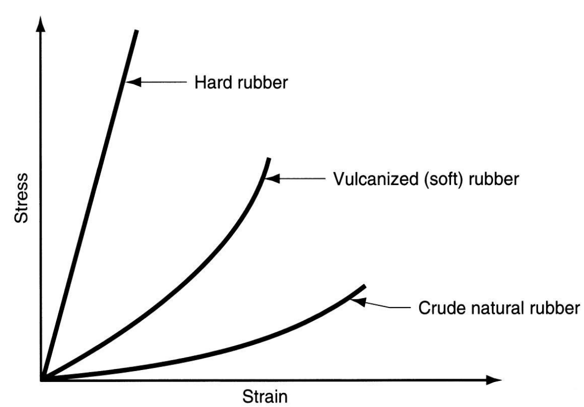
1. *Tooling* Cost – highly dependent on mold complexity and usage environment (temperature, pressure, cycle speed). Dominate at low production volume.
2. *Processing* cost – highly dependent on part's cycle time. A long cycle will have a high labor/overhead cost per part. *Thicker parts take longer to cool. Cooling is proportional to the square of the part's wall thickness*.
3. *Material* cost – entirely variable cost. Dominate at high production volume.

Elastomer Behavior



- When stretched, the molecules uncoil and straighten, providing the initial elastic modulus of the material
- Under further strain, the covalent bonds of the cross-linked molecules begin to play an increasing role in the modulus, and stiffness *increases*
- More cross-linking, makes the elastomer *stiffer* and its modulus of elasticity is more *linear*

Stiffness of Rubber



Increase in stiffness as a function of strain for three grades of rubber: natural rubber, vulcanized rubber, and hard rubber.

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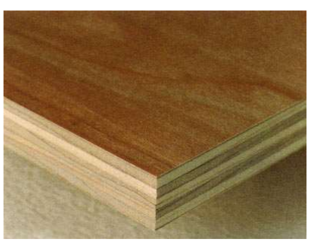
ME 270
Design for Manufacturability

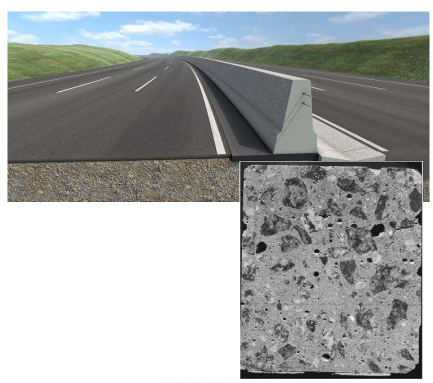
Timothy H. Lee, PhD

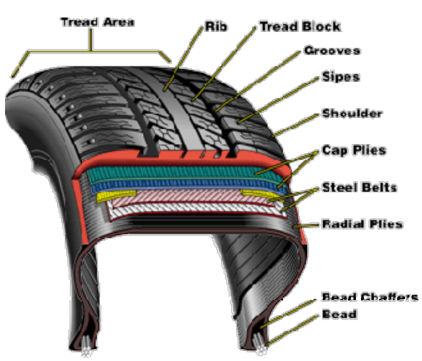
Fall 2021

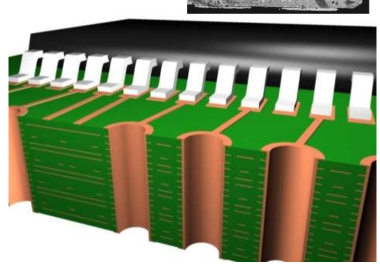
Lecture 11: Composites

ME 270 – Lecture 6 – Composites

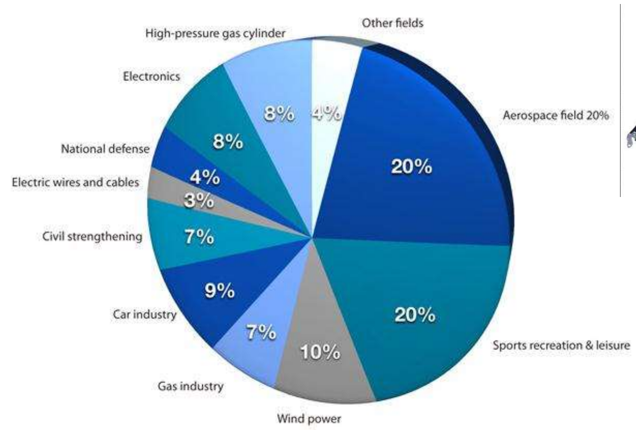


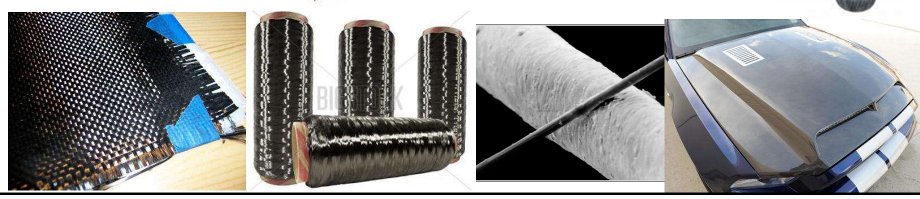






Carbon Fiber Market





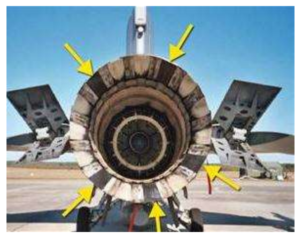
Components in a Composite Material

Most composite materials consist of ***two phases***:

1. The primary phase within which the other phase is imbedded:
   - Shares the load, and in some cases deforms so that the stress is essentially born by the reinforcing agent
2. The secondary phase or imbedded phase that strengthens the composite:
   - Generally in the form of ***fibers, particles, flakes*** or various other geometries

Types of Composite Materials

1. Metal Matrix Composites (MMCs) - mixtures of ceramics and metals
2. Ceramic Matrix Composites (CMCs) - Al_2O_3 and SiC imbedded with fibers to improve properties
3. Polymer Matrix Composites (PMCs) - polymer resins imbedded with filler or reinforcing agent



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Polymer Matrix Composite Advantages

- High *Strength-to-weight* and stiffness-to-weight ratios
- *Fatigue* properties are better
- *Toughness* is often greater
- Possible to achieve combinations of properties not attainable with metals, ceramics, or polymers alone.
- Good machinability: personal protection equipment needed

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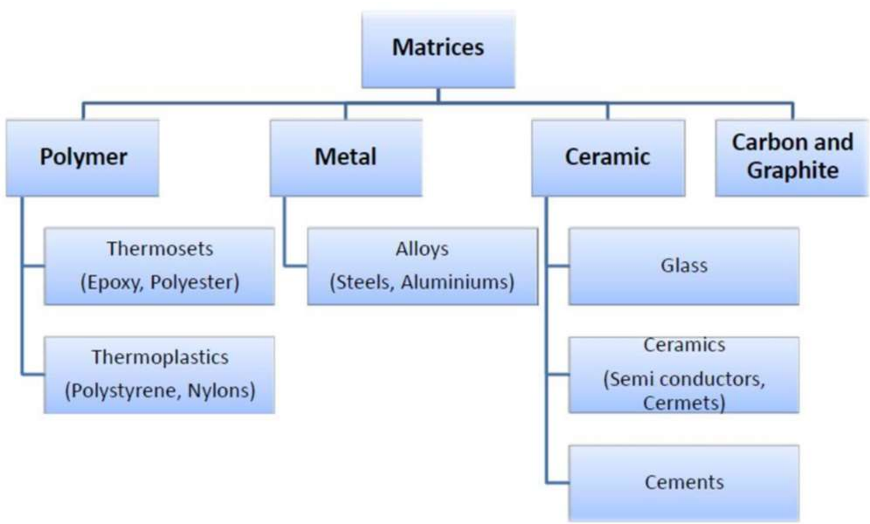
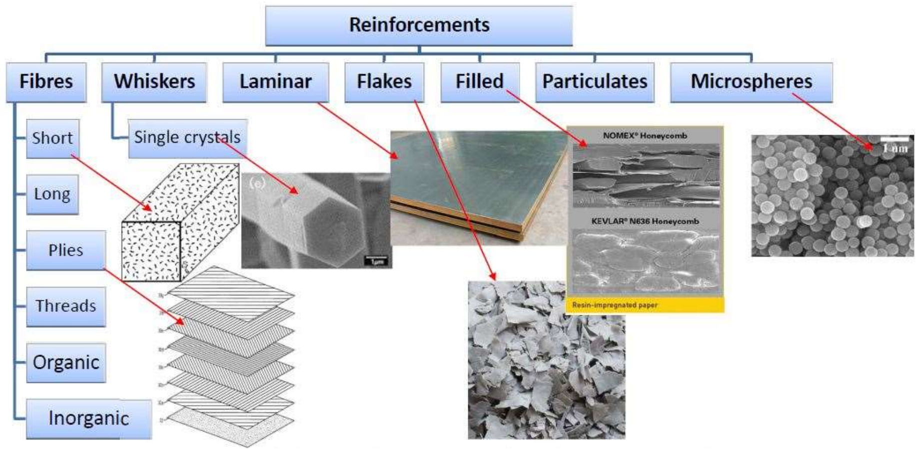
Disadvantages

- Properties are generally
- Can be *weakened* by chemicals or solvents
- Generally
- Manufacturing methods often
- Usually not environmentally friendly
- Low re-usability

Primary Phase: Matrices

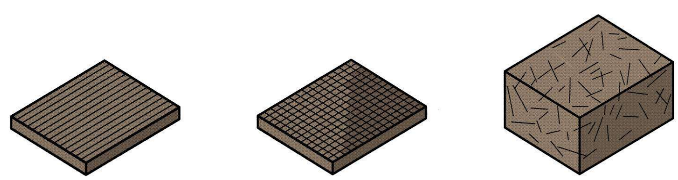


Secondary phase: reinforcement



Fiber Orientation – Three Cases

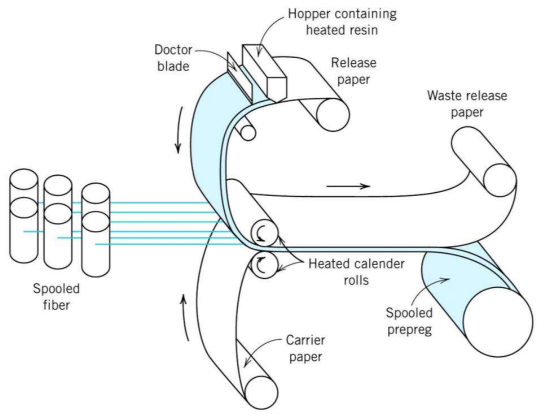
- One-dimensional reinforcement – maximum strength and stiffness obtained in the direction of the fiber
- Planar reinforcement, i.e. two-dimensional woven fabric
- Random or three-dimensional in which the composite material tends to possess *isotropic* properties



(a) (b) (c)

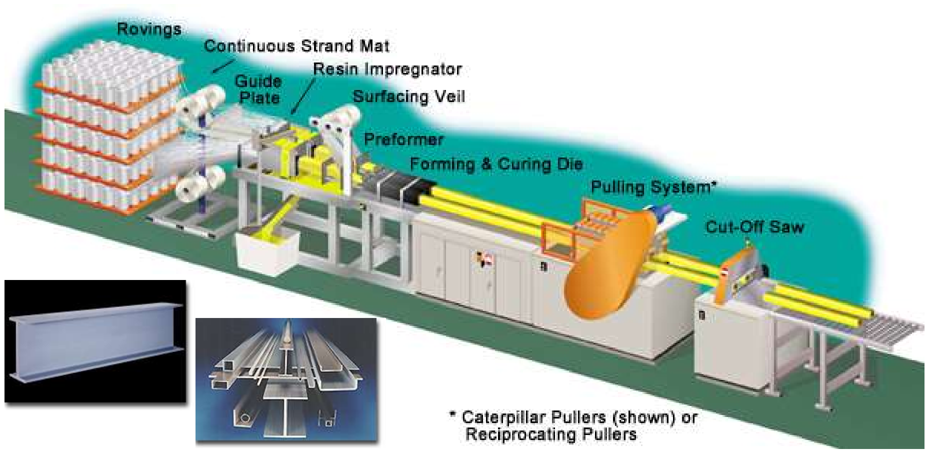
Fiber Sheet Prepreg

- Resin added to fibers, then rolled (pressed) and heated into sheets
- Cures at or just above room temperature, so generally must be stored at 0C.



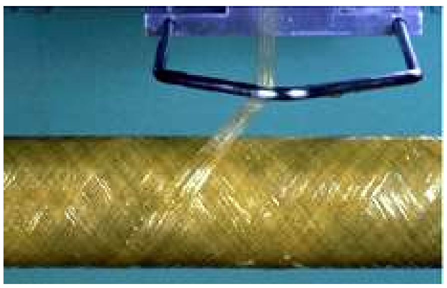
Pultrusion

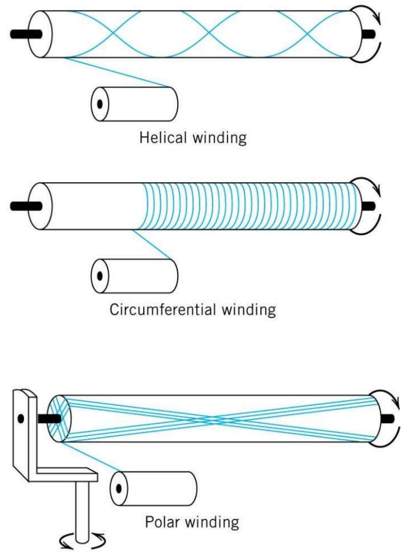
- Fibers -> impregnate with polymer resin -> pass through a die of near final/final shape + heating to cure
- High strength to weight, corrosion resistant, non conductive, electromagnetically transparent



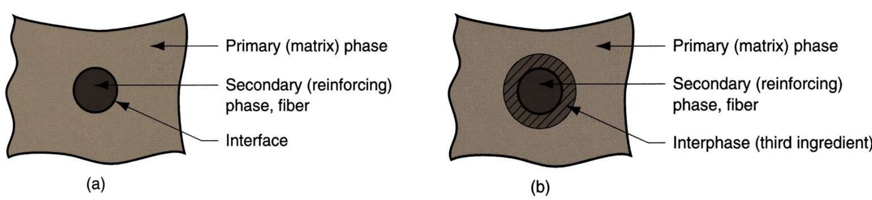
Fabrication with Filaments

- Filament Winding
  - Wind either fibers or narrow prepreg structures around a mandrel using various patterns.
  - High strength to weight.
  - "Most economically attractive."



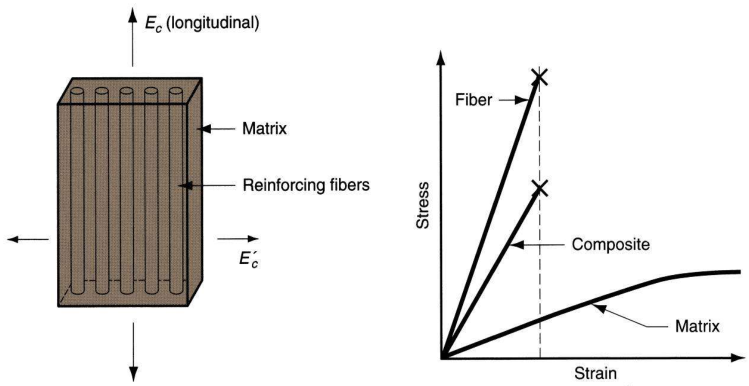


The Interface & Interphase



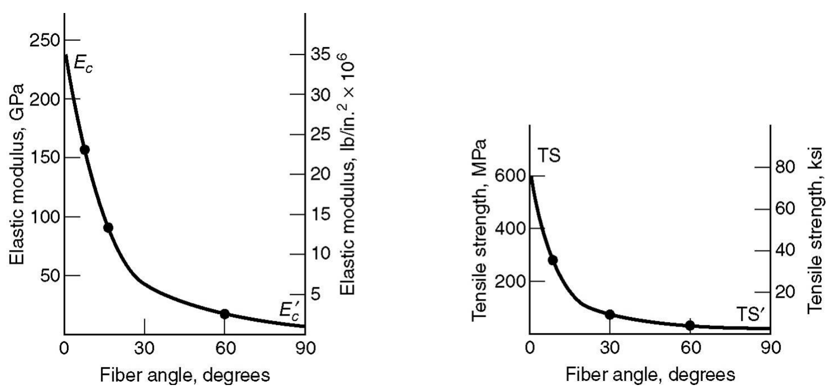
- *Interface:* the surface between the primary and secondary phases in a composite material
  - Strength failure typical occurs here
- *Interphase: a 3rd* phases between the matrix and reinforcing phase
  - to improve the adhesion

Strength of Fiber Reinforced Polymer



Rule of mixture:

Variations in Strength and Stiffness

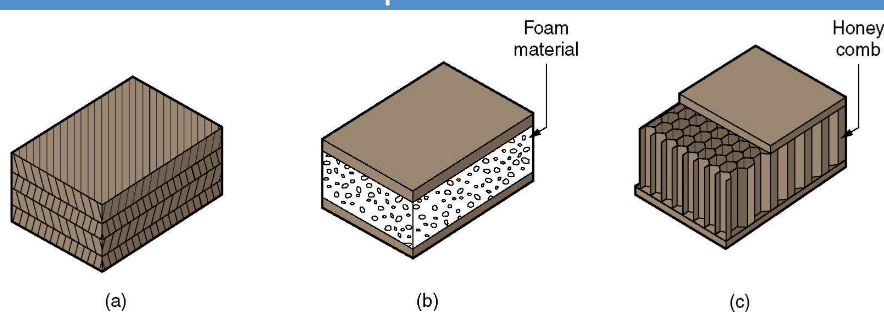


Variation in elastic modulus and tensile strength as a function of direction relative to the longitudinal axis of the carbon fiber.

Compression vs Tension Strength

- Composites generally are less strong and stiff in compression than in tension.
- Kevlar has about 1/10th the strength in compression as tension.
- Carbon fiber has about 35-45% less strength in compression as tension.
- In general Carbon fiber is the most stiff, being about twice as strong as Kevlar and about 5 times as stiff as glass fiber.

Other Composite Structures



- Laminar: two or more layers bonded together. Example: plywood.
- Sandwich: thick core of foam bonded on both faces to thin sheets of a different material
- Honeycomb: Alternative to foam core

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ME 270
Design for Manufacturability

Timothy H. Lee, PhD

Fall 2021

Lecture 12: Sand Casting

FUNDAMENTALS OF METAL CASTING:

Process by which a liquid material is poured into a mold, a hollow cavity of the desired shape, and then allowed to solidify.

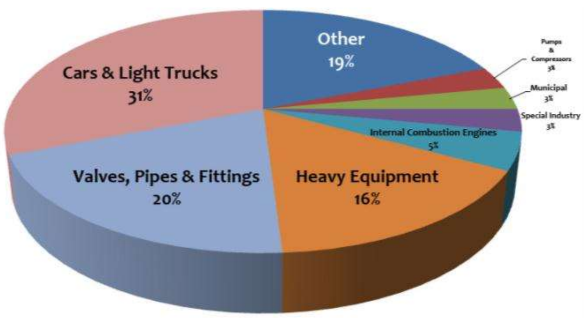
The solidified part is also known as a casting, which is ejected or broken out of the mold to complete the process.

Casting is a 6000 year old process
Aluminum is the most common cast material today

The Casting Industry

- 12 million tons of castings are produced every year, over $30 billion in total value
- Most common materials: gray iron, ductile iron, aluminum alloys, and copper alloys





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Advantages and Disadvantages of Casting

Advantages:

1. Can create: : Complex part geometries
2. Can create both external and internal shape
3. Less machining – parts considered near net shape
4. Part size can be very: large

Disadvantages:

1. *mechanical properties* (microstructure, alloy segregation, etc.)
2. *dimensional accuracy* and *surface finish* for some processes; e.g., sand casting
3. *Safety hazards* to workers due to hot molten metals

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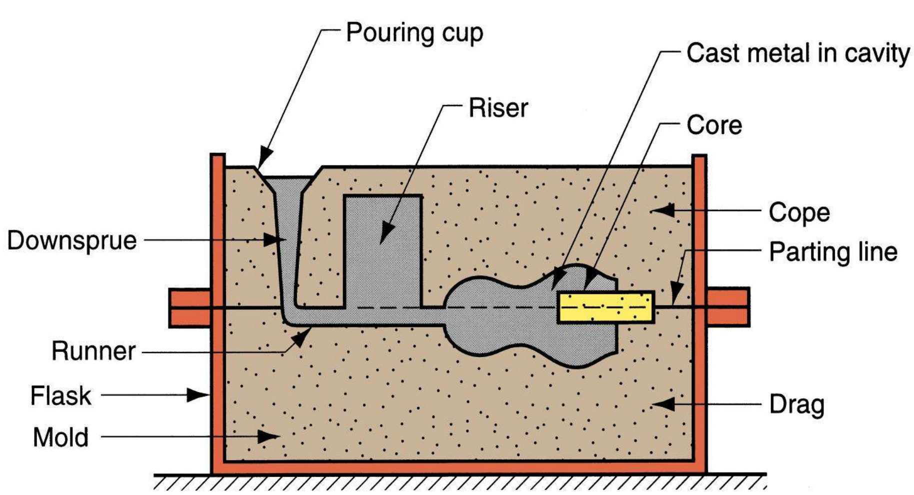
Two Main Categories

1. Expendable mold casting processes
   - Mold made of sand with various binders and is

2. Permanent mold casting processes
   - Mold made of metal or a ceramic refractory material and is

Sand Casting Mold



Sand Casting Mold Terms

- Mold consists of two halves:
  - Upper half of mold:
  - Bottom half of mold:
- Mold halves are contained in a box, called:
- The two halves separate at the:
- Gating system consists of:
  - Horizontal tube openings through which metal travels to the main cavity:
  - Vertical tube opening of varying diameter designed to control metal flow velocity:
  - Topmost opening designed to minimize splash and turbulence:

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Riser

- Reservoir in the mold which acts as a source of liquid metal during solidification to compensate for part:shringkage
- In order to satisfy its function, the riser must be designed to freeze (the main casting

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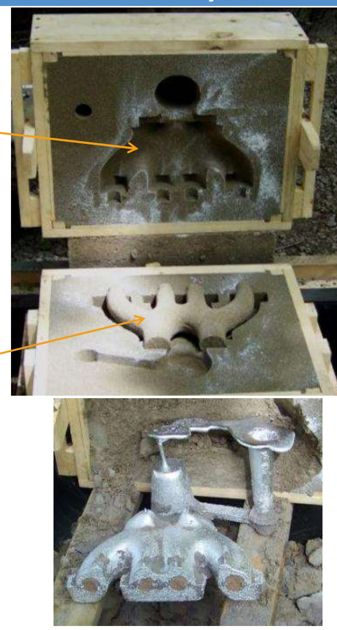
Use of a Core in the Mold Cavity

- The mold cavity provides the external surfaces of the cast part
- In addition, a casting may have internal surfaces, determined by ***a core***, placed inside the mold cavity to define the interior geometry of part

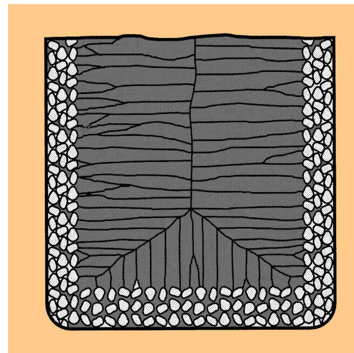


Types of Sand Molds

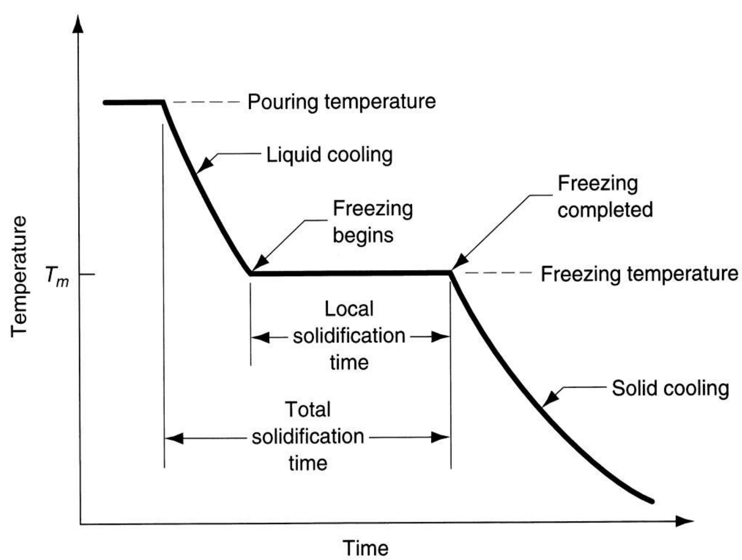
- *Green-sand mold* - mixture of sand, clay, and water – sometimes oil is added to improve the sand malleability.
  "Green" is not the color of the sand, but like "green" wood, it is not in a hardened (or compacted) state.
- *Dry-sand mold* - mold is baked in an oven at 200° to 320°C to remove moisture and improve strength.
- *Resin-infused mold* – sand that is mixed with an organic resin that binds the sand together.
  Significantly stronger than other mold types but more expensive and limited ability to re-use the mold material. *Cores are made from resin infused sand*.

Solidification of Pure Metals

- Due to chilling action of mold wall, a thin skin of solid metal is formed at the interface immediately after pouring
- Randomly oriented grains of small size form near the mold wall, and large columnar grains oriented toward the center of the casting form later

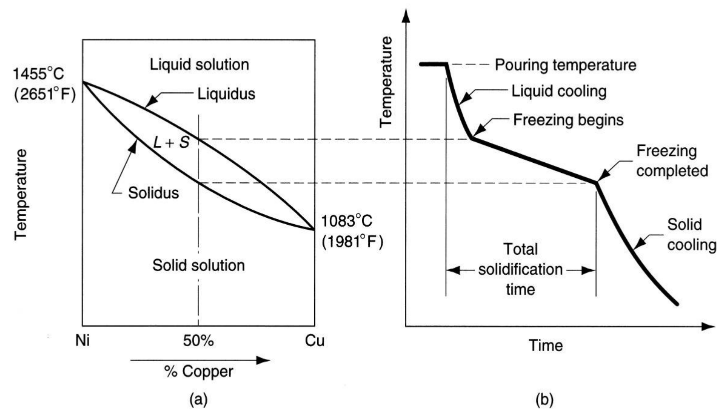


Cooling Curve for a Pure Metal



Solidification of Alloys

- Most alloys freeze over a temperature range rather than at a single temperature



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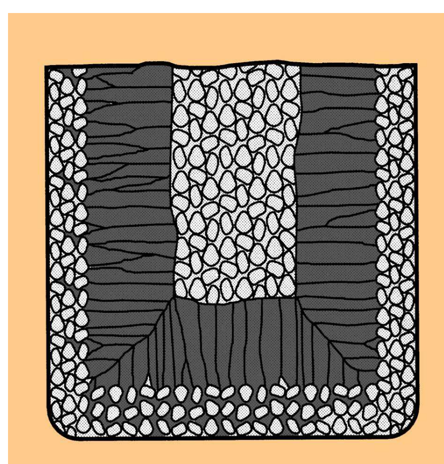
Solidification of Alloys

Characteristic grain structure in an alloy casting, showing segregation of alloying components in center of casting.

Are edges Ni rich or Cu rich? Why?



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Solidification Time

- T_{TS} depends on size and shape of casting by relationship known as *Chvorinov's Rule*

$$T_{TS} = C_m \left(\frac{V}{A}\right)^n$$

where T_{TS} = total solidification time;

V = volume of the casting;

A =

n = exponent with typical value = 2;

C_m = mold constant *(determined experimentally)*

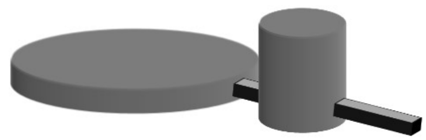
Mold Constant in Chvorinov's Rule

- Mold constant C_m depends on:
  1. Mold material (sand permeability , etc.)
  2. Thermal properties of casting metal
  3. *Pouring temperature* relative to melting point
- Value of Cm for a given casting operation can be based on experimental data from previous operations (carried out using same mold material, metal, and pouring temperature,)
  even though the shape of the part may be quite diffe

In-class exercise: solidification time

- Disk diameter D = 500 mm thickness t = 20 mm
- Riser diameter D= 150 mm, height h =200mm
- Material: Al, C_m = 2.0 sec/mm^2 in Chvorinov's Rule, n=2
- Find: V/A and T_{TS} of casting and riser

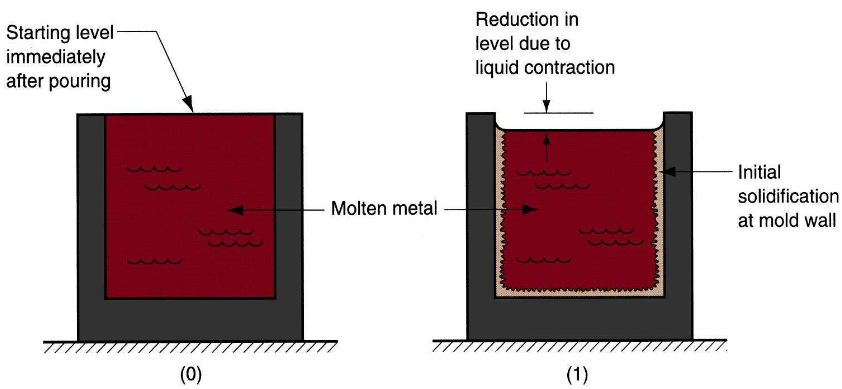
$$T_{TS} = C_m \left(\frac{V}{A}\right)^2$$



What Chvorinov's Rule Tells Us

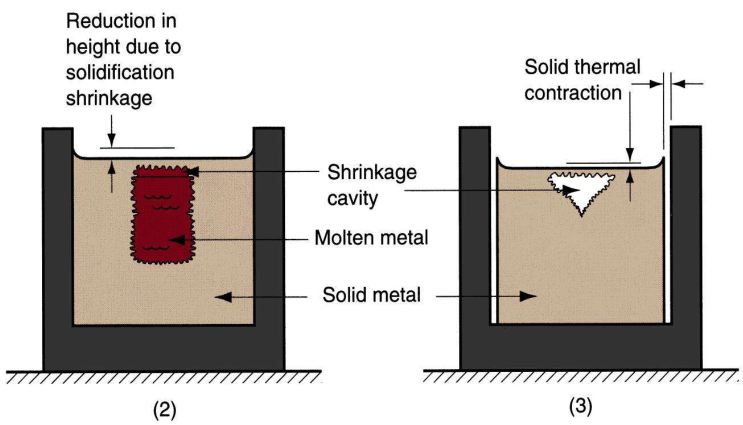
- A casting with a higher volume-to-surface area ratio cools and solidifies more slowly
  - To feed molten metal to the main cavity, TTS for the riser must be greater than TTS for the main casting
- Since mold constants of the riser and casting will be equal, design the riser to solidify last by having its volume-to-area ratio as compared to the main casting: larger
  - This minimizes the effects of: shrinkage
- Ideally a riser would have a solidification time of ~1.25 – 1.5 times that of the cast part.

Shrinkage in Solidification and Cooling



Shrinkage of a cylindrical casting during solidification and cooling: (0) starting level of molten metal immediately after pouring; (1) reduction in level caused by liquid contraction during cooling (dimensional reductions are exaggerated for clarity).

Shrinkage in Solidification and Cooling



(2) reduction in height and formation of shrinkage cavity caused by solidification shrinkage; (3) further reduction in height and diameter due to thermal contraction during cooling of solid metal (dimensional reductions are exaggerated for clarity).

Shrinkage Allowance

- Patternmakers account for solidification shrinkage and thermal contraction by making mold cavity **oversized**
- Amount by which mold is made larger relative to final casting size is called **pattern shrinkage allowance**
- Casting dimensions are expressed **linearly,** so allowances are applied accordingly

Shrinkage Allowance

TABLE 14 CASTING SHRINKAGE ALLOWANCE

METAL	TYPICAL PERCENT SHRINKAGE
Grey Iron	0.7% - 1.05%
Steel	2.0%
Brass	1.4%
Aluminum	1.8%
Bronze	1.05% - 2.1%
Magnesium	1.8%
Zinc	2.5%

Exception: cast iron high carbon content

due to graphitization during final stages of freezing which causes expansion that counteracts volumetric decrease associated with phase change.

Achieving Directional Solidification

- Desired directional solidification is achieved using Chvorinov's Rule
- Locate sections of the casting with lower *V*/*A* ratios away from riser, so freezing occurs first in these regions, and the liquid metal supply for the rest of the casting remains open
- *Chills* - internal or external heat sinks that cause rapid freezing in certain regions of the casting

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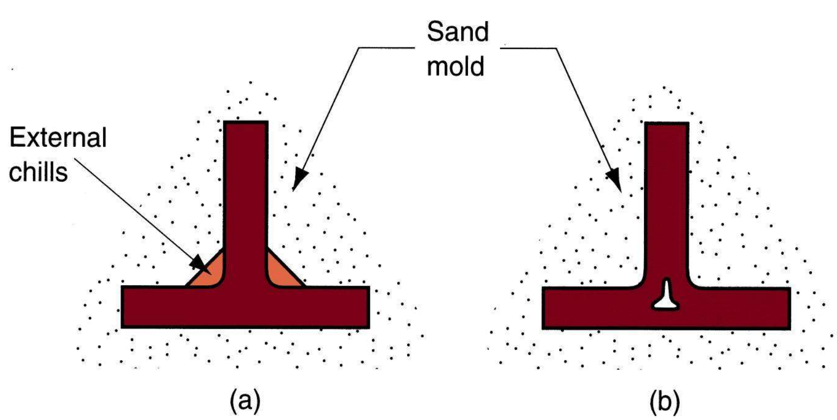
External Chills



(a) External chill to encourage rapid freezing of the molten metal in a thin section of the casting; and (b) the likely result if the external chill were not used.

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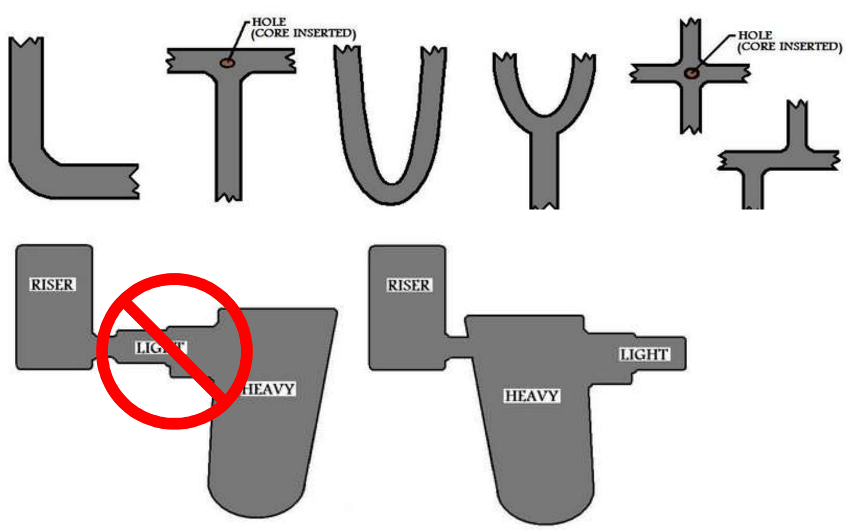
ME 270
Design for Manufacturability

Timothy H. Lee, PhD

Fall 2021

Lecture 13: Sand Casting

Design Considerations in casting



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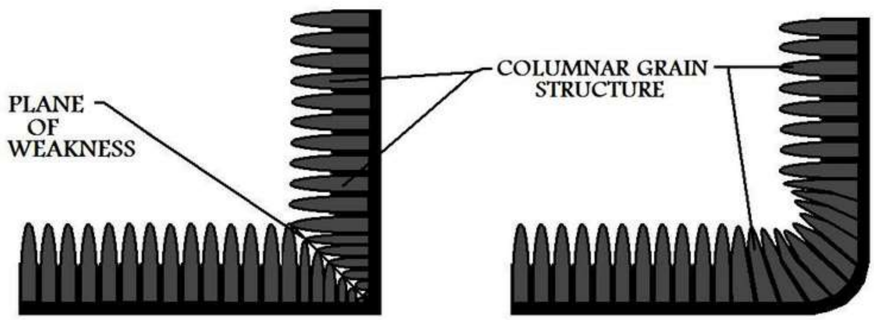
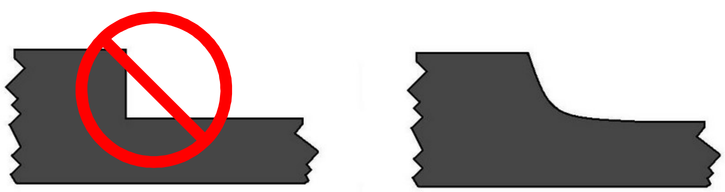
Design Considerations in casting

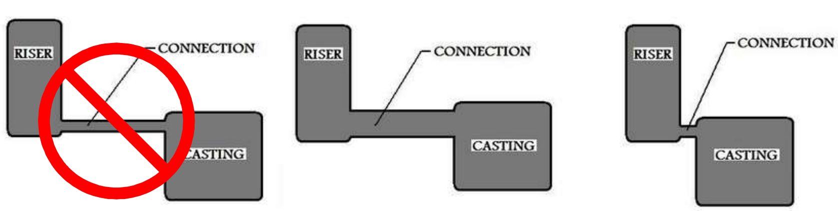
- Micro-structure induced weaknesses



Design Considerations in casting

- Material flow in the mold





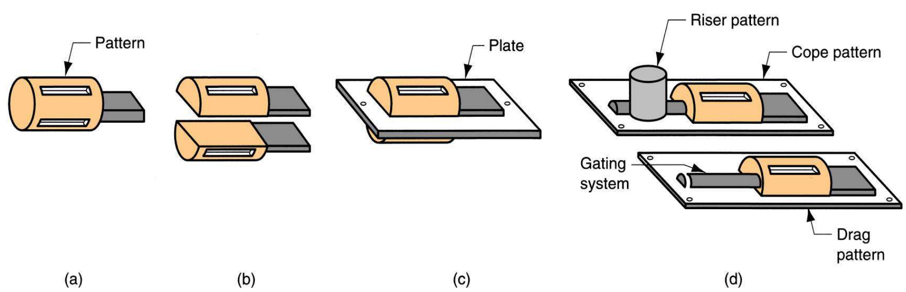
Patterns

Pattern – a model of the part, slightly ***larger*** to account for shrinkage and machining allowances

Types of patterns used in sand casting:

(a) solid pattern, (b) split pattern, (c) match-plate pattern

(d) cope and drag pattern



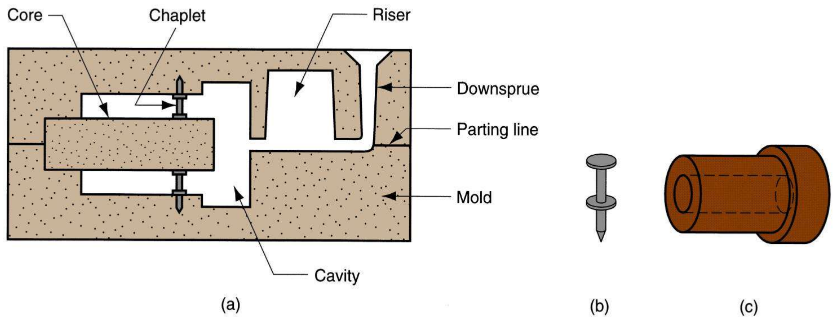
Making the Sand Mold

- The *cavity* in the sand mold is formed by packing sand around a pattern, then separating the mold into two halves and removing the pattern
- The mold must also contain gating and riser system
- If casting is to have internal surfaces, a ***core*** must be included in mold
- A new sand mold must be made for each part produced

Chaplet to Support Core

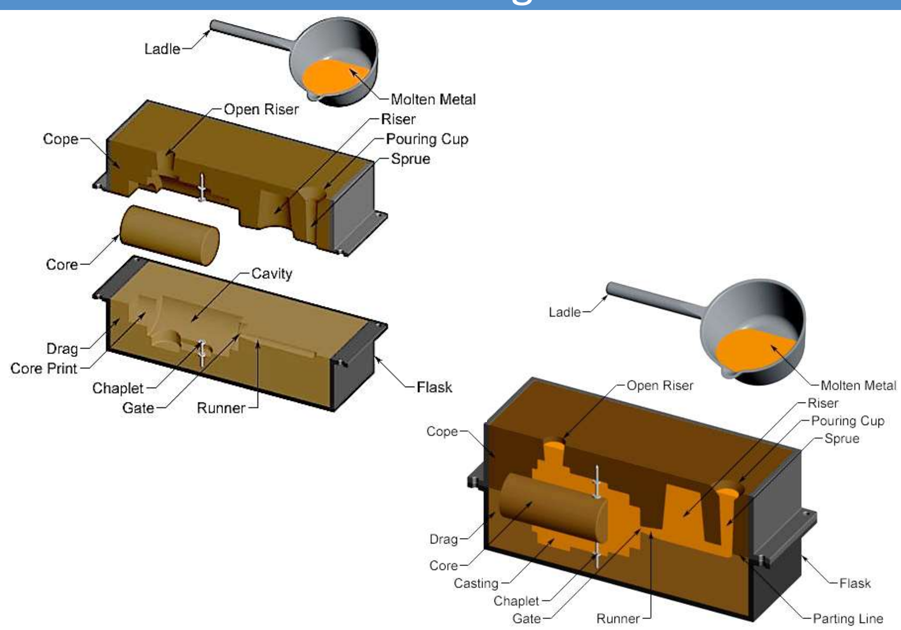
Full-scale model of   surfaces of part

- May require supports to hold it in position in the mold cavity during pouring, called



(a) Core held in place in the mold cavity by chaplets, (b) possible chaplet design, (c) casting with internal cavity.

Sand Casting Mold

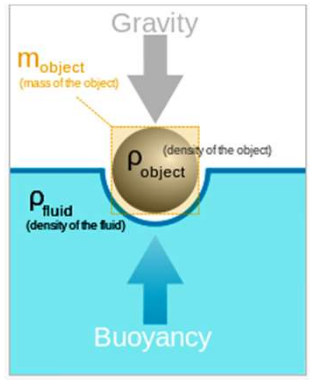


Buoyancy in Sand Casting

- Buoyancy is an upward force, in opposition to the gravitational force, proportional to the *weight of the fluid that is displaced*.

  $\downarrow F_{gravity}$ =

  $\uparrow F_{buoyancy}$ =



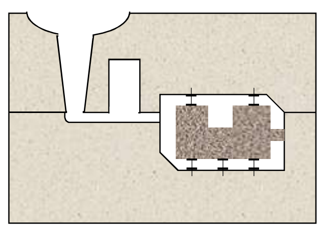
* *Wikipedia*

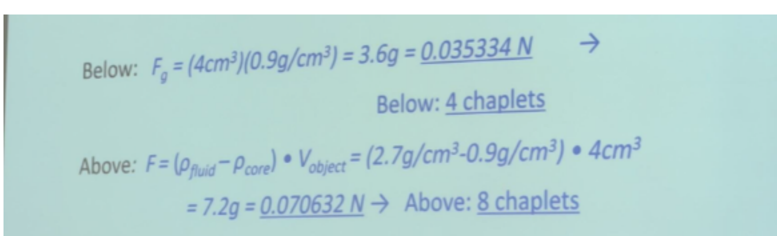
- If $F_g > F_b$ then the object sinks, if $F_b > F_g$ then the object floats.
- Chaplets are needed *beneath a core* to support its before casting, and *above* for when the

  $\uparrow F_{top\text{-}chaplets}$ =

Chaplet Example

- If a casting contains a core (density = **0.9g/cm³**, volume = **4 cm³**, and metal density = **2.7g/cm³**) and each chaplet can support **0.01 N** of force, then how many chaplets are needed above and below the core? *(gravity: 1kg = 9.81 N)*




Below: $F_g = (4cm^3)(0.9g/cm^3) = 3.6g = \underline{0.035334\ N}$ →

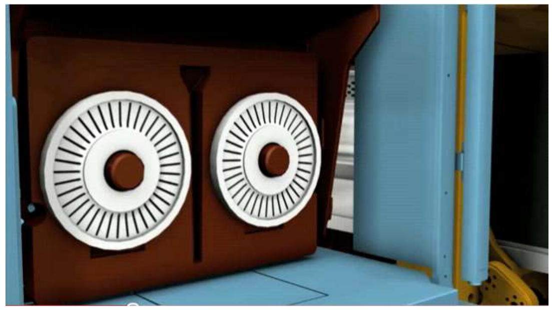
Below: 4 chaplets

Above: $F = (\rho_{fluid} - \rho_{core}) \bullet V_{object} = (2.7g/cm^3 - 0.9g/cm^3) \bullet 4cm^3$

$= 7.2g = \underline{0.070632\ N}$ → Above: 8 chaplets

Automatic Sand Casting

- Vertical Mold Making Machines
  - Highest speed casting ~ 350 parts/hour
  - Iron and steel
  - Good surface finish (high pressure/density sand pack)
- Horizontal Mold Making Machines
  - Larger parts possible ~200 parts/hr
  - Easier for Manual placement of cores (gravity hold cores in place



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Adv. and Disadv. of Sand Casting

Advantages

- Parts with high degree of *complexity* can be made.
- *Large parts* of several tons weight can be cast.
- A *majority of metal* materials can all be cast: iron, aluminum, and copper alloys
- Nearly all components can be recycled (sand, mold)

Disadvantages:

- Slow cooling means large grain size, which means *decreased part strength*
- Considerably more *labor intensive* than other casting methods
- *Poor surfaces finish* – possibly worst of any manufacturing process.
- Design *restrictions* due to wall *thickness* and *draft angles*.

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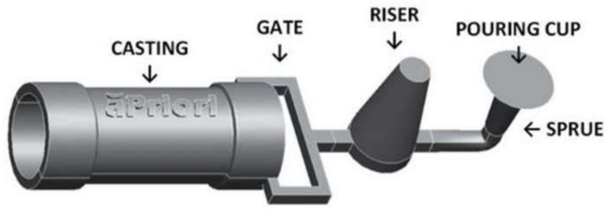
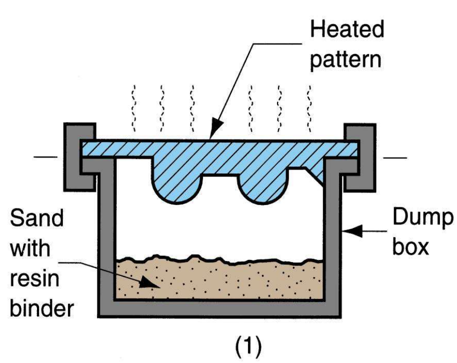
Other Expendable Mold Casting Processes

- Shell Molding
- Expanded Polystyrene Process
- Investment Casting



1. Shell Molding

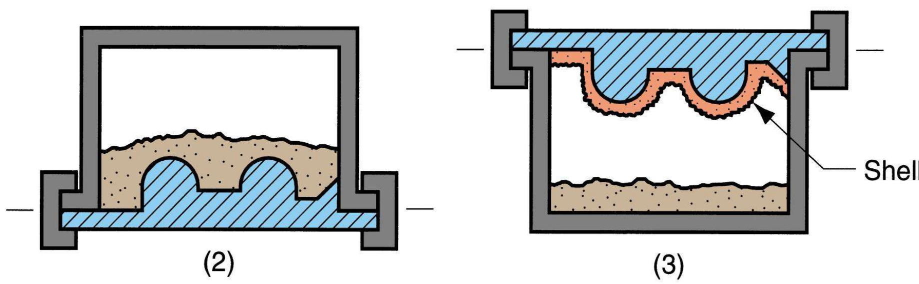
Casting process in which the mold is a thin shell of sand held together by thermosetting resin binder



Steps in shell-molding: (1) a match-plate or cope-and-drag metal pattern is heated and placed over a box containing sand mixed with thermosetting resin.

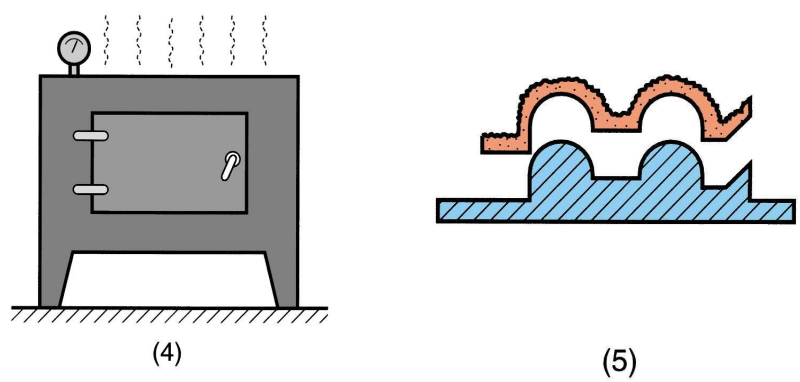
1. Shell Molding

Steps in shell-molding: (2) box is inverted so that sand and resin fall onto the hot pattern, causing a layer of the mixture to partially cure on the surface to form a hard shell; (3) box is repositioned so that loose uncured particles drop away;

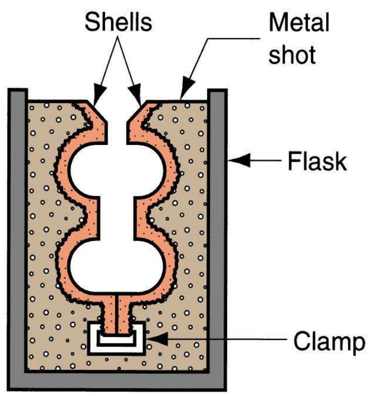


1. Shell Molding

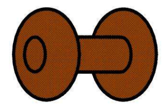
Steps in shell-molding: (4) sand shell is heated in oven for several minutes to complete curing; (5) shell mold is stripped from the pattern;



1. Shell Molding



(6)



(7)

Steps in shell-molding: (6) two halves of the shell mold are assembled, supported by sand or metal shot in a box, and pouring is accomplished; (7) the finished casting with sprue removed.

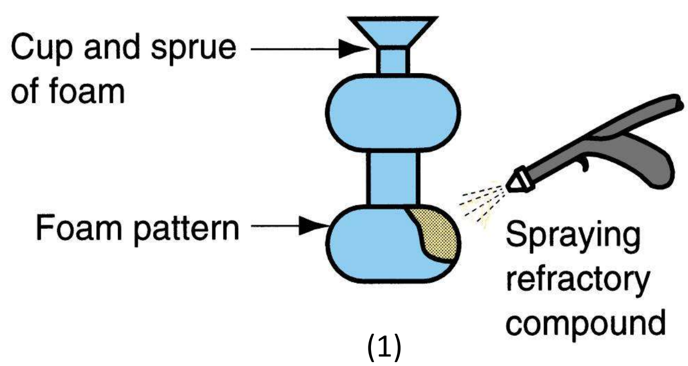
Adv. and Disadv. of Shell Molding

- Advantages:
  - Better surface finish
  - Good dimensional accuracy
    - machining often not required
  - Less cracks in casting
- Disadvantages:
  - Takes more time
  - Because of resin, more expensive
  - Shell not reusable
  - Not air premeable

2. Expanded Polystyrene Process

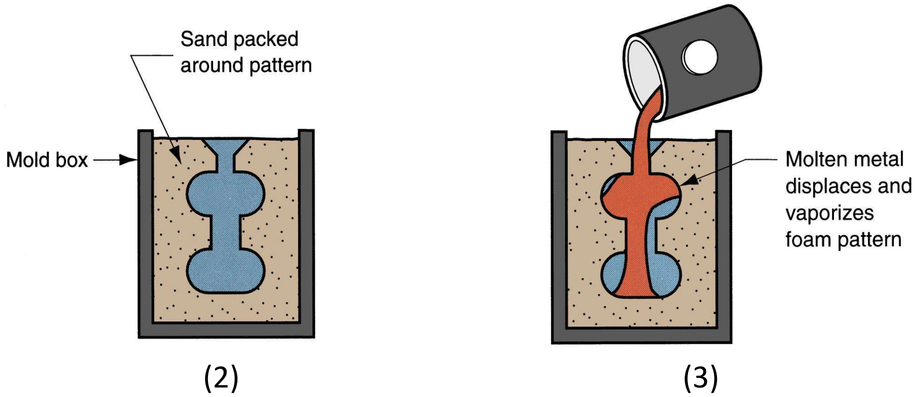
- Uses a mold of sand packed around a polystyrene foam pattern which vaporizes when molten metal is poured into mold
- Other names: lost-foam process, lost pattern process, evaporative-foam process, and full-mold process
- Polystyrene foam pattern includes sprue, risers, gating system, and internal cores (if needed)
- *Mold does not have to be opened into cope and drag sections*

2. Expanded Polystyrene Process



(1) pattern of polystyrene is (repeatedly) coated with refractory compound and dried.

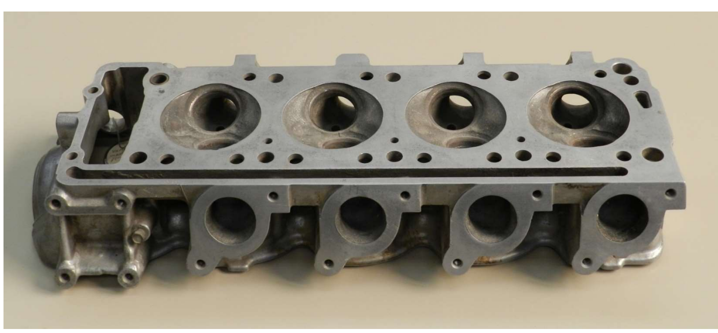
2. Expanded Polystyrene Process



(2) coated foam pattern placed in the mold box, and sand is compacted around the pattern; (3) molten metal is poured and the polystyrene foam is vaporized ahead of the advancing liquid.

Applications

- Mass production of automobile engines and parts
- Aluminum engine head produce using Expanded Polystyrene Process:

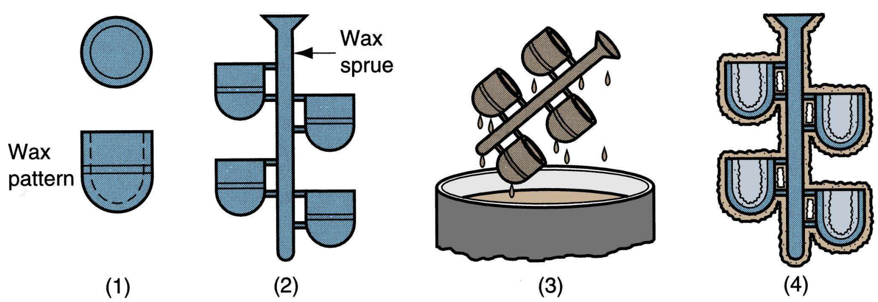


Adv. and Disadv. of Exp Polystyrene Process

- Advantages of expanded polystyrene process:
  - *No draft angles* - part does not need to be removed from the mold
  - *Faster*: two mold halves are not required
- Disadvantages:
  - A new pattern is needed for every casting
  - *Cost* is higher because it takes longer and refractory material is not inexpensive.

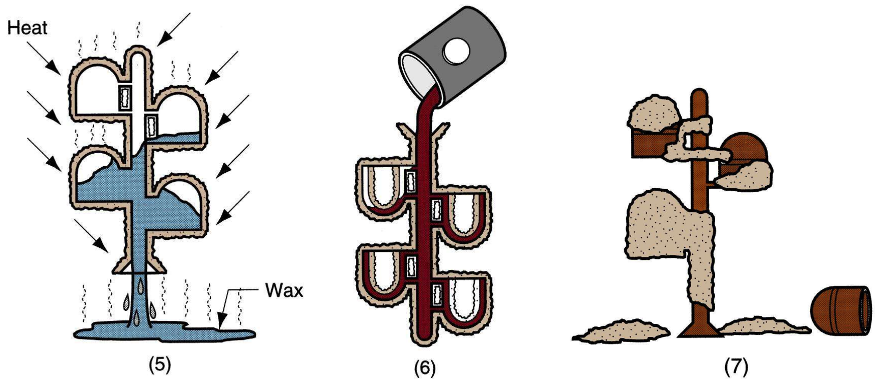
3. Investment Casting (Lost Wax Process)

- "Investment" means "to cover completely,"
- A wax pattern is covered with a refractory material prior to melting away the wax and pouring the metal.



Steps: (1) wax patterns are produced, (2) patterns are attached to a sprue to form a pattern tree, (3) the pattern tree is repeatedly coated with a refractory material, (4) the mold is dried to make it rigid

3. Investment Casting



Steps: (5) the mold is held in an inverted position and heated to melt the wax and permit it to drip out of the cavity, (6) the mold is preheated to a high temperature, the molten metal is poured, and it solidifies, (7) the mold is broken away from the finished casting and the parts are separated from the sprue.

3. Investment Casting

Could this be made by sand casting?

By the expanded polystyrene process?

A one-piece compressor stator with 108 separate airfoils made by investment casting (photo courtesy of Howmet Corp.).

Advantages and Disadvantages

- Advantages of investment casting:
  - Parts of great complexity and highest intricacy can be cast
  - Close dimensional control and excellent surface finish
  - Wax can usually be *recovered* for reuse
  - Additional machining is not normally required - this is a *net shape* process
- Disadvantages
  - Many processing steps are required - - time
  - Relatively *expensive* and time consuming process

UIUC-ZJU PARTNERSHIP

University of Illinois at Urbana-Champaign - Zhejiang University Partnership

ME 270
Design for Manufacturability

Timothy H. Lee, PhD

Fall 2021

Lecture 14: Sand Casting

Permanent Mold Casting Processes

- One mold used over and over again
- The processes include:
  1. Basic permanent mold casting
  2. Die casting

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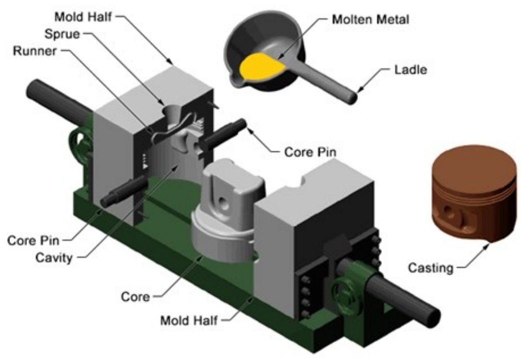
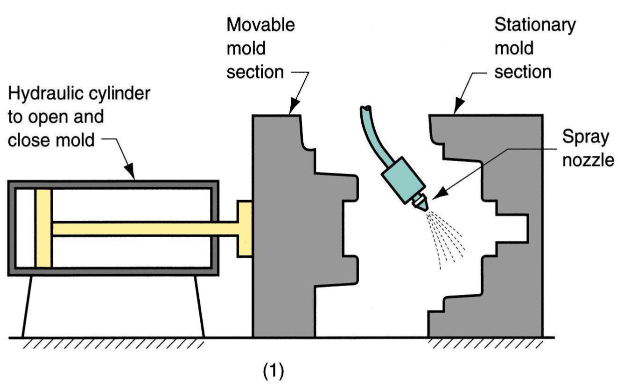
1. Basic Permanent Mold Casting



- Metal mold must have a *higher melting temperature* than the pouring metal (e.g. cast iron mold for copper, brass, tin, or bronze, and a graphite mold for casting steel)

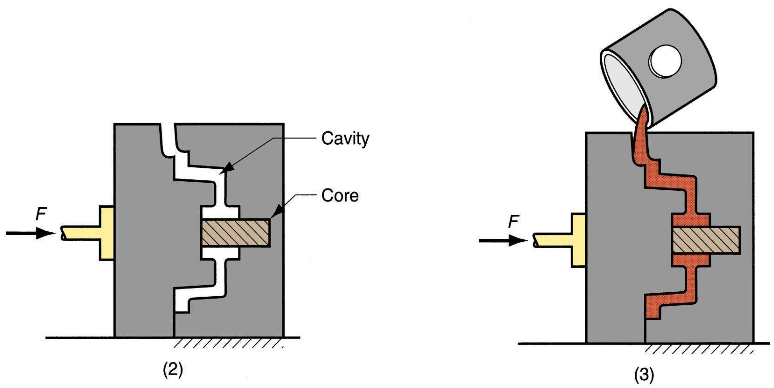
- Mold is typically coated with a *refractory material* to *prevent sticking*.
- Mold must be *preheated* to prevent premature solidification of metal
- *Venting* occurs though the *crack* between the molds.
- Solidification is fast to *no riser* is generally used.

1. Permanent Mold Casting



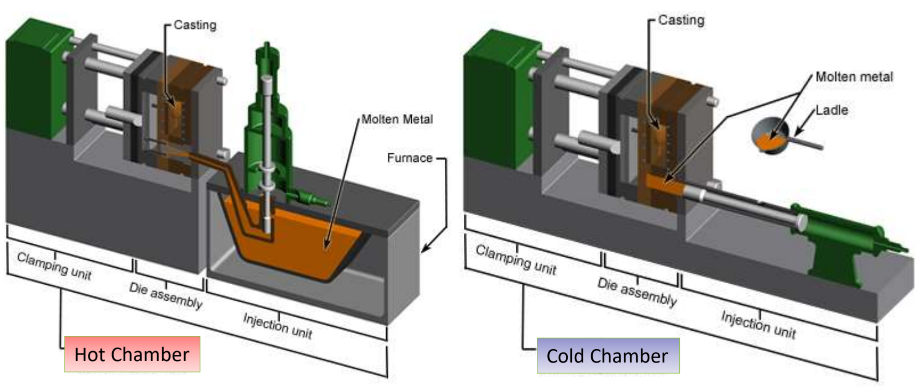
Steps in permanent mold casting: (1) mold is preheated and coated

1. Permanent Mold Casting



Steps in permanent mold casting: (2) cores (if used) are inserted and mold is closed, (3) molten metal is poured into the mold, where it solidifies.

2. Die Casting – Pressurized Metal Injection



- Molds in this casting operation are called *dies*
- Use of high pressure to force metal into die cavity improves pattern fidelity and enables thinner patterns

2. Pressurized Injection of Metal

Hot Chamber Process

- Can produce parts up to 15 per minute
- Can't be used with Aluminum since it picks up iron while in the molten pool

Cold Chamber Process

- Aluminum, magnesium, and copper can all be cast this way
- Slower than hot chamber process, but the fastest way to cast aluminum.

Adv. and Disadv. – Permanent Mold Process

Advantages

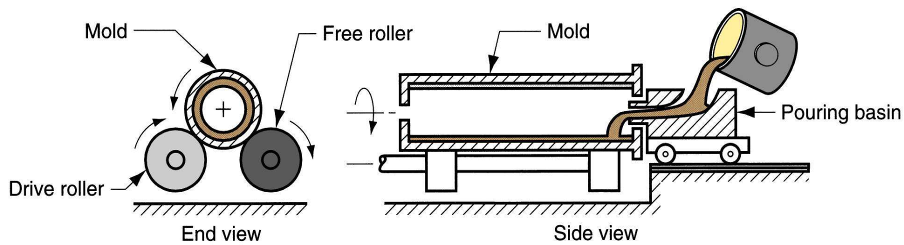
- Highest casting *production rates*
- Most *economical* for high production rates
- *Finer features, higher tolerances, and smoother surfaces*
- With a metal mold, the part cools quickly, improving microstruction, making a *stronger part*.

Disadvantages

- Only *non-ferrous metals* can be die cast
- Initial cost for *dies is expensive*
- Complexity limited, only simple geometries, due to need to open mold.
- Part *size limited*

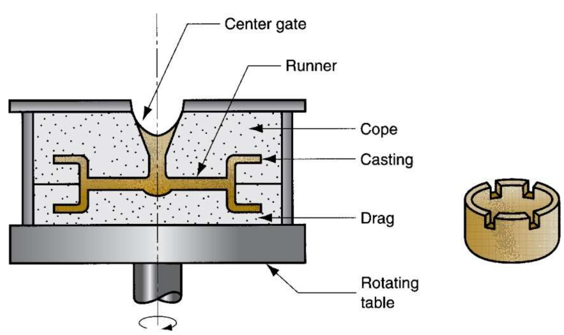
Centrifugal Casting

A casting processes where the mold is rotated at high speed so centrifugal force distributes molten metal to outer regions of die cavity. Example:



Semi-centrifugal Casting of Small Parts

- Density greater and pressure greater at outer sections – stronger and higher pattern fidelity
- Well suited for wheels and pulleys



Additional Steps After Solidification

- Trimming
  - Removal of sprues, runners, risers, parting-line flash, fins, chaplets, and any other excess metal
- Removing the core
  - Most cores fall out, some by shaking, in rare cases, removed by chemically dissolving bonding agent
- Surface cleaning – primarily removal of sand
- Inspection
- Repair, if required
- Heat treatment

Design Advisor - Casting

Can Cast These:

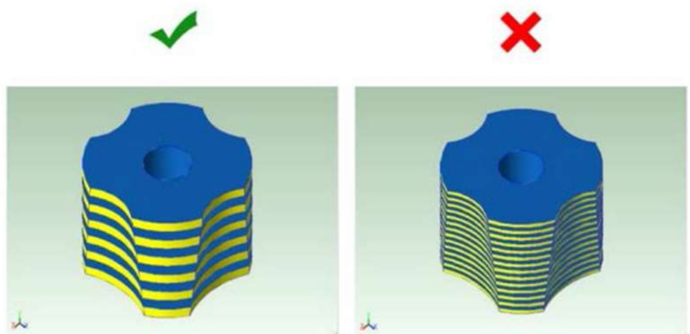
- Grey iron, nodular iron, aluminum alloys, aluminum-silicon alloys, brass, copper alloys, castings-specific steels, zinc alloys, magnesium alloys

Can not Cast These:

- High-strength aluminum (2xxx, 6xxx, and 7xxx series), titanium, plain carbon steel, alloy steel (4xxx series)
- High performance alloys do not cast well
- High strength parts made by other means

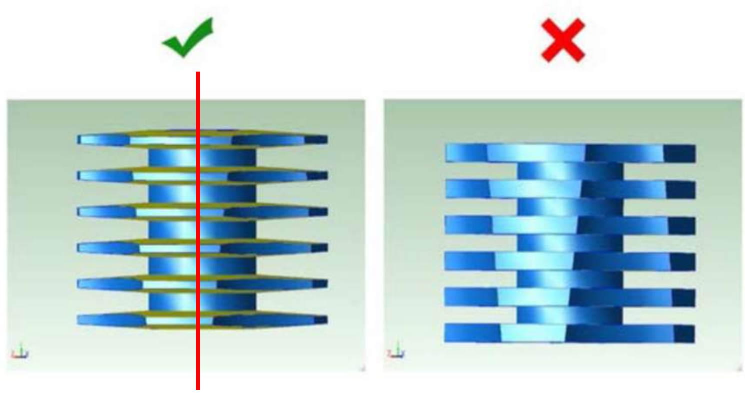
Design Advisor – Wall thickness

- Wall thickness must be >5mm for gravity filled molds
- Pressurized injection die casting can have thinner parts



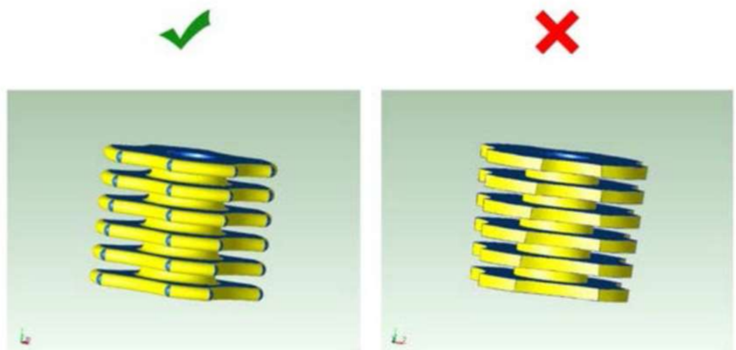
FUNDAMENTALS OF METAL CASTING: Design Advisor – Draft Angles

- Draft angles on all parting line features
- Choose parting line and draft angle direction that uses these fewest cores.



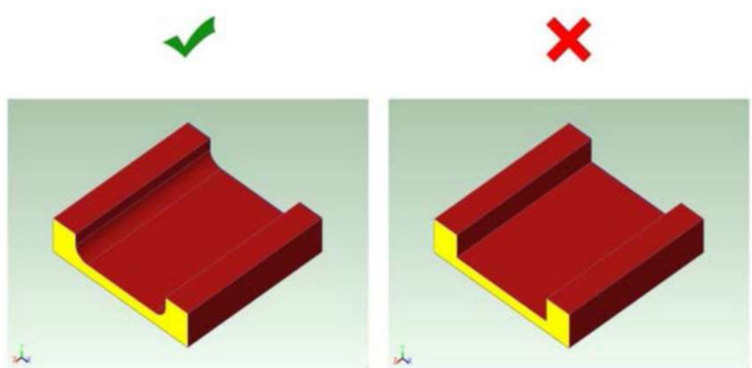
Design Advisor - Corners

- Avoid sharp corners - metal flow will erode and turbulence will weaken cast
- Filleted corners will fill better.



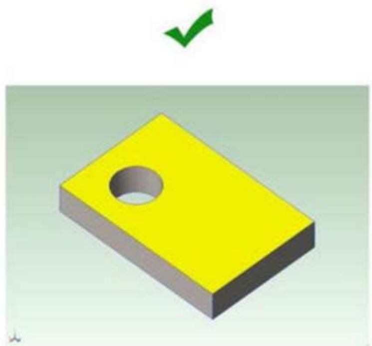
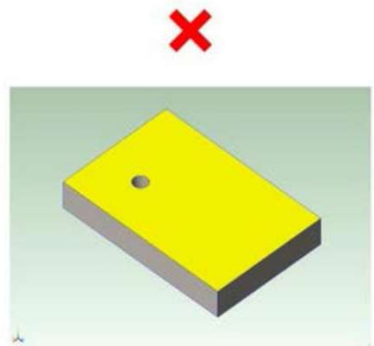
Design Advisor – Thickness Transition

- When transitioning section thickness, a fillet with radius 1/3rd the width of the thicker section should be used.



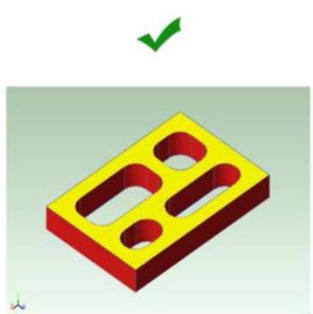
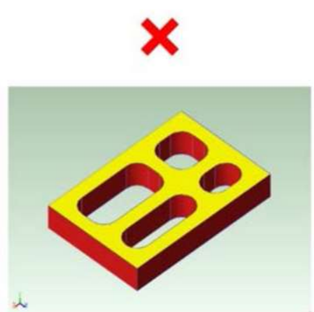
Design Advisor – Hole Size

- Can not sand casting holes less than ¼” dia.
- In general holes do not cast well, and require a taper.

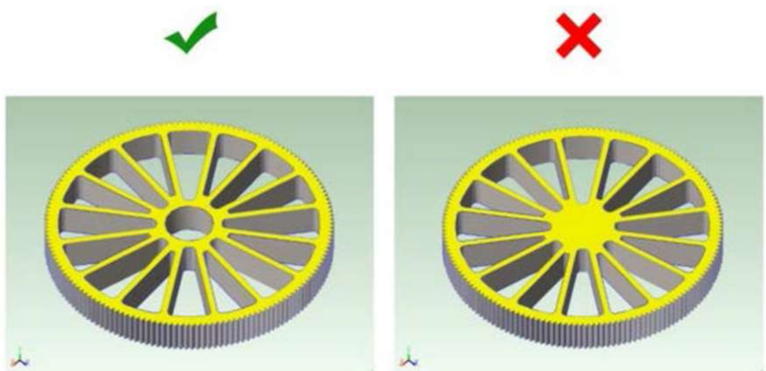
Design Advisor – Intersecting Ribs

- Avoid intersecting ribs due uneven cooling:
  - Shrinkage defects near intersection
  - Irregular grain structure near intersection
  - Thermal stress near intersection

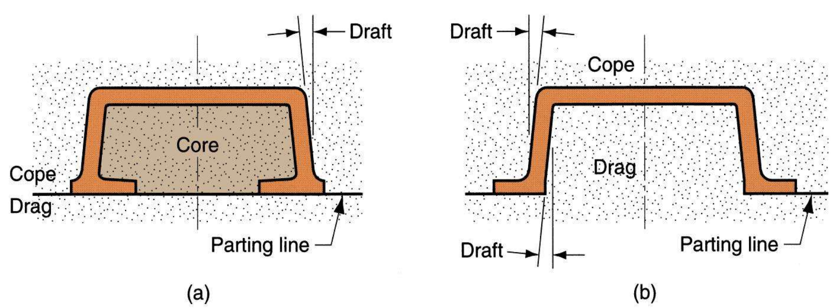
Design Advisor – Uniform Cross-Section

- Add holes to make cooling rates more uniform



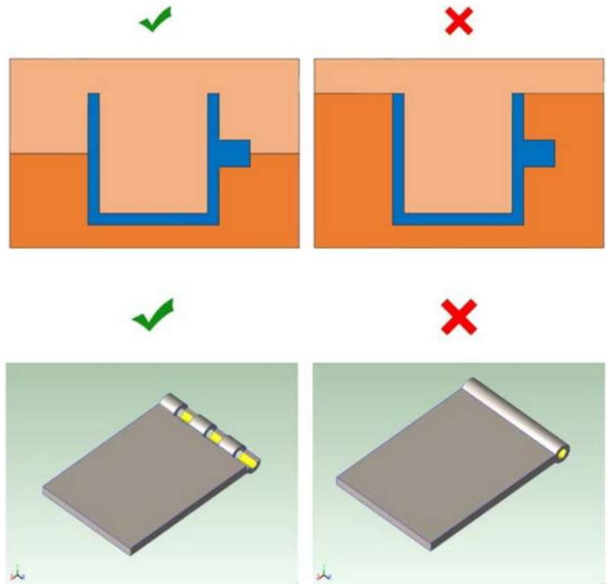
Design Advisor – Eliminate Cores

- Minor changes in part design can reduce need for coring



Design change to eliminate the need for using a core: (a) original design, and (b) redesign.

Design Advisor – Eliminate Cores



Design Advisor – Surface Finish

TABLE 13 TYPICAL AS-CAST SURFACE ROUGHNESS

CASTING PROCESS	TYPICAL ROUGHNESS (MICROINCHES RMS)
Horizontal Sand Mold	250-900
Vertical Sand Mold	250-900
Shell Mold	70-150
Die Cast	90-200
Permanent Mold	250-420
Investment Mold	50-125

Investment casting is the most expensive method due to multiple time-consuming stages of mold preparation

Product Design Considerations

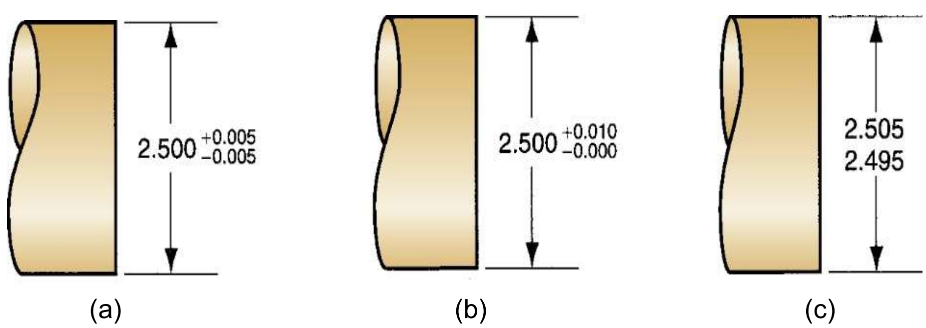
1. Increase *draft angles* (sandcasting ~1°, permanent mold ~2° - 3°)
2. Sand casting gives poor finish and lower dimensional accuracies, while die casting and investment casting give better *dimensional accuracies and finish*.
3. Additional material, called the *machining allowance*, is needed for surfaces where post process machining is necessary

Mechanical Science & Engineering

ME270 – Metrology, GD&T, Quality

- Tolerance & Measurement Tools
- Datums & Tolerance References
- Tolerance Stack Up
- Will it Fit? Tolerance & Assembly
- GD&T
- MMC vs LMC
- Bonus Tolerance
- Clearance
- Tolerance in Manufacturing Processes
- Quality Control
- Gaussian vs. Uniform random distributions

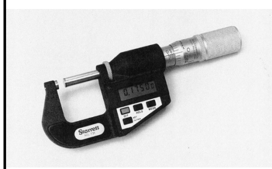
Specify Coordinate Tolerance



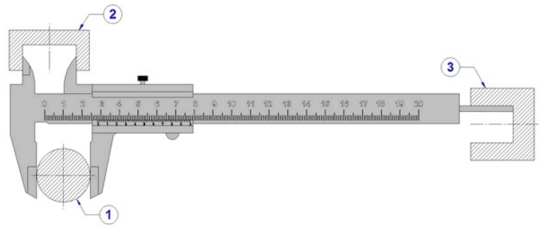
Three ways to specify tolerance: (a) bilateral, (b) unilateral, and (c) limit dimension

Tolerances, include both accuracy and precision, and can be used to specify *lengths, angles, concentricity, surface roughness*, etc.

Measurement Devices

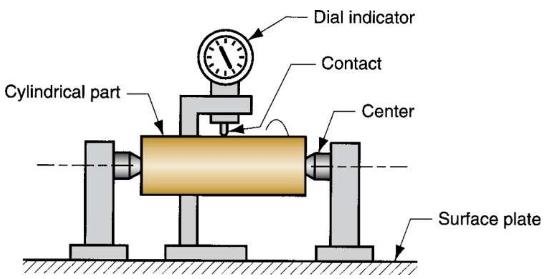


Micrometer

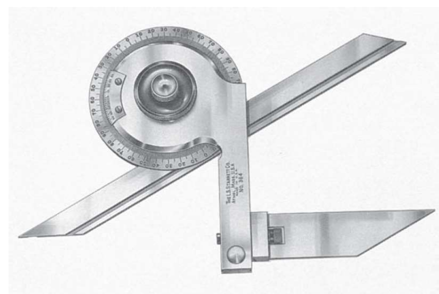


Caliper

Dial Indicator



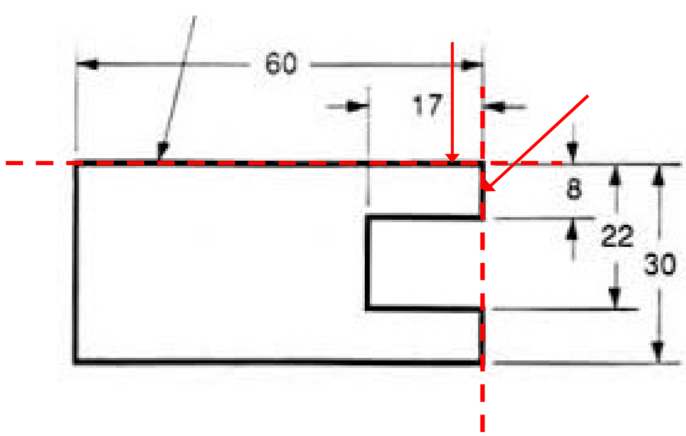
Diameter, Surface Flatness, Concentricity, etc.



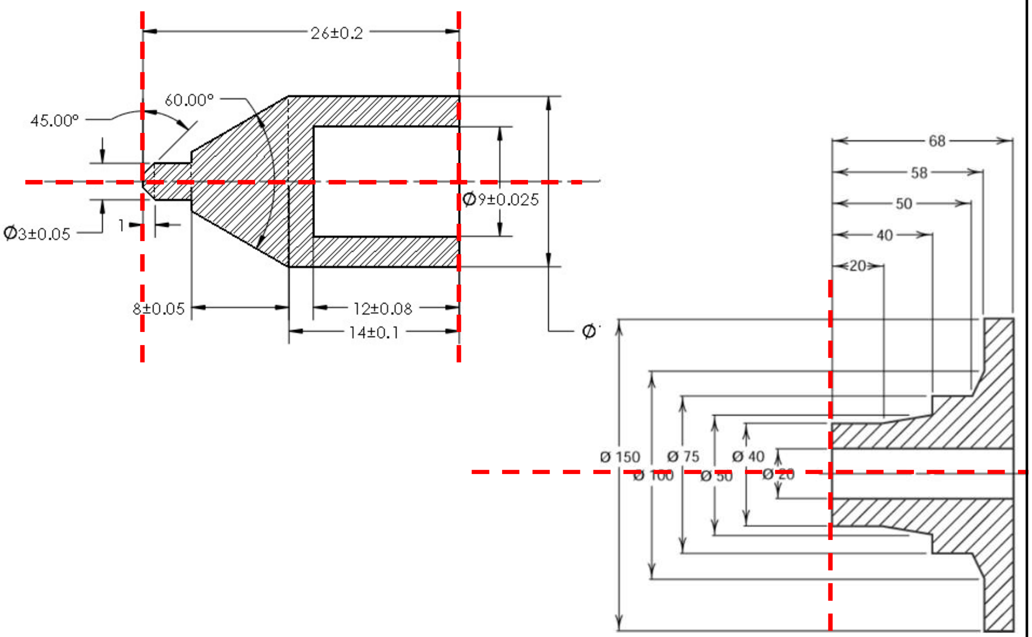
Protractor

Datum and Tolerance Reference

- Datum: a surface, a line, or point off of which
- Which of the below surfaces are Datums?

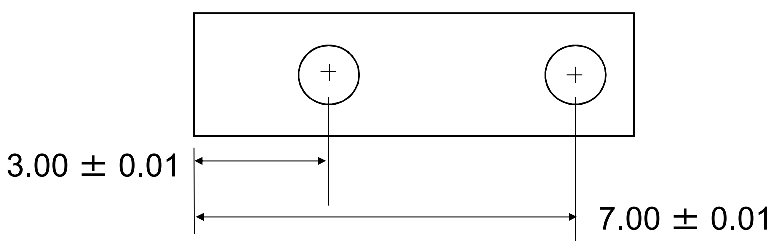


Which are Datums?



Tolerance “Worst Case” Determination

What is the effective dimension and tolerance between the two holes?



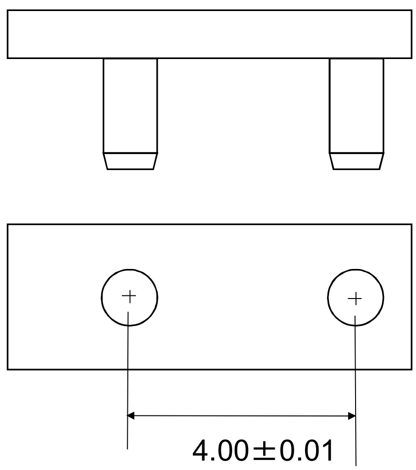
The furthest apart is:

The closest is:

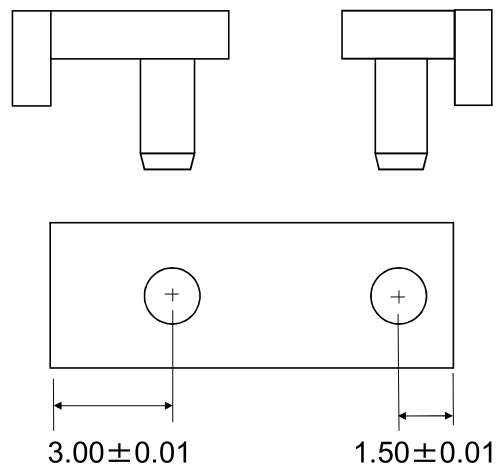
Proper Way of Dimensioning

It is important to specify the dimension and tolerance at the location most important to function.

Case one:

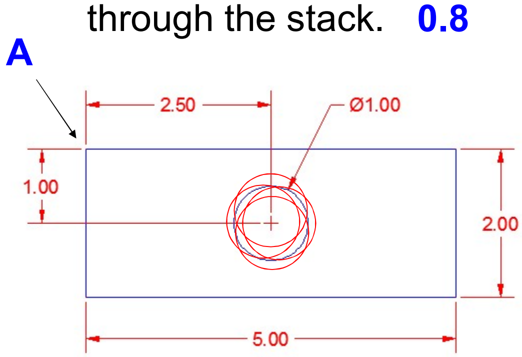


Case two:



Tolerance Stack-up from a Datum

- Assume the block below has a thickness of 1.0 ± 0.1 and 10 are stacked together with corner **A** all aligned.
- What is the tallest the stack could be? **11**
- What is the shortest? **9** → thickness = 10 ± **1**
- If the position of the hole has a lateral tolerance (from **A**) of ±0.1 what is the largest pin that could *always* fit through the stack. **0.8**



- Would this depend on the number of blocks if all aligned with corner "A"?

No, hole position has a common datum, point "A." (thickness doesn't have a common datum, so it "stacks up")

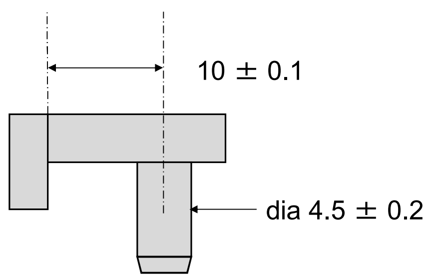
Tolerance Stack-Up

Problems due to tolerance stack-ups include:

- Failure to assemble
- Interference between parts
- Failure of parts to engage
- Failure to function as intended

Will it Fit?

Will this pin with variable *position* and *diameter* always fit into the “perfect” part below?

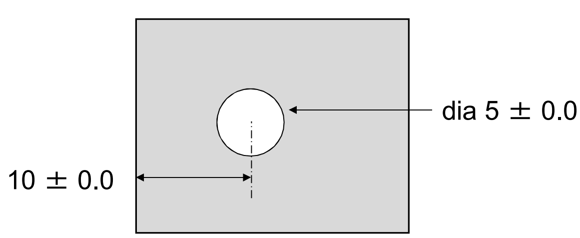


Start with the largest diameter pin and add 2x its positional tolerance. Then compare to mating condition

$4.5 + 0.2 + 2*0.1 = 4.9$

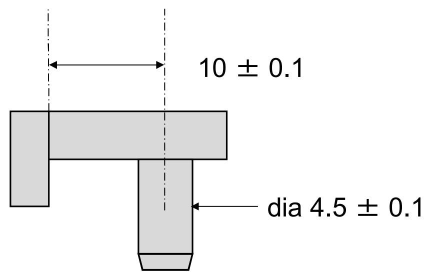
$4.9 < 5.0$

Yes it will always fit!



Will it Fit?

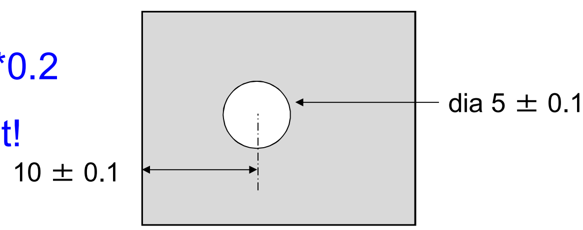
Will these parts both with variable *position* and *diameter* always mate?



Compare the largest pin plus 2x its positional tolerance with the smallest hole minus 2x positional tolerance

4.6 + 2*0.1 ?? 4.9 – 2*0.2

No it will NOT always fit!



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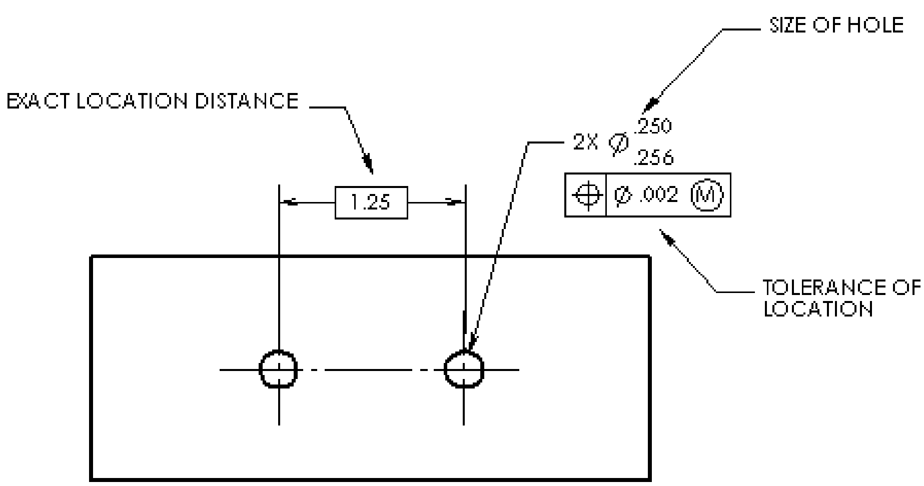
GD&T Example



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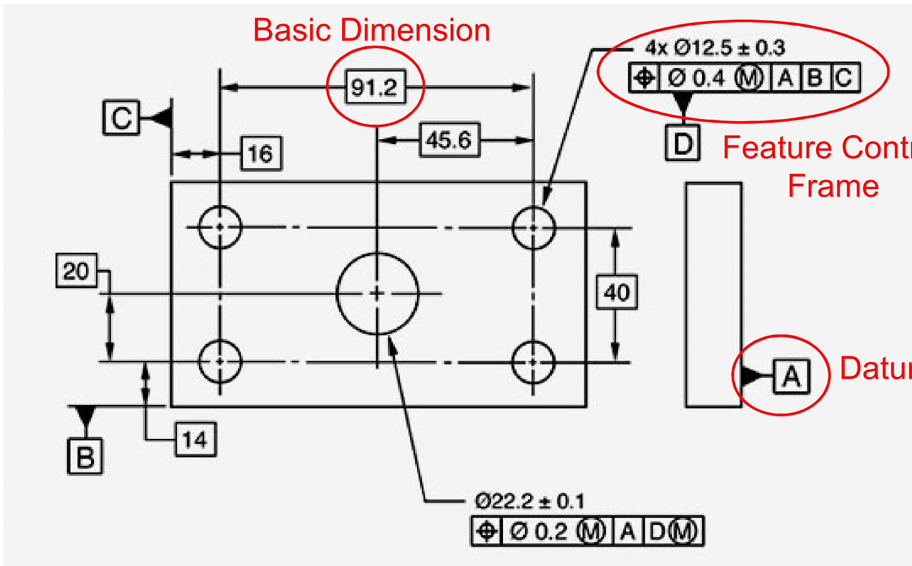
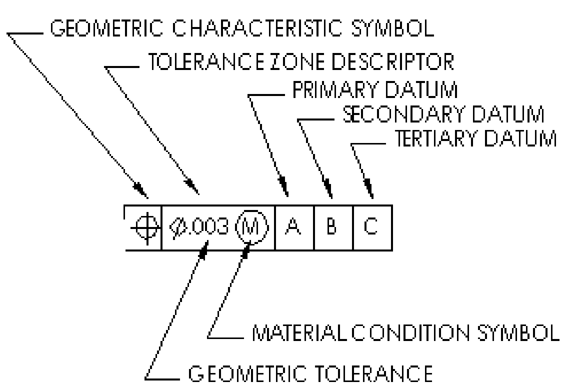
Geometric Dimensioning and Tolerancing

GD&T is an international way to specify tolerances in modern engineering drawings.



How to Read Feature Control Frame?



- Reads as: the position of the feature must be within a .003 diametrical tolerance zone at maximum material condition relative to datums A, B, and C.

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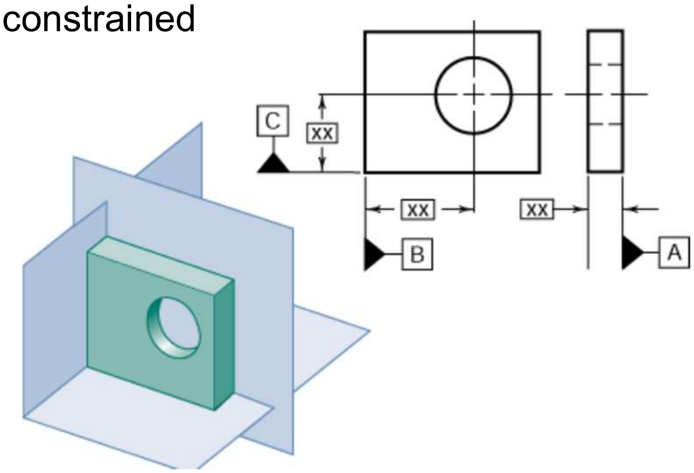
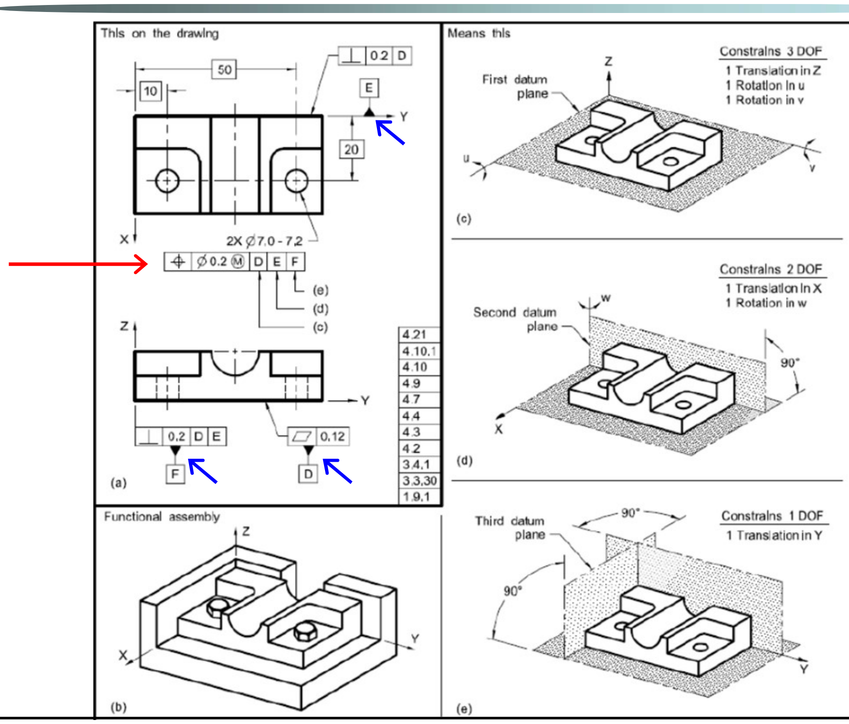
Datums – related to part use

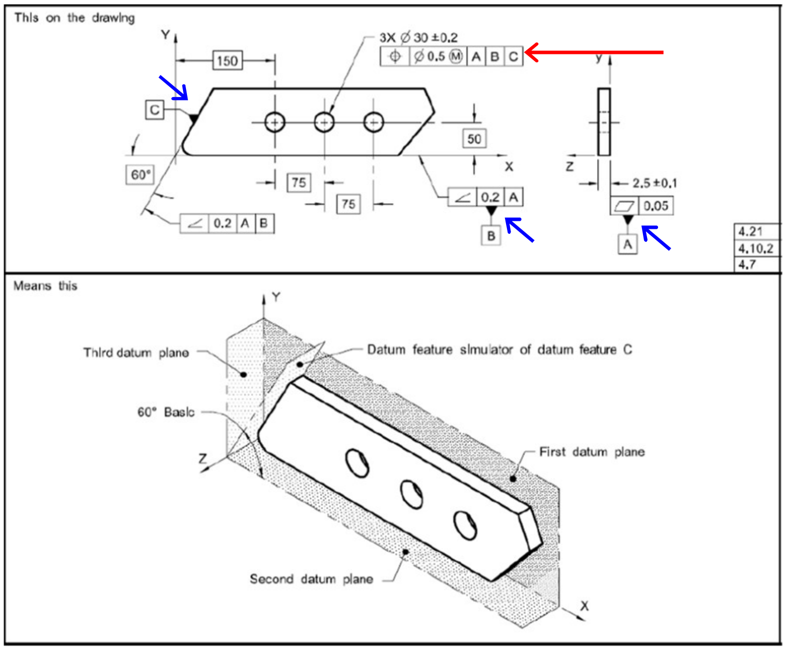
- Part is first located using surface A – 3 points
- Then located using surface B – 2 points
- Finally using surface C – 1 point
- Part is fully constrained



Sequence of Datum Features



Inclined Datum Feature



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Feature Control Frame

- Describes the conditions and tolerances

Geometric characteristic (i.e. position)

Nominal Part Tolerance

Primary, secondary, and tertiary datum

Diameter symbol

Material condition modifier

TYPE	SYMBOL
MAXIMUM MATERIAL CONDITION	M
LEAST MATERIAL CONDITION	L
REGARDLESS OF FEATURE SIZE	S

MMC vs LMC

- Maximum Material Condition = when the part ***weight*** is the most.
  - Largest allowable shaft or pin size,
  - Smallest allowable hole size
  - MMC for a shaft Ø 0.40±0.02? 0.42
  - MMC for a hole Ø 0.40±0.02? 0.38
- Least Material Condition = when the part ***weight*** is the least.
  - Smallest allowable shaft or pin size,
  - Largest allowable hole size
  - LMC for a shaft Ø 0.40±0.02? 0.38
  - LMC for a hole Ø 0.40±0.02? 0.42

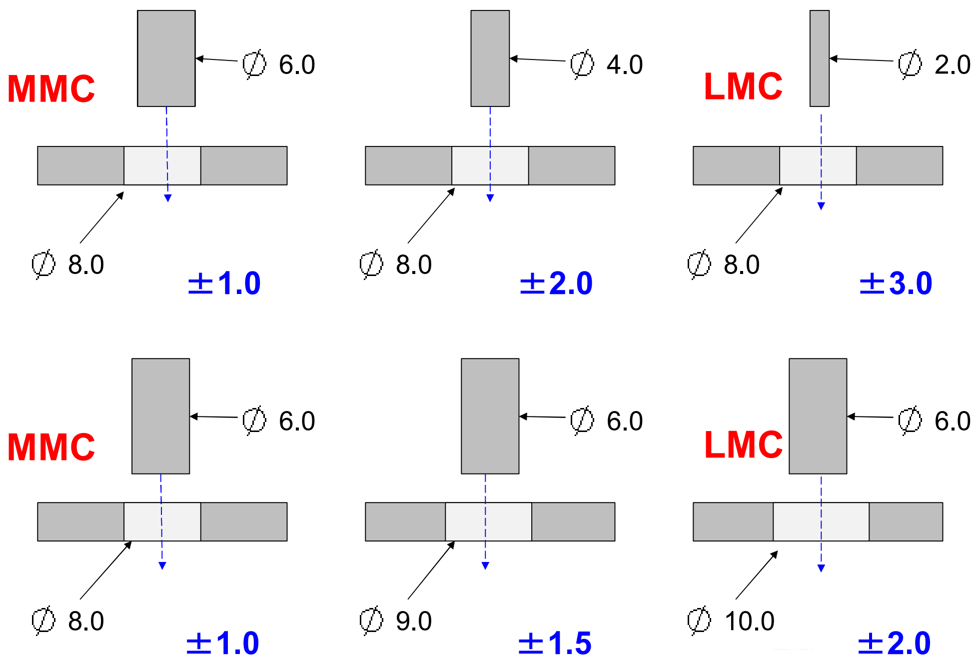
Bonus Tolerance??

- The “M” in the circle after the tolerance designation:

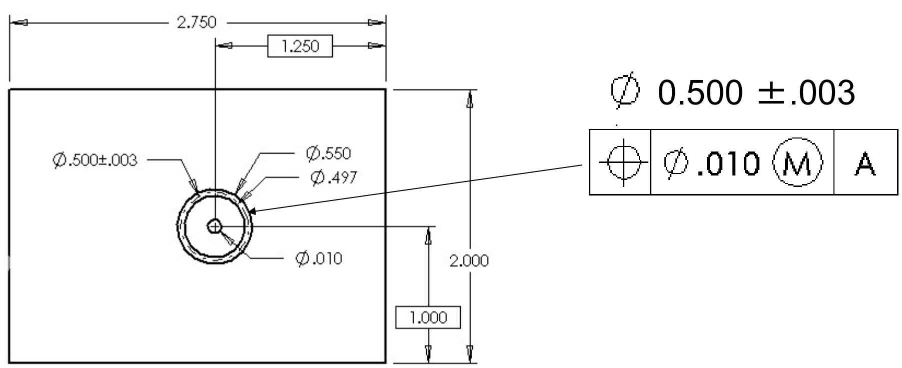
⌖	Ø .010 Ⓜ	A

  - the tolerance is 0.010 <u>if</u> the hole size is the MMC size (aka 0.497). If the hole is bigger we get a <u>bonus</u> tolerance equal to the difference between the MMC size and the actual size.
  - *For a hole, the larger the hole, the more it can deviate from its true position and still fit a mating pin or shaft*.

Greatest Position Tolerance for Each Case?



Bonus Tolerance Example for a Hole

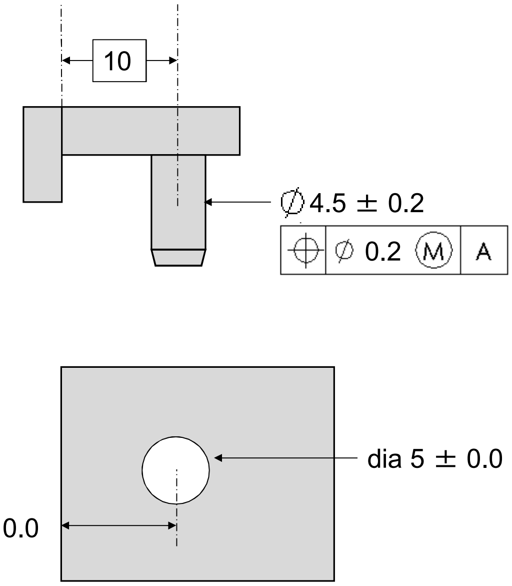


Actual Hole Size	Bonus Tolerance	Ø of Tol. Zone
Ø .497 (MMC)	0	**.010**
Ø .499 (.499 - .497 = .002)	**.002**	**.012**
Ø .500 (.500 - .497 = .003)	**.003**	**.013**
Ø .502	**.005**	**.015**
Ø .503 (LMC)	**.006**	**.016**

Will it Fit?

Will this pin with variable *position* and *diameter* always fit into the "perfect" part below?

Diameter		Tolerance	
4.7	**+**	**0.2**	**< 5**
4.6	**+**	**0.3**	**< 5**
4.5	**+**	**0.4**	**< 5**
4.4	**+**	**0.5**	**< 5**
4.3	**+**	**0.6**	**< 5**



Yes it will always fit!

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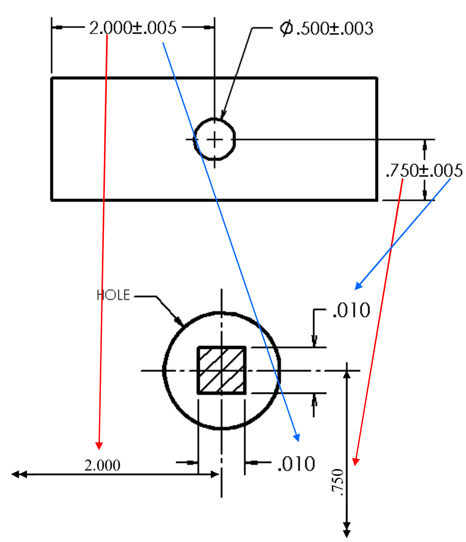
Problem with "Coordinate System" Positioning

- In the old method of drawings the positional location of the center of the hole is shown in the bottom right.
- The vertical uncertainty of the hole position is ±0.010, but along a diagonal it is greater.
- Total hole positional tolerance is actually ±0.014



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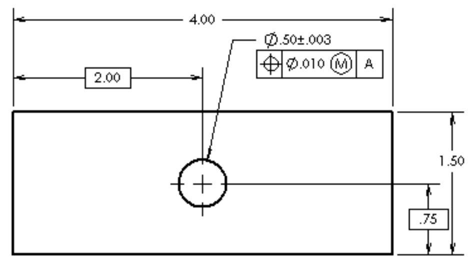
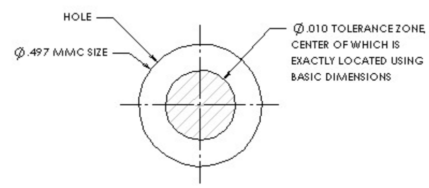
GD&T Positional Tolerancing

- Now the overall hole positional tolerance is ±0.010.
- Center of hole must lie in the shaded area.
- MMC size refers to the "maximum material condition" which for a hole is its smallest allowable diameter (e.g. 0.497)



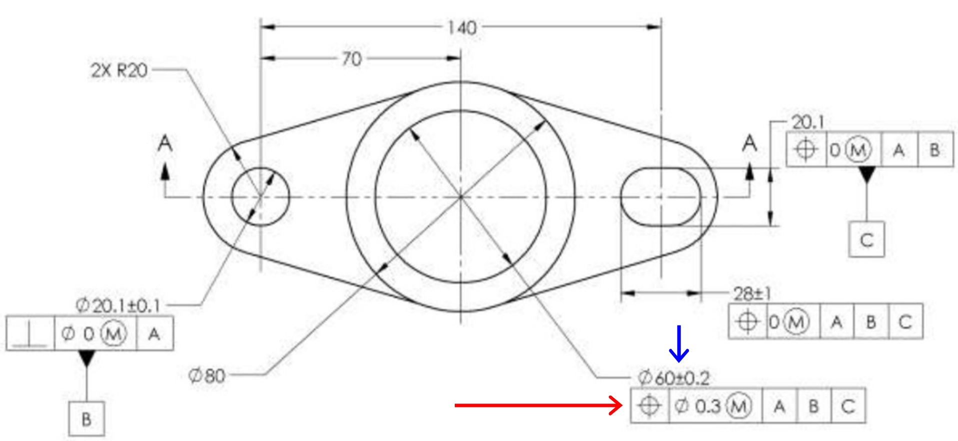


Center Hole Inner Boundary?

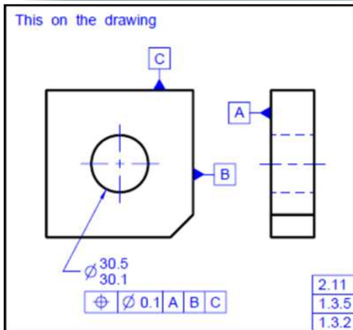
What is the largest pin that could always go inside this middle hole ?

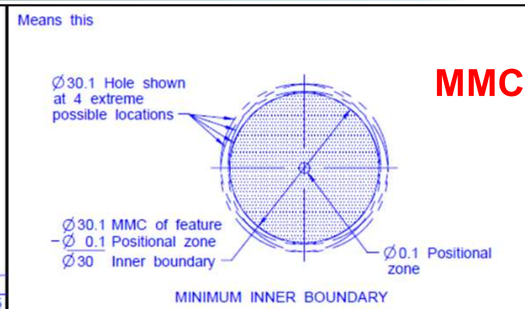
59.8 – 0.3 = 59.5

Also known as the Minimum Inner Boundary



Hole Max and Min Boundary from Datum?





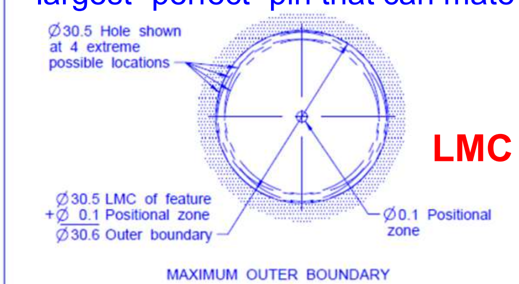
IB is area guaranteed to have "hole"
= largest "perfect" pin that can mate

	ØHOLE	ØTOL	IB	OB*
LMC	30.5			30.6
	30.4			
	30.3	0.1		
	30.2			
MMC	30.1		30	

The inner boundary (IB) of the internal feature is a single value equal to its maximum material condition MINUS its stated geometric tolerance.

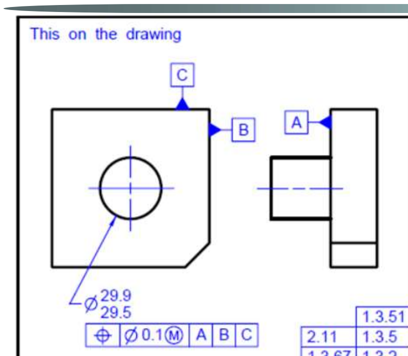
The outer boundary (OB) of the internal feature is a single value equal to its least material condition PLUS its stated geometric tolerance.

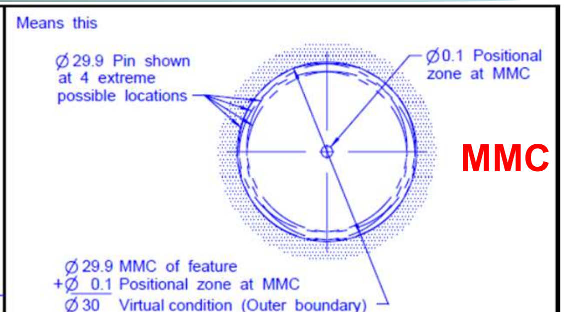
* Calculaions do not include form variations of the feature.



OB is shaded area without a hole

Pin Max and Min Boundary from Datum?



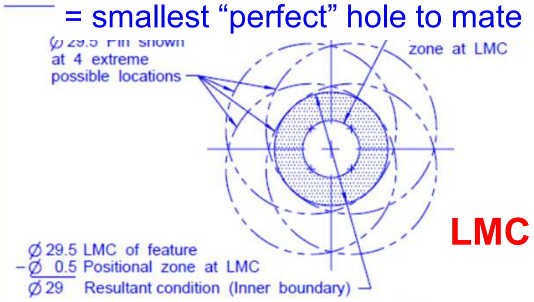


VC is area that is "pin" free
= smallest "perfect" hole to mate

	ØPIN	ØTOL	VC	RC
MMC	29.9	0.1		
	29.8	0.2		
	29.7	0.3	30	
	29.6	0.4		
LMC	29.5	0.5		29

The virtual condition (VC) of the external feature is a constant value equal to its maximum material condition PLUS its applicable geometric tolerance.

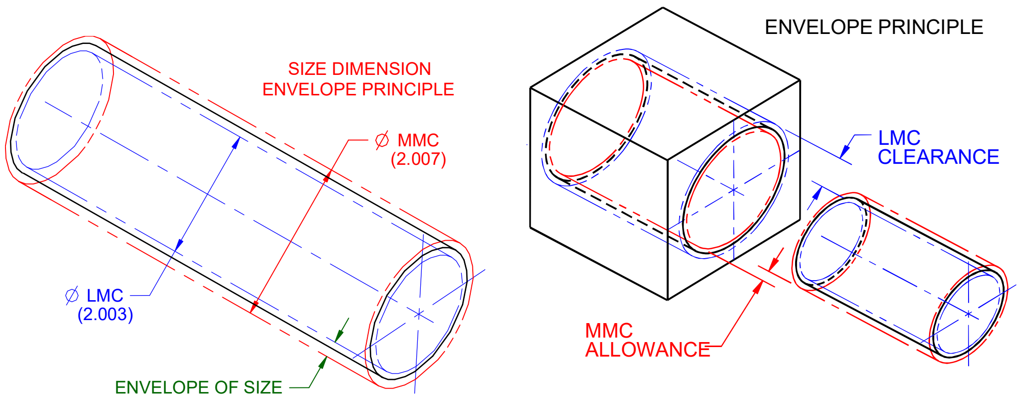
The resultant condition (RC) of an external feature is a single value equal to its least material condition MINUS its applicable geometric tolerance.



RC is area guaranteed to have a "pin"

Limits of Size

- Envelope of Size is the volume difference between the maximum size envelope (MMC) and the minimum size envelope (LMC)



MMC Allowance or Difference = IB – VC = clearance

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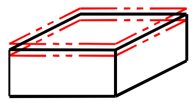
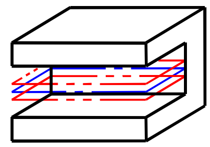
Geometric Characteristics

	TYPE OF TOLERANCE	CHARACTERISTIC	SYM
FOR INDIVIDUAL FEATURES	FORM	STRAIGHTNESS	—
		FLATNESS	▱
		CIRCULARITY	○
		CYLINDRICITY	⌭
FOR INDIVIDUAL OR RELATED FEATURES	PROFILE	PROFILE OF A LINE	⌒
		PROFILE OF A SURFACE	⌓
FOR RELATED FEATURES	ORIENTATION	ANGULARITY	∠
		PERPENDICULARITY	⊥
		PARALLELISM	//
	LOCATION	POSITION	⌖
		CONCENTRICITY	◎
		SYMMETRY	⌯
	RUNOUT	CIRCULAR RUNOUT	↗
		TOTAL RUNOUT	⌰

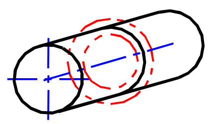
Form Features (commonly used)



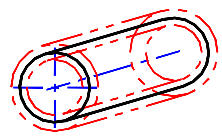
▱ Flatness



— Straightness



○ Circularity



⌭ Cylindricity

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Why GD&T is Important

- GD&T ensures design, dimension, and tolerance requirements as they *relate to actual function*.
- Ensures *interchangeability* of mating parts
- Highlights *datum references* that are critical for part *function* or interchangeability.

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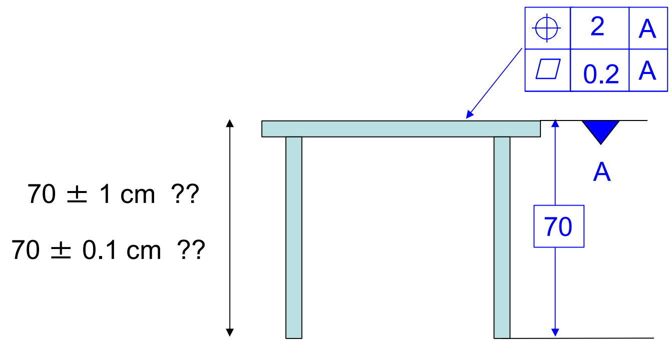
Motivation Example

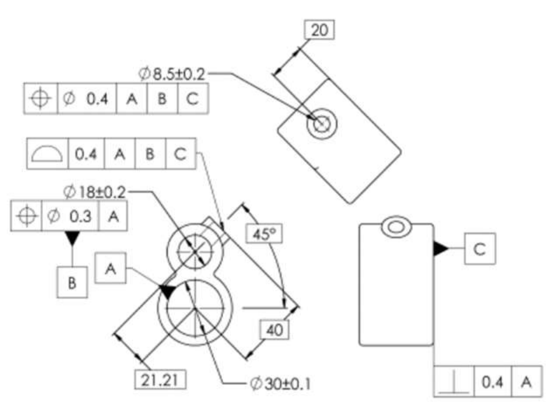
- Assume you want tables whose height is 70 ± 1 cm, but the flatness of the top needs to be ±1 mm? How to specify this in a drawing?



 slide 33 ILLINOIS

Requirements of Drawings

1) Not be subjected to **more than one** interpretation



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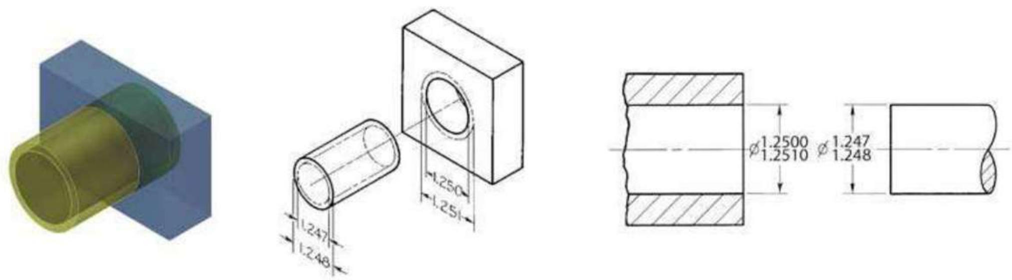
Requirements of Drawings

2) Dimensions should suit the **mating relationship** of the parts



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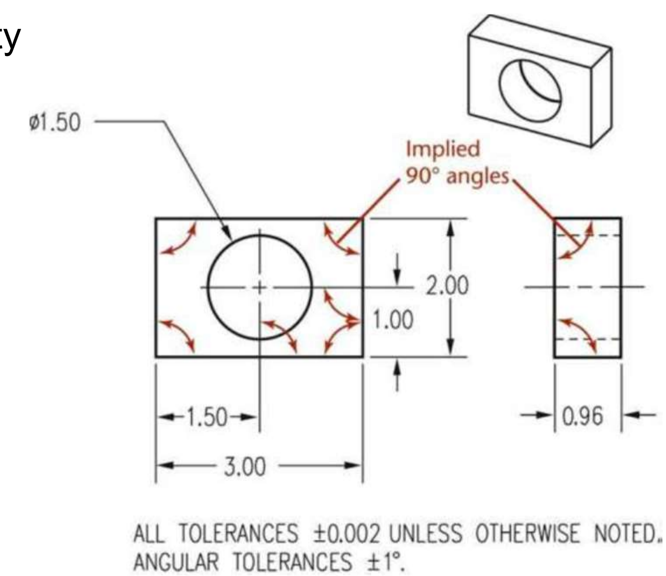
Requirements of Drawings

3) Perpendicularity is **assumed**. When no angle is expressed, 90 degrees is implied. Other symmetry is assumed.



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Goals of Dimensional Tolerancing

- Dimensional control required – exact dimensions are not possible nor necessary
- Maximum and minimum limits of dimensions (length and angle)
  - Set tolerance small enough to ensure functionality and
  - Set tolerance as large as possible to reduce

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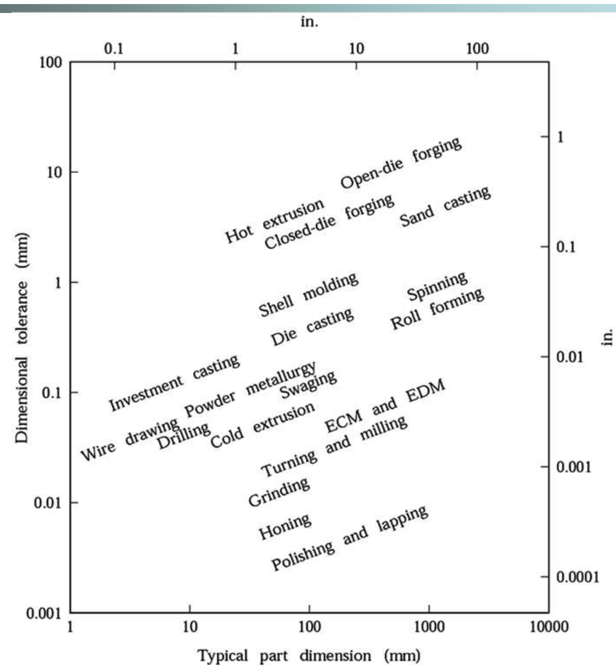
Tolerances of Typical Manufacturing Processes



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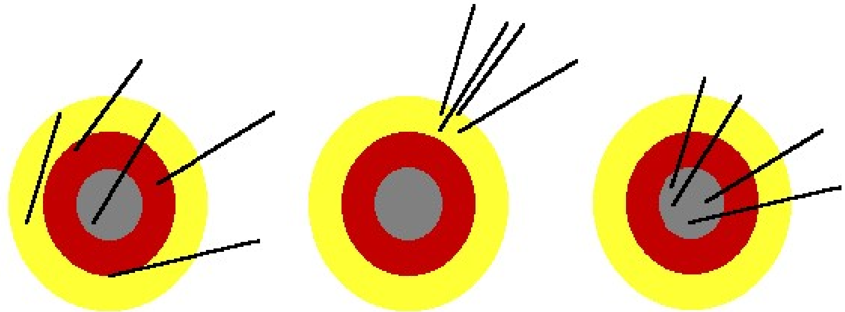
Accuracy and Precision



good accuracy
poor precision

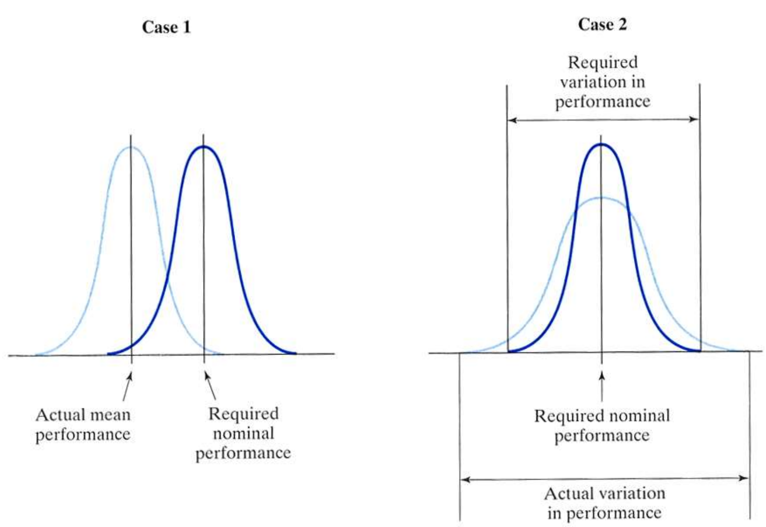
poor accuracy
good precision

good accuracy
good precision

- - the degree to which the measured value agrees with the true value of the quantity of interest
- - the degree of repeatability in the measurement process

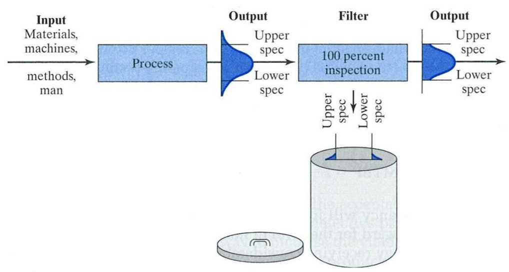
Goal of Quality Control

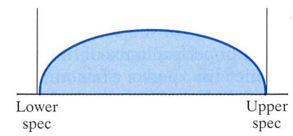
Strategic view of Quality Design and Improvement:



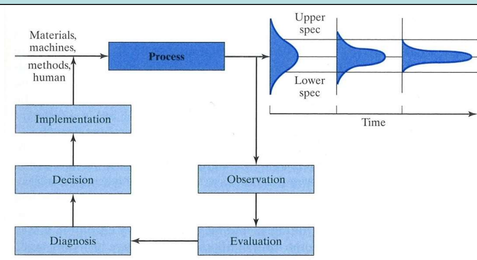
Two Approaches to Quality Control:

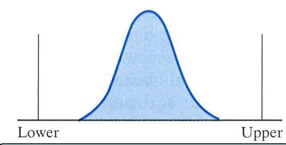
1.





2.





Gaussian Distributions

Gaussians have:

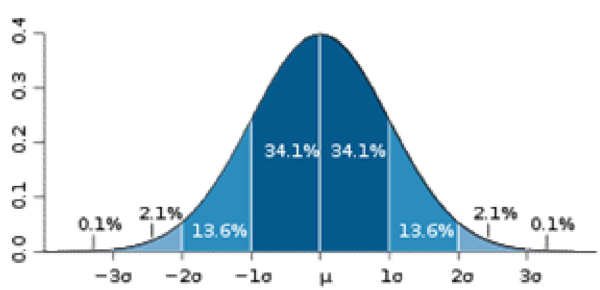
1. Mean (average), μ
2. Standard deviation, σ
3. Variance, σ^2
4. Tolerance:

Standard Tolerance

$2\sigma =$

$4\sigma =$

$6\sigma =$



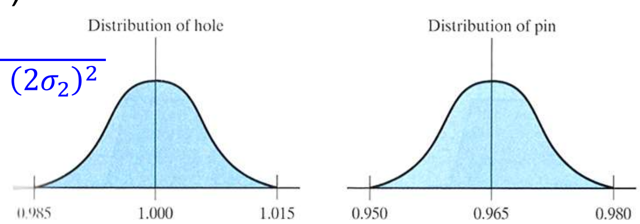
Variance of a system: $\sigma^2 =$

Tolerance of a system: $2\sigma =$

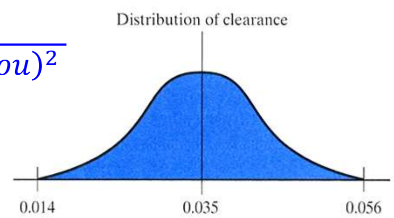
Quality Control: Gaussian Distribution

A part with a "hole" must match up with another containing a "pin." The hole and pin tolerances ( ) are 15 thou. Find the **clearance** and **clearance tolerance** (assume Gaussian distribution):

$$(\mu_{hole} - \mu_{pin}) \pm \sqrt{(2\sigma_1)^2 + (2\sigma_2)^2}$$



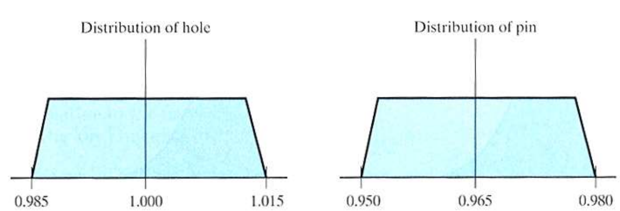
$$(35\ thou) \pm \sqrt{(15\ thou)^2 + (15\ thou)^2}$$



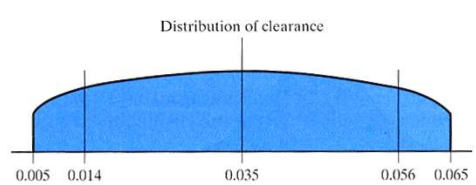
$$35 \pm 21\ thou$$

Quality Control: Rework Distribution

Same problem as before (uniform distribution tolerances are 15 thou). The clearance (with tolerance) is:



$$(\mu_{hole} - \mu_{pin}) \pm (2\sigma_{hole} + 2\sigma_{pin})$$

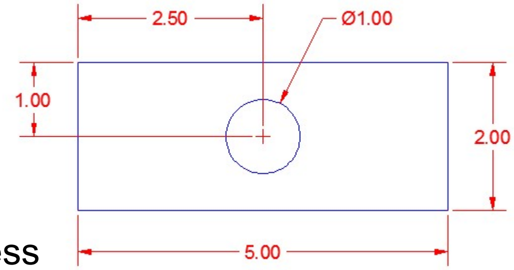


$$35 \pm 30\ thou$$

Conclusion: Gaussian distributions have better system tolerances (or variability)

Tolerance Stack-up

- Assume the stack of 10 parts as earlier. If the 1.0 thick parts have a Gaussian distribution with a tolerance of 0.1 what is the stack thickness and stack tolerance?



$$10.0 \pm \sqrt{(0.1)^2 + (0.1)^2 + (0.1)^2 + (0.1)^2 + \ \ldots}$$

10.0 ± 0.32 $\rightarrow$ *1/3rd the tolerance of a uniform distribution!*

Quotes

- The [person] who views the world at fifty the same as he did at twenty has wasted thirty years of his life. – Muhammad Ali
- Life does not have to be perfect to be wonderful. – Annette Funicello
- "Felix qui potuit rerum cognoscere causus" (Virgil). Translation: happy is he who knows the cause of things

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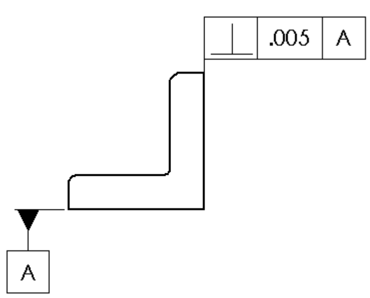
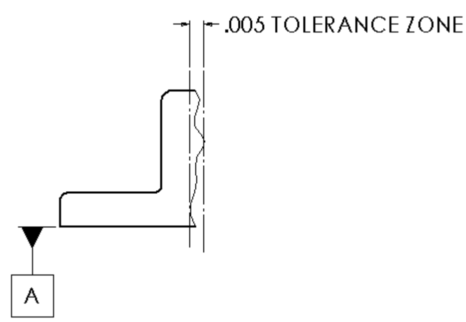
Perpendicularity

This on a drawing:

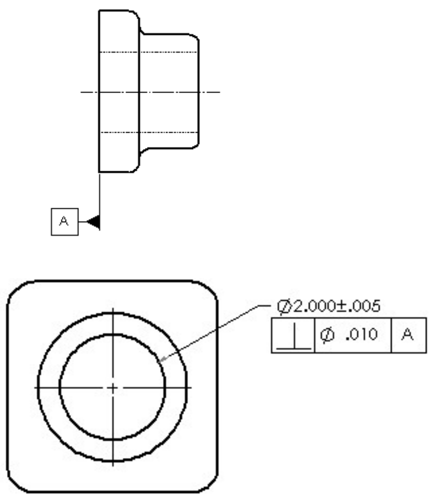


means any point on the vertical surface can deviate by no more than 0.005 from the corner edge.

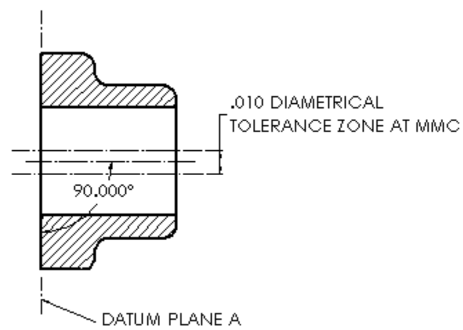


Perpendicularity

This on a drawing:



Means the hole axis must be perpendicular within a diametrical tolerance zone of 0.010 relative to datum surface A.



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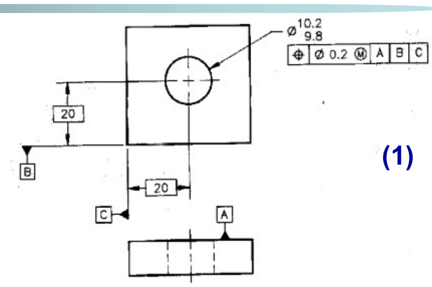
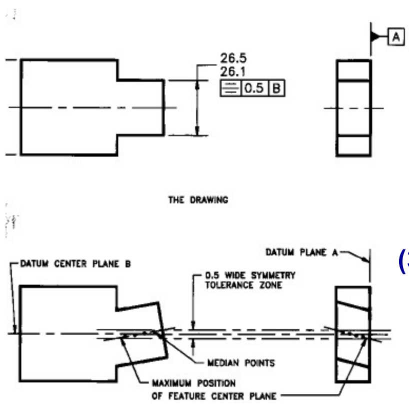
Location Tolerances

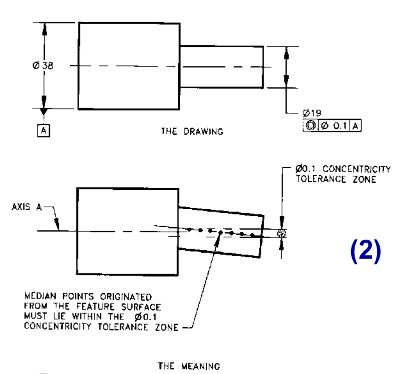
1. Position tolerance
2. Concentricity
3. Symmetry



(1)



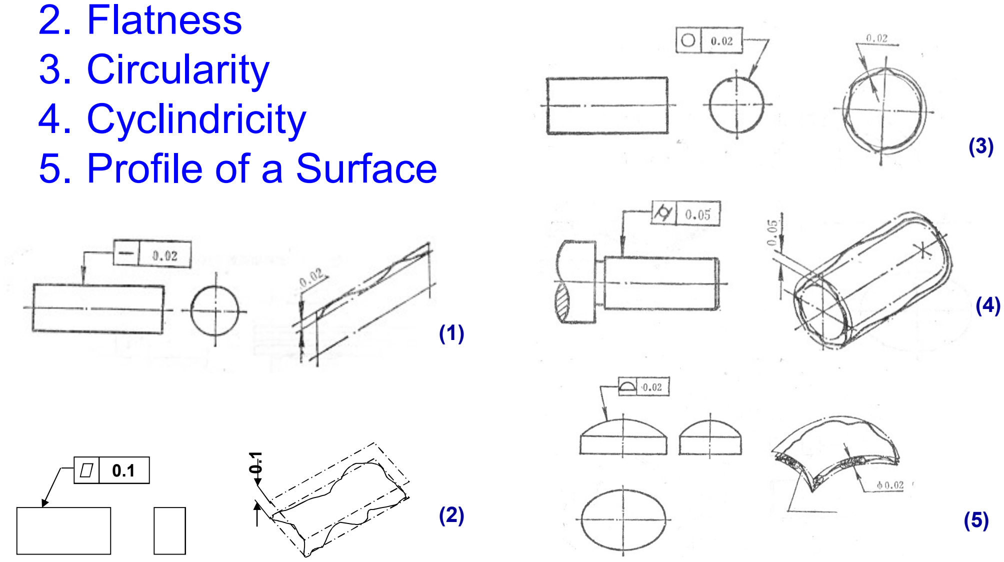
(3)



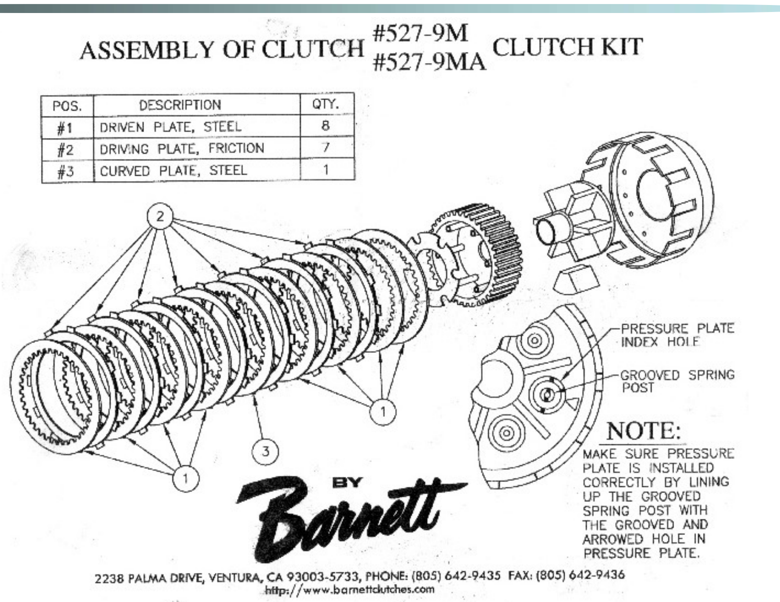
(2)

Form and Profile Tolerances

1. Straightness
2. Flatness
3. Circularity
4. Cyclindricity
5. Profile of a Surface

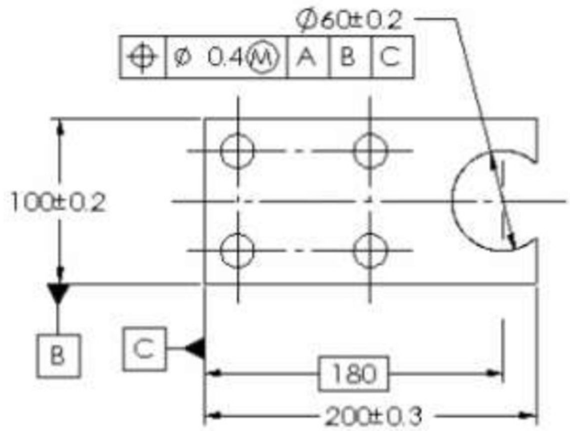


Part number ↑ magnitude of problem ↑

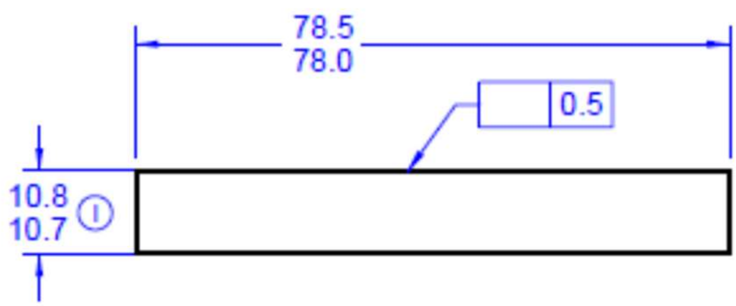


POS.	DESCRIPTION	QTY.
#1	DRIVEN PLATE, STEEL	8
#2	DRIVING PLATE, FRICTION	7
#3	CURVED PLATE, STEEL	1

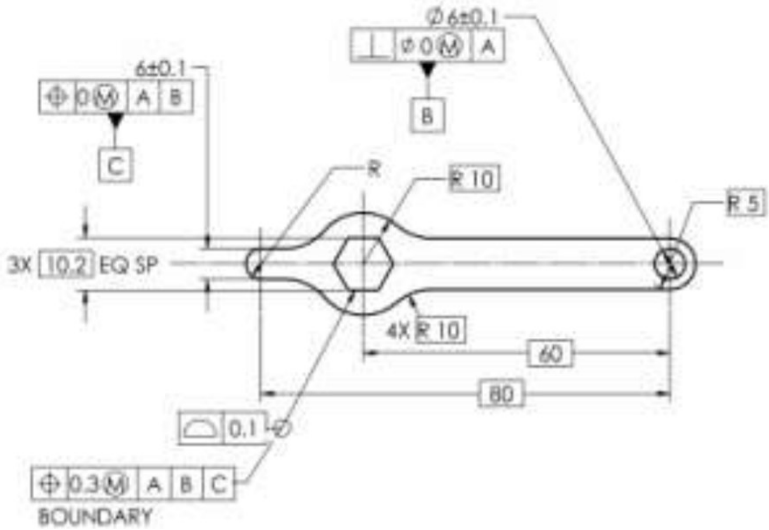
The variability of thickness in each clutch plate can compound to a large uncertainty in stack thickness



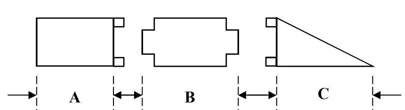
Ø60±0.2
Ø 0.4Ⓜ A B C
100±0.2
B
C
180
200±0.3



78.5
78.0
0.5
10.8
10.7



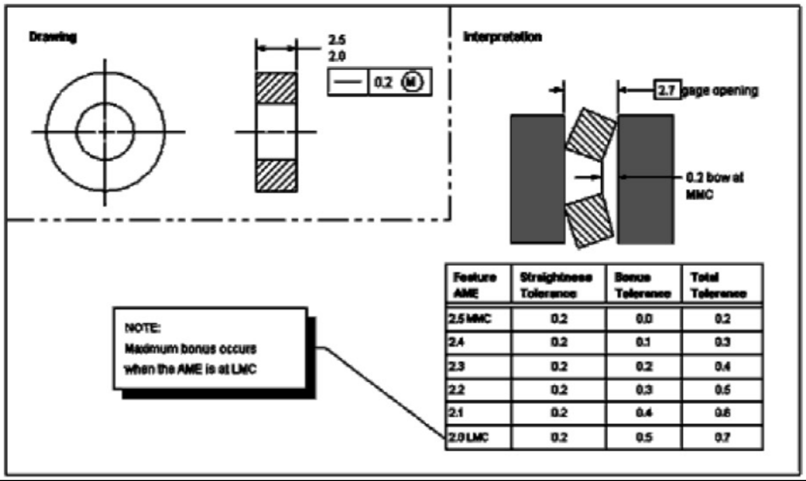
Ø 6±0.1
⊥ Ø 0 Ⓜ A
B
6±0.1
⌖ 0 Ⓜ A B
C
R
R 10
R 5
3X 10.2 EQ SP
4X R 10
60
80
⌓ 0.1
⌖ 0.3 Ⓜ A B C
BOUNDARY



A
B
C

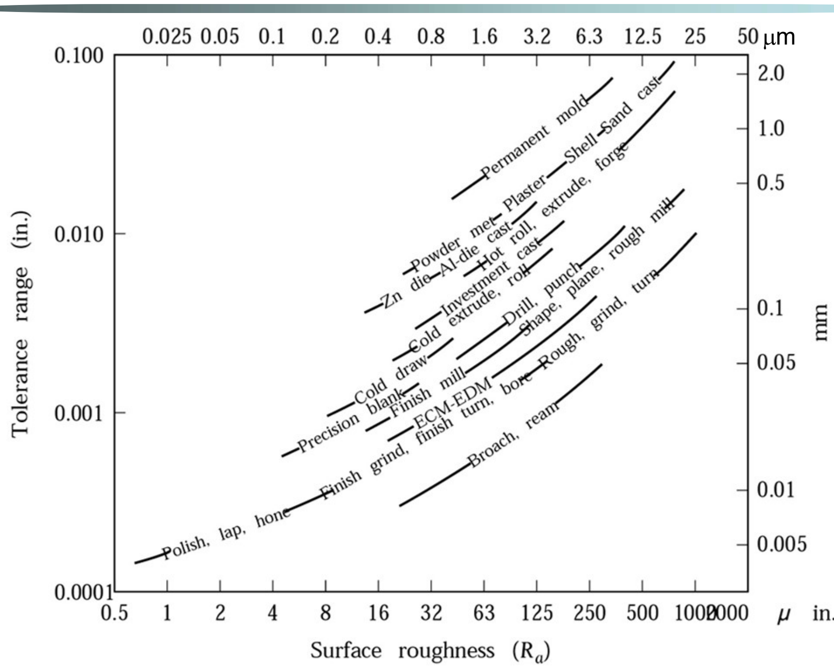
Bonus Tolerance

- The below washers are tested using a gauge opening, since the gage opening is constant, the thinner the washer becomes, the more straightness tolerance it could have and still pass through the gauge.

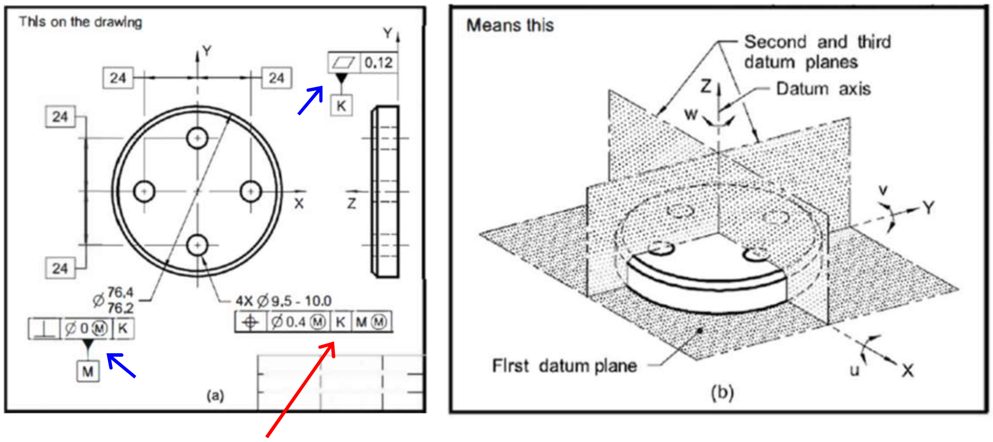


Feature AME	Straightness Tolerance	Bonus Tolerance	Total Tolerance
2.5 MMC	0.2	0.0	0.2
2.4	0.2	0.1	0.3
2.3	0.2	0.2	0.4
2.2	0.2	0.3	0.5
2.1	0.2	0.4	0.6
2.0 LMC	0.2	0.5	0.7

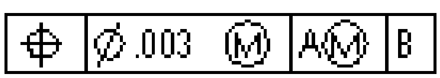
Tolerances and Roughness



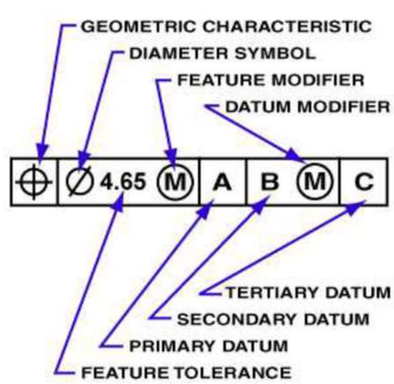
Cylindrical Datum Features



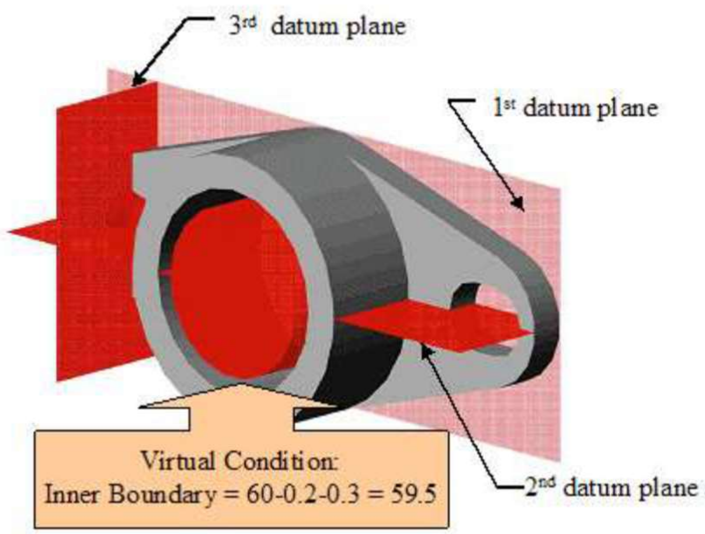
Use Feature Control Frames for Tolerance?



- Reads as: The position of the feature must be within a .003 diametrical tolerance zone at maximum material condition relative to datums A at maximum material condition and B.



Solution



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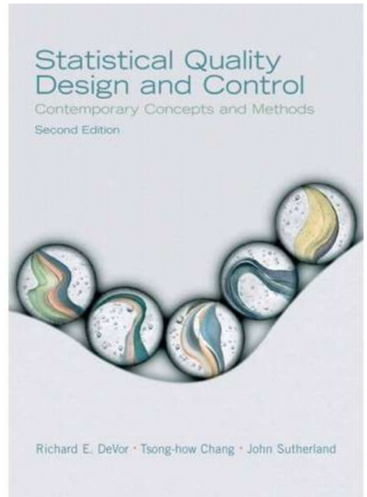
ME 270 – Lecture 17 – DOE

Design of Experiments

Book at Grainger in reference section covering chapters 17 & 18 (IE 400)



- 2^k Factorial Design & Analysis of Effects
- System Characteristic Equation
- Statistically Significant Effects
- Noise & Cumulative Probability Graphs

Role of DOE

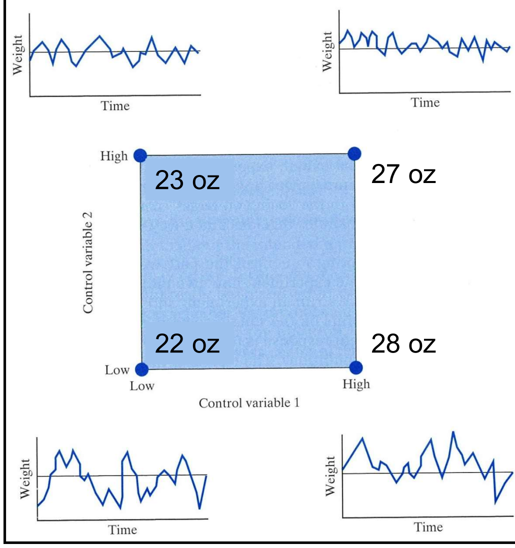
- Mathematical method to systematically determine *cause-effect* relationships – especially "hidden," "confounded," or subtle relationships.
- Produces a "system" *equation* that relates settings to expected *output* values.
- Enables *reduction in variability* in product.
- Much *more efficient* than changing "*one variable at a time*" to optimize a system.

Example Experiment

Control variable 1, x_1: extruder temperature (150 or 200ºC)

Control variable 2, x_2: injection time (2 or 4 sec.)

Output measurement, y: part weight (goal is 26 oz)

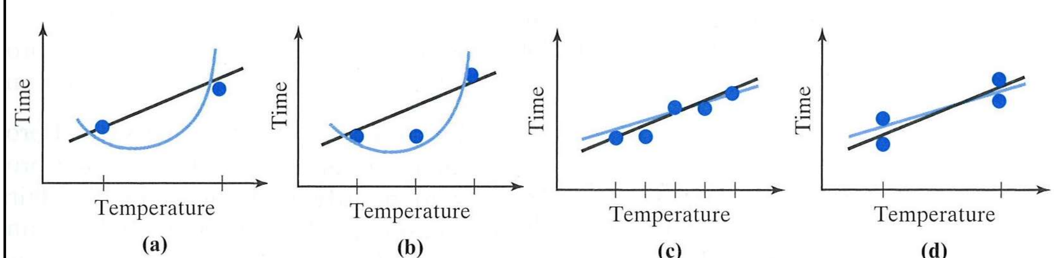


1. Which variable has the largest effect on part weight, but very little effect on weight variability?

2. Which variable has the largest effect on weight variability, but very little effect on part weight.

2^k Factorial Design – Test Settings

- “k” refers to the number of variables being tested
- Assumes a linear, or near linear output response when changing an input variable - very typical
- Tests points only at the extremes - more efficient

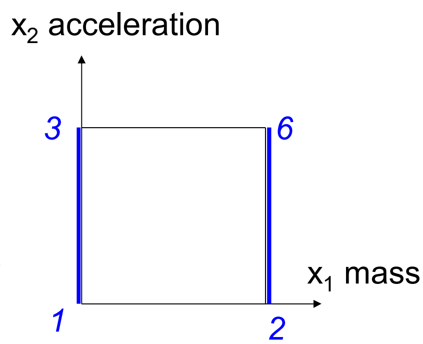


2^k Factorial designs are ideal for learning the most information with the fewest experiments.

2^2 Example: F = m*a

Variable 1, mass, has values of 1 kg (x_1= -1) or 2 kg (x_1= 1).
Variable 2, acceleration has values of 1 or 3 m/s^2 ($x_2 = \pm$ 1)
Thus the design matrix and test response would be:

Test	x1	x2	y = m*a
1	-1	-1	
2	-1	1	
3	1	-1	
4	1	1	



Points on each line have the same mass.
Thus the "effect" of variable 1 is found:

$$E_1 = \frac{y_4 + y_3}{2} - \frac{y_2 + y_1}{2} = 2$$

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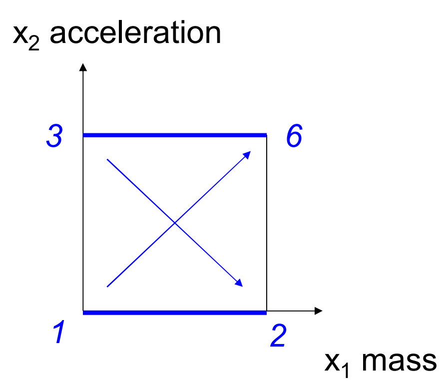
2^2 Example (cont)

E_2 can be similarly found:

$$E_2 = \frac{y_4 + y_2}{2} - \frac{y_3 + y_1}{2} = 3$$

Test	x1	x2	y
1	-1	-1	
2	-1	1	
3	1	-1	
4	1	1	



And the compounded effect E_{12}:

$$E_{12} = \frac{y_4 + y_1}{2} - \frac{y_3 + y_2}{2} = 1$$

$$y = \bar{y} + \frac{E_1}{2} x_1 + \frac{E_2}{2} x_2 + \frac{E_{12}}{2} x_1 x_2$$

$$y = 3 + x_1 + \frac{3}{2} x_2 + \frac{1}{2} x_1 x_2$$

Does this agree with the values in the table?

Can we get back to the equation F = m*a ?

- Variable 1: mass high = 2 kg, mass low = 1 kg
  - Thus:

$$m = \frac{1}{2}x_1 + \frac{3}{2}kg \qquad x_1 = 2m - 3kg$$

- Variable 2: acceleration high = 3 m/s^2, low = 1 m/s^2
  - Thus:

$$a = x_2 + 2 \qquad x_2 = a - 2$$

- Substituting into our equation yields:

$$y = 3 + x_1 + \frac{3}{2}x_2 + \frac{1}{2}x_1x_2$$

$$y = 3 + (2m-3) + \frac{3}{2}(a-2) + \frac{1}{2}(2m-3)(a-2)$$

$$y = m \cdot a$$

2^3 Factorial Design Example

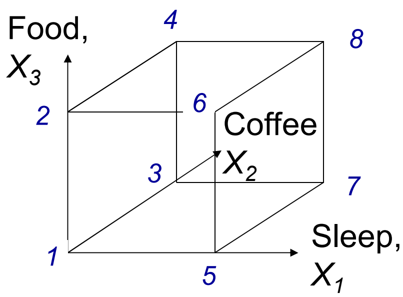
- Study on the alertness of students in the morning
- Variables

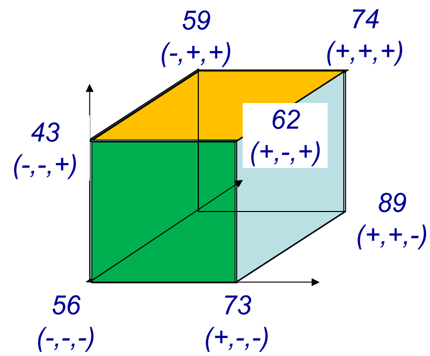
Variables	low	high
1. Hours of Sleep	4	8
2. Ounces of Coffee	4	16
3. Number of Donuts	0	3

- Design Matrix

Test	x1	x2	x3	Alertness (%)
1	-1	-1	-1	56
2	-1	-1	1	43
3	-1	1	-1	68
4	-1	1	1	59
5	1	-1	-1	73
6	1	-1	1	62
7	1	1	-1	89
8	1	1	1	74

Effect of Variables?





$$E_1 = \frac{y_8 + y_7 + y_6 + y_5}{4} - \frac{y_4 + y_3 + y_2 + y_1}{4} = 18$$

$$E_2 = \frac{y_3 + y_4 + y_7 + y_8}{4} - \frac{y_1 + y_2 + y_5 + y_6}{4} = 14$$

$$E_3 = \frac{y_2 + y_4 + y_6 + y_8}{4} - \frac{y_1 + y_3 + y_5 + y_7}{4} = -12$$

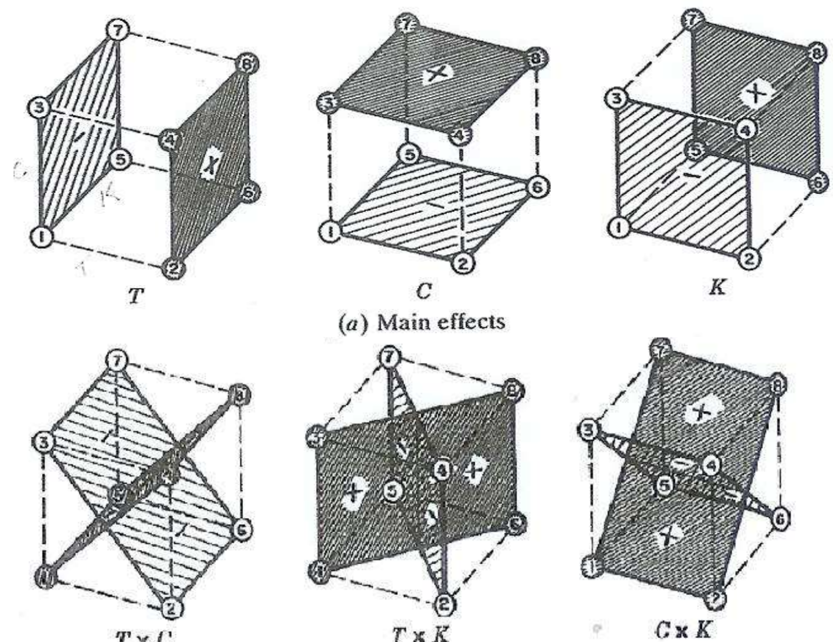
Use Matrix Algebra to Solve:

Test	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	Alertness (%)
1	-1	-1	-1	1		1	-1	56
2	-1	-1	1	1	-1	-1	1	43
3	-1	1	-1	-1	1	-1	1	68
4	-1	1	1	-1	-1	1	-1	59
5	1	-1	-1	-1	-1	1	1	72
6	1	-1	1	-1	1	-1	-1	62
7	1	1	-1	1	-1		-1	89
8	1	1	1	1	1	1	1	74
	E1	**E2**	**E3**	**E12**	**E13**	**E23**	**E123**	**Y_{ave}**

$$\hat{y} = \bar{y} + \frac{E_1}{2}x_1 + \frac{E_2}{2}x_2 + \frac{E_3}{2}x_3 + \frac{E_{12}}{2}x_1x_2 + \frac{E_{13}}{2}x_1x_3 + \frac{E_{23}}{2}x_2x_3 + \frac{E_{123}}{2}x_1x_2x_3$$

Eliminating “insignificant effects” yields the “system characteristic equation:”

Graphical Understanding

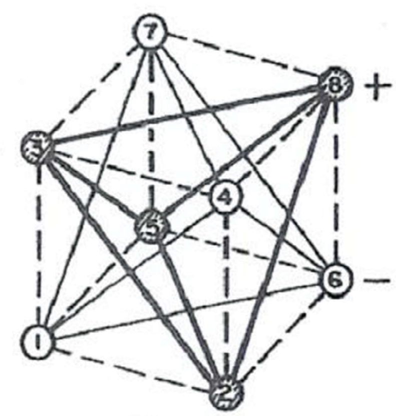


(a) Main effects

(b) Two-factor interactions

Graphical Understanding (cont)

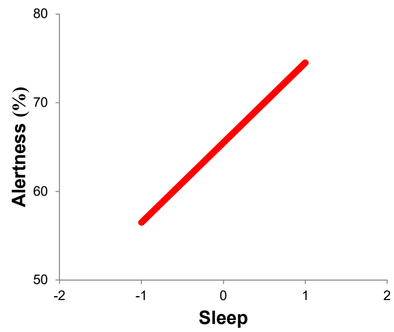
- Average corners of inscribed regular tetrahedrons of diagonals and subtract
- One tetrahedron should include the (-,-,-) corner and the other should include the (+,+,+) corner



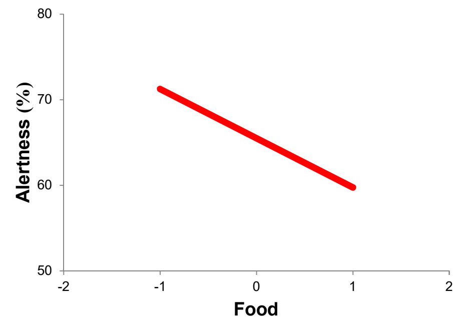
(c) Three-factor interaction

Effect of Variables

- The magnitude indicates the effect:
- The sign of the effect indicates its correlation – whether the response is
- If a compound effect is small or negligible then the two effects are said to be:



E_1 = 18



E_3 = -12

Determining Statistically Significant Effects

Two methods:

1. **Statistical**: if test experiments are duplicated (at least once) then result variance can be calculated. If the Effect value is outside of the natural system variability, then it is significant.
2. **Graphical**: if *all* effects are insignificant then they will form ***what*** distribution around zero? *Gaussian*. Variable effects that fall outside this distribution are significant.

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System Variance

- "Variance" (σ^2) is the *square* of "standard deviation."
- Only "variance" can be averaged across individual tests to determine an average "system variance" (the square root of which is the system standard deviation).
- System variance: (*average of the individual variances)*

$$\sigma^2 = \frac{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_{2^k}^2}{2^k}$$

Alertness Test with Replication

Variables	low	high
1. Hours of Sleep	4	8
2. Ounces of Coffee	4	16
3. Number of Donuts	0	3

Test	x1	x2	x3	Alertness (%)	Alertness (%)
1	-1	-1	-1	56	58
2	-1	-1	1	43	42
3	-1	1	-1	68	67
4	-1	1	1	59	61
5	1	-1	-1	72	68
6	1	-1	1	62	59
7	1	1	-1	89	88
8	1	1	1	75	74

- System Standard Deviation? ***σ = 1.52***

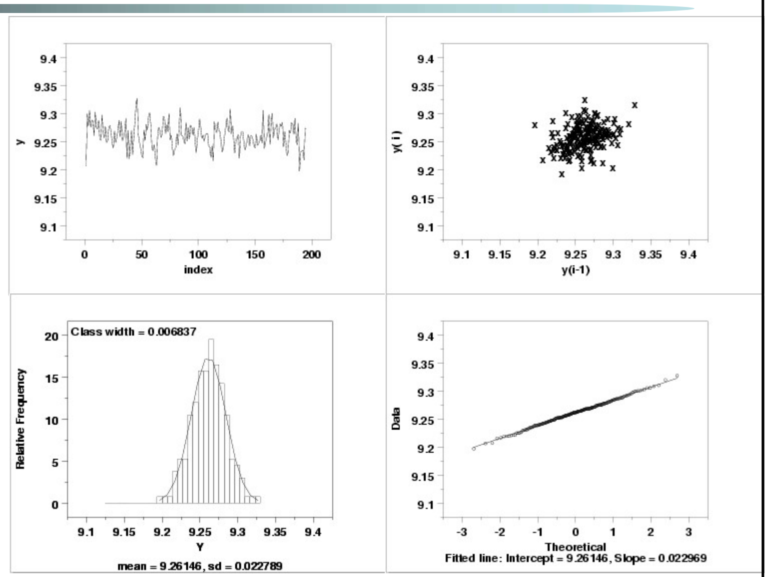
1. Effects Outside ±2-Sigma Interval

- Use the System Standard Deviation to determine the 95% confidence interval:
- Effects *outside* of this range (positive or negative), are:
- Significant effects:

E_1	E_2	E_3	E_{12}	E_{13}	E_{23}	E_{123}	Y_{ave}
16.6	15.1	-11.4	1.1	-0.4	0.6	-2.9	65.1

2. Gaussian Analysis of "Noise?"

Ave. measurement is 9.27, with some variability; there are measurements less than 9.2, but not very often. The farther from the mean the less likely a reading will occur. Norm. Prob. Plot is a straight line for <u>*noise*</u>.



Non-significant effects will be like "noise" – lying along a straight line roughly centered around zero on a Norm. Prob. graph.

*http://www.itl.nist.gov/div898/handbook/pri/pri.htm

2. Cumulative Probability Graph

- A 2^k factorial experiment was run with the following "Effects" calculated: -0.15, -0.45, 0.2, 0, 0.85, 0.45, -0.9
- Is the 0.85 significant? How about the -0.9?
- To determine the significant effects, put them first in ascending order:

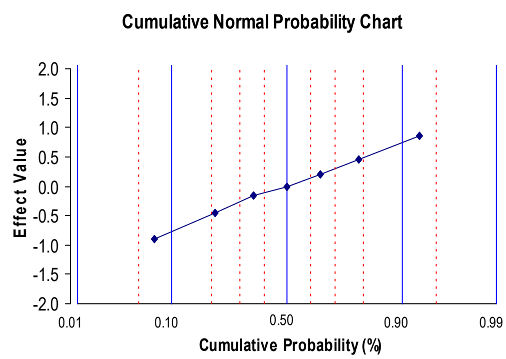
The lowest value should represent the lower $\frac{100\%}{7}$, or the 0 to14.29% range (on a graph placed midway at 7.14%). The next value represents the 14.3 to 28.5% range.

Cumulative Probability: $p_i = \frac{100(i-0.5)}{2^k-1}$

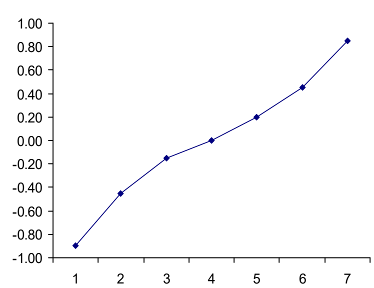
Effect Values:	Rank:	Cum. Prob%
-0.90	1	7.14
-0.45	2	21.43
-0.15	3	35.71
0.00	4	50.00
0.20	5	64.29
0.45	6	78.57
0.85	7	92.86

2. Graphical Analysis

Effect Values:	Rank:	Cum. Prob%
-0.90	1	7.14
-0.45	2	21.43
-0.15	3	35.71
0.00	4	50.00
0.20	5	64.29
0.45	6	78.57
0.85	7	92.86



- Since all the effects end up on a straight line around zero (i.e. 50%), their values are due to "noise" and are not significant in value.
- Instead of creating Cumulative Probability Plots, is there an easier way? Equidistant plots work well?



Creating a Normal Probability Graph

- Order the main effects from lowest to highest and give them a rank #

Rank	normsinv x-pos	Ranked Main Effects
1	-1.47	-11.38
2	-0.79	-2.88
3	-0.37	-0.38
4	0.00	0.63
5	0.37	1.13
6	0.79	15.13
7	1.47	16.63

- For the x-position:

$$\boldsymbol{x\_position = normsinv\left({}^{(rank\# - 0.5)}/_{max\_rank} \right)}$$

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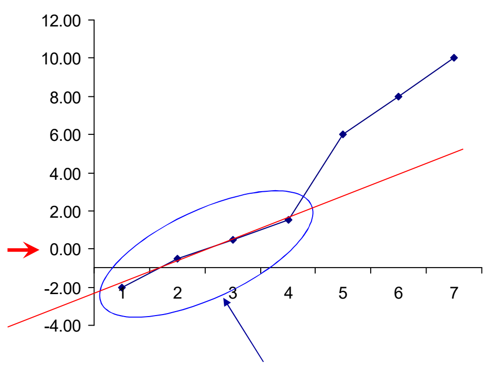
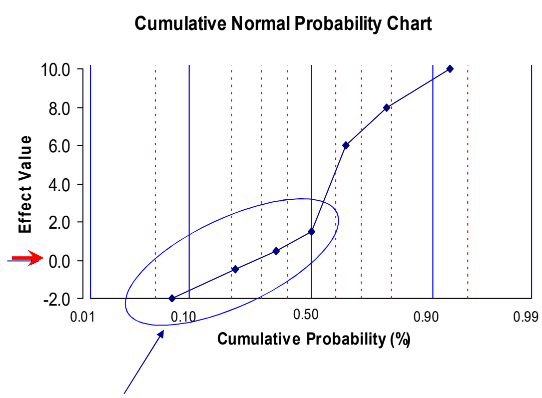
2. Graphical Approach Example

- Assume the Effect values were:

  8, 1.5, -0.5, 6, -2, 10, 0.5   Which are insignificant?





Insignificant effects are on a “flat” line around zero

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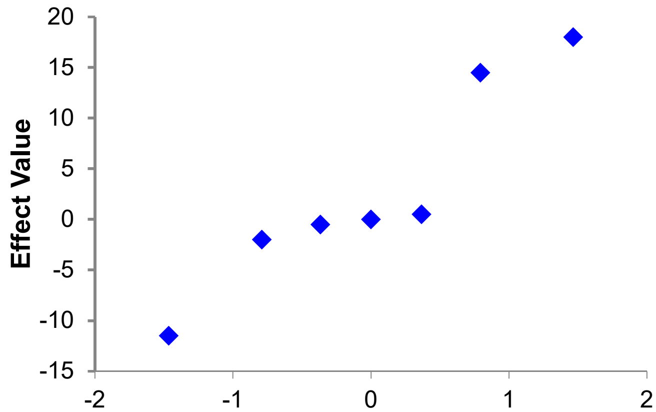
2. Equidistant Graph?

- Which are significant?
- First find (0,0) point – draw flattest line (smallest effects)
- Points not on/near line are:



2^2 DOE Example from Beginning: data analysis

Objective is better control part weight, goal: 26 oz.

Variable 1: extruder temperature

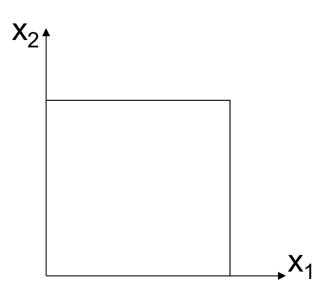
high = 200 °C (x_1 = 1) low = 150 °C (x_1 = -1)

Variable 2: injection time

high = 4 sec (x_2 = 1) low = 2 sec (x_2 = -1)

Experimental Results:

Test	x_1	x_2	y
1	-1	-1	22 ± 2.4 oz.
2	-1	1	23 ± 1.1 oz.
3	1	-1	28 ± 2.2 oz.
4	1	1	27 ± 0.9 oz.



Goal: on target with least variation!

Step 1 - "Noise" or Variability analysis:

Test	x_1	x_2	x_1x_2	Y	σ	var
1	-1	-1		2.4		
2	-1	1		1.1		
3	1	-1		2.2		
4	1	1		0.9		
	E1:	E2:	E12:	Sys (2σ)	Sys. σ:	Var(ave)

For ***main*** effects to be significant they need to be what?

To minimize "noise" what should our input variables be set to?

Goal: on target with least variation!

Step 2: Calculate "main effects" using y-average values:

Test	x_1	x_2	x_1x_2	y (oz.)
1	-1	-1		
2	-1	1		
3	1	-1		
4	1	1		
	E1:	E2:	E12:	y-ave:

Reduced System Characteristic Equation? (only sig effects)

What should x_1 be set to for 26 oz parts?

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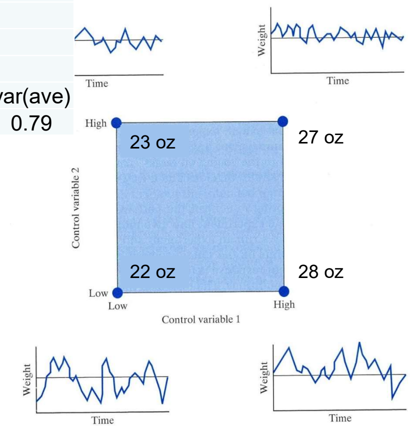
Goal: on target with least variation!

Step 3: final analysis

Test	x_1	x_2	x1x2	Yave	2σ	σ	var
1	-1	-1	1	22	2.4	1.20	1.44
2	-1	1	-1	23	1.1	0.55	0.30
3	1	-1	-1	28	2.2	1.10	1.21
4	1	1	1	27	0.9	0.45	0.20
Main:	E1	E2	E12	Yave			
Noise:	E1	E2	E12		Sys (2σ)	Sys σ	var(ave)
					1.78	0.89	0.79



Reduced System Characteristic Equation:

Input settings:

Steps of DOE

1. Design the experiment:
   - Choose "*inputs*" and the *amounts* they are to vary
   - Determine "*output*" to optimize and a way to
2. Collect data:
   - *Randomize* the order of experiments
   - *Replicate* each experiment at least once.
3. Analysis of Data
   - Excel computation and graphs of effects
4. Report Conclusions
   - Reduced "*system characteristic equation*?"
   - *Optimal settings* for each input variable?

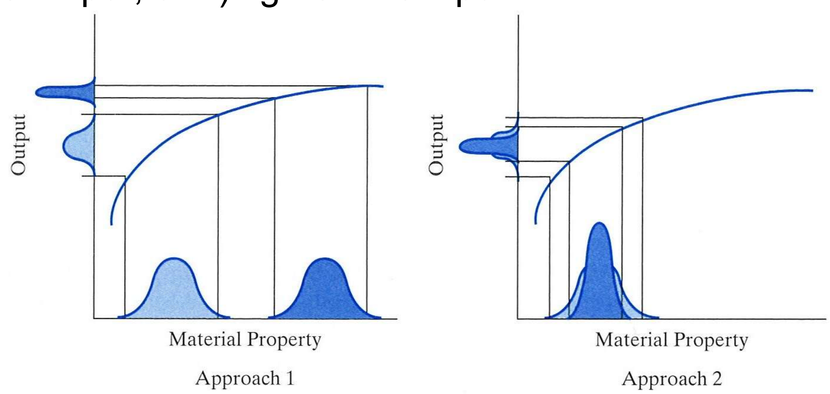
Fractional Factorial Design

- Assuming there are 7 variables to test, then 2^7 (128) experiments will need to be run
- Fractional Factorial designs can accomplish this with only 8 tests:

Trial	A	B	C	D	E	F	G
1	Lo	Lo	Lo	Lo	Lo	Lo	Lo
2	Lo	Lo	Lo	Hi	Hi	Hi	Hi
3	Lo	Hi	Hi	Lo	Lo	Hi	Hi
4	Lo	Hi	Hi	Hi	Hi	Lo	Lo
5	Hi	Lo	Hi	Lo	Hi	Lo	Hi
6	Hi	Lo	Hi	Hi	Lo	Hi	Lo
7	Hi	Hi	Lo	Lo	Hi	Hi	Lo
8	Hi	Hi	Lo	Hi	Lo	Lo	Hi

Common Approaches to Reduce Variability:

1) Choose an output region with less variability for a given input, or 2) tighten the input



Material Property	Output
Polymer Viscosity	Extruder Injection Pressure
Lathe Tool Hardness	Number of Parts before Failure

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DoE Example 4

- Students are trying to optimize their prototype and decide to test 3 variables:
  - Motor Speed
  - Motor Size (force)
  - Lever arm length
- They wisely tested each test case multiple times and created the Excel workbook.
- What should they calculate first?
  -
- What is the system standard deviation?
  -

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"Effects" Calculations & Optimization

1. Calculate the main effects and the noise effects
2. What is the characteristic equation of this system? (answer to tenths place)

   $y = 49.90 - 3.99\, x_1 + 10.75\, x_3 + 14.20\, x_1 x_2$

   How many noise effects are significant? How can you tell? Graph them to see if you are correct.

3. Lastly, what settings would you recommend to maximize output (minimizing noise is assumed)?

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Quotes:

- "You can not manage what you can't measure"
- "If you cannot measure it, you can not control it, if you cannot control it, you can not manage it"
- Life's deepest meaning is not found in accomplishments but in relationships.

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ME 270
Design for Manufacturability

Timothy H. Lee, PhD
Professor Bruce Flachsbart

Fall 2021

Lecture 19 - Assembly

Chapter 12

Assembly: fabricated parts joined together.

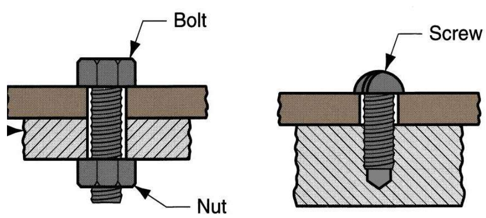
Methods that allow for

1. Threaded Fasteners
2. Interference Fits
3. Miscellaneous Methods

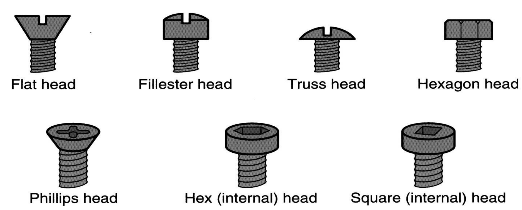
Methods that create ________ joining:

1. Rivets
2. Adhesives, Brazing & Solder
3. Welding

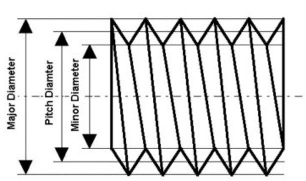
Threaded Fasteners

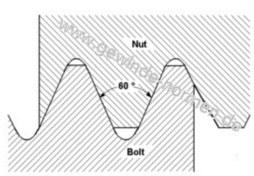


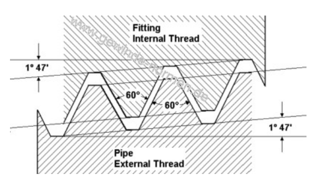
- : *threaded shaft that goes into a (non-affixed)*
- : *threaded shaft that goes into a threaded hole*



Thread Standards







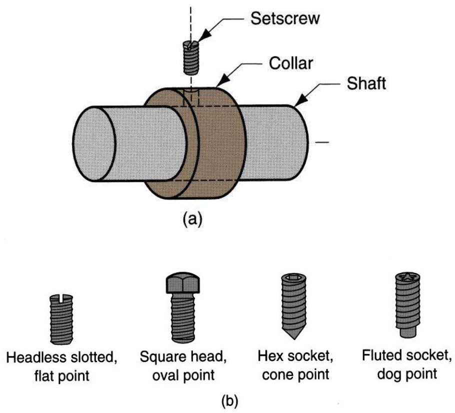
M3 x 1

¼-28

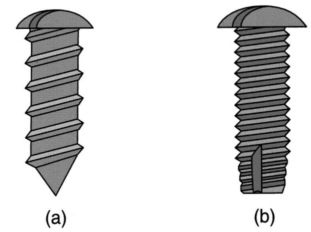
http://www.gewinde-normen.de/en/index.html

Setscrews | Self-Tapping Screws

Function: to *fasten* collars, gears, and pulleys to shafts



Function: to *form or cut* threads into a hole



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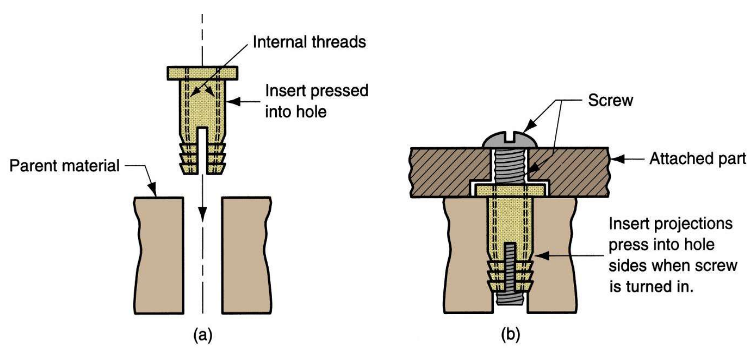
Screw Thread Inserts

Internally threaded plugs or wire coils designed to be inserted into an unthreaded hole

- Usually assembled into weaker materials to provide strong threads



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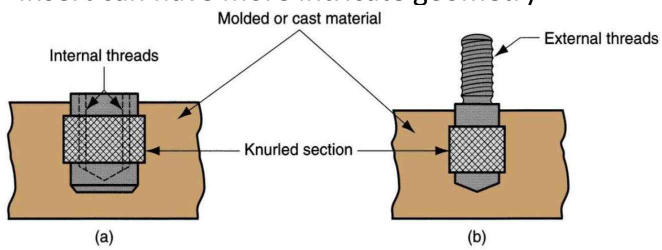
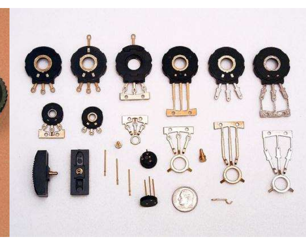
Molding Inserts

- Advantages:
  - Insert can be stronger than molded or cast material
  - Insert can have more intricate geometry

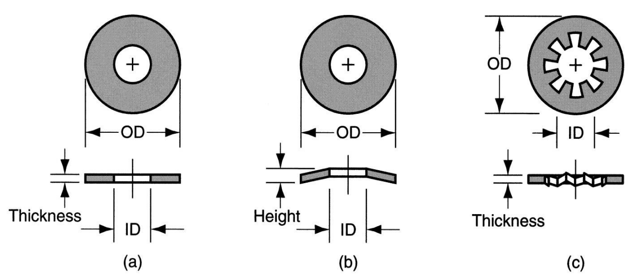




Washer

Functions:

1. Distribute stresses / provide support
2. Protect part surfaces and/or seal the joint
3. Resist unfastening/ increase spring tension

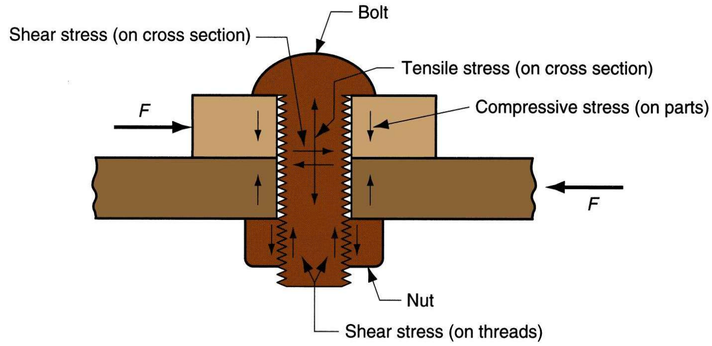


(a) washers; (b) washers, (c) washer

Bolt Strength

Means of bolt failure:

1. Stripping of external threads
2. Stripping of internal threads
3. Excessive tensile stress in cross-sectional area



Most common failure:

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Tensile Stress on a Bolt (or Screw)

Bolt proof strength (or tensile stress):

$$\sigma = \frac{F}{A_s}$$

where, *F* – maximum load, typically "*proof stress*" or "*yield strength*"

A_s – bolt cross-sectional area

metric (ISO):

ANSI:

Preload: *torque applied during assembly*

where, *T* – torque (N-mm)

C_t – torque coefficient (typically between 0.15-0.25)

D – nominal bolt or screw diameter

F – preload tension force (N)

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Bolt Strength Example

A metric *6x1.0* bolt is tightened to produce a preload of *200 N*. The torque coefficient is *0.20*. Determine (a) the torque that is applied (Nm) and (b) the resulting stress on the bolt (MPa).

Interference Fits

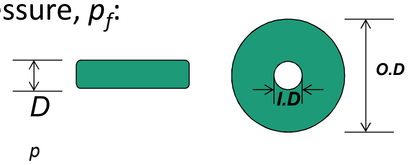
Assembly based on mechanical "interference" between two mating parts

Examples:

1. Press fitting
2. Shrink and expansion fits
3. Snap fits
4. Retaining rings

1. Press Fitting

- Examples: pin-in-hole, or collar-on-shaft, where starting inside dia of hole **<** outside dia of pin
- Radial or "interference fit" pressure, p_f:



where, E – modulus of elasticity,

i – interference ("***overlap***" between ID & OD)

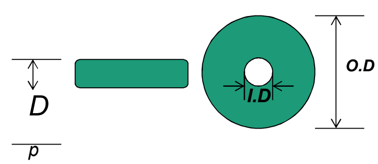
D_c – outside diameter of collar

D_p – pin or shaft diameter

- Maximum Joining Stress: (max elastic deformation)

Example – Press Fitting

- A dowel pin made of steel (elastic modulus = 209 GPa) is to be press fitted into a steel collar. The pin has a nominal diameter of 16.03 mm, and the collar has an O.D. of 27.0 mm and I.D. of 16.00mm. (a) Compute the *radial pressure* and the *maximum effective stress*.



2. Shrink and Expansion Fits

Assembly of two parts (e.g., shaft in collar) that have an interference fit at room temperature

- *Shrink fitting* - *external* part is enlarged by *heating*; the other part either stays at room temperature
- *Expansion fitting* - *internal* part is contracted by *cooling* and inserted into mating component

- Change in diameter: $\Delta D = \alpha D_0 (T_2 - T_1)$

Example Shrink Fit

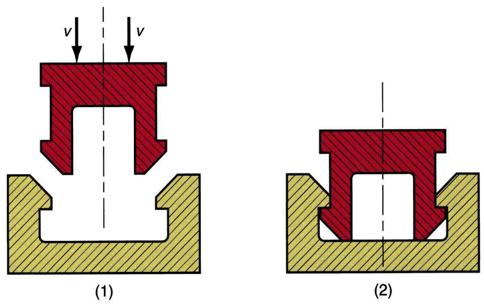
A steel ring has an inside diameter = *30 mm* and an outside diameter = *50 mm* at room temperature (*21 ℃*). The coefficient of thermal expansion for steel $\alpha = 12(10^{-6})\ °C^{-1}$. Determine the inside diameter of the ring when heated to *400 ℃* (mm – 5 digit answer).

3. Snap Fits

Mating elements possess a temporary interference during assembly, but once assembled interlock

- During assembly, one or both parts elastically deform
- Usually designed for slight interference after assembly

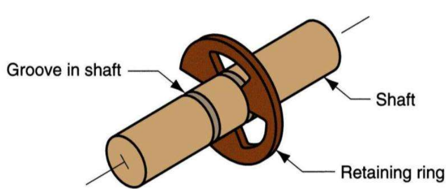
Originally conceived to be used by industrial robots

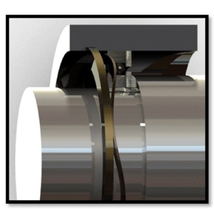


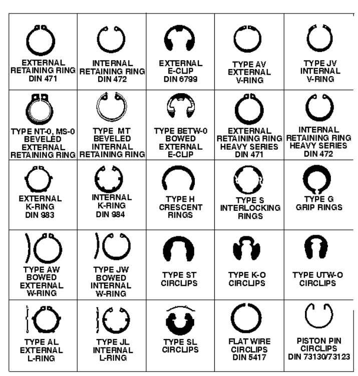
4. Retaining Ring

Fastener that snaps into a circumferential groove on a shaft or tube to form a shoulder

- Used to locate or restrict movement of parts along a rotational axis





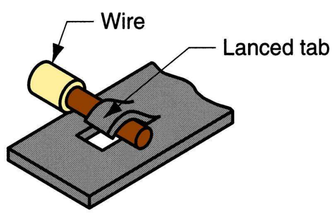


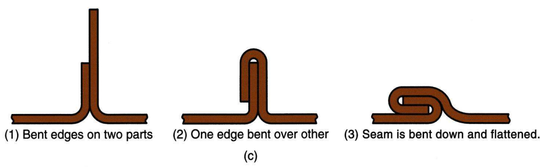
Integral Fasteners

Components are deformed so they interlock as a mechanically fastened joint

Lanced tabs: to attach wires or shafts to sheetmetal parts

Seaming: edges of sheetmetal parts are bent over to form the fastening seam





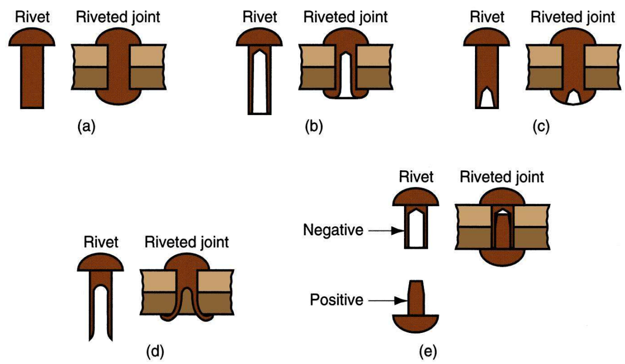
Permanent Assembly

Often referred to as "   " – where parts cannot be disassembled or be damaged in disassembly.

Some assembly methods are in between – not necessarily permanent but also not allowing for easy disassembly.

Rivets

- Most widely used permanent fastening method
- Typically a pneumatic hammer delivers a succession of blows to upset the rivet



Types: (a) solid, (b) tubular, (c) semitubular, (d) bifurcated, and (e) compression.

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Rivets used in airplanes.

There are about 1.5 million rivets on a Boeing 747!!

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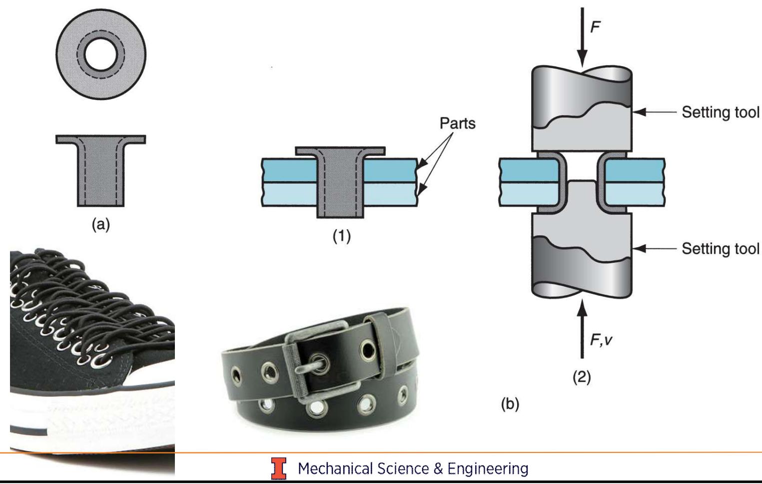
Eyelets

(a) Eyelet, (b) assembly sequence: (1) inserting eyelet through holes and (2) setting operation



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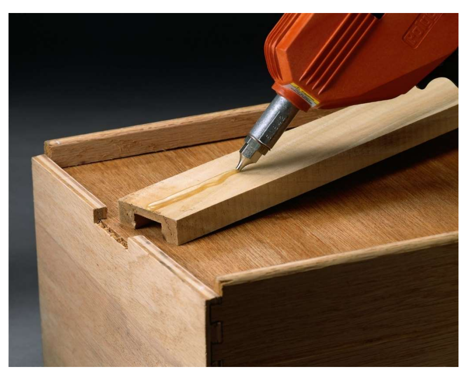
Overview of Adhesive Bonding

Uses forces of attachment between a filler material and two closely-spaced surfaces to bond the parts

- Filler material in adhesive bonding is
- Joining process can be carried out at *room temperature* or only modestly above



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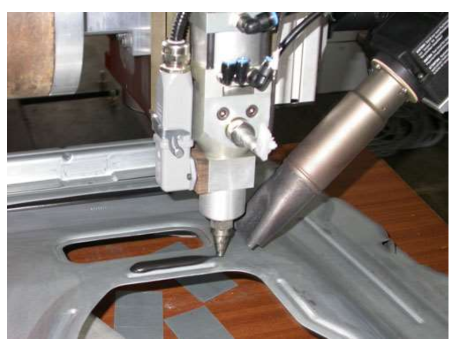
Application Methods

- Manual brushing and rolling
- Silk screening
- Flowing, using manually operated dispensers
- Spraying
- Automatic applicators
- Roll coating

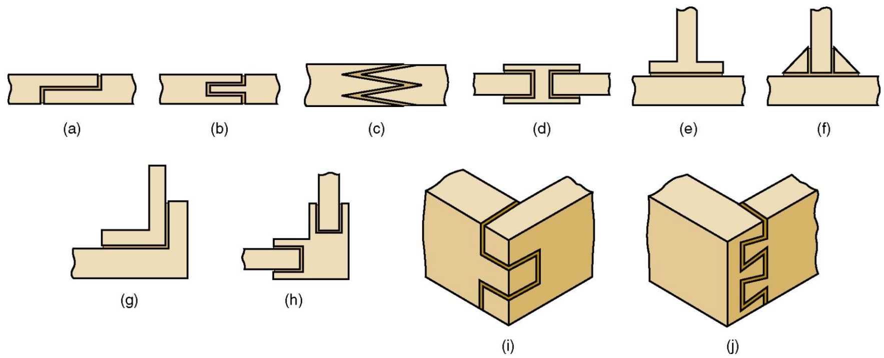
Adhesive Curing

- Mixing *catalyst* or reactive ingredient with polymer prior to applying
- *Heating* to initiate chemical reaction
- *Radiation* curing, such as UV light
- Curing by of water
- Films or *pressure*-sensitive coatings



Adhesive Joint Design – Increase Surface Area

Joint designs: (a) - (d) butt joints; (e) & (f) T-joints; (g) - (j) corner joints



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ME 270
Design for Manufacturability

Timothy H. Lee, PhD
Professor Bruce Flachsbart

Fall 2021

Lecture 20 - Assembly

Overview of Brazing and Soldering

- Both use filler metals to permanently join metal parts, but there is
- Use brazing or soldering over welding when:
  - Metals have
  - *Dissimilar metals* are to be joined
  - Intense *heat* of welding may *damage* components
  - *Geometry* of joint not suitable for welding
  - *High strength* is not required
- Brazing definition: filler metal T_m >
- Solder definition: filler metal T_m <

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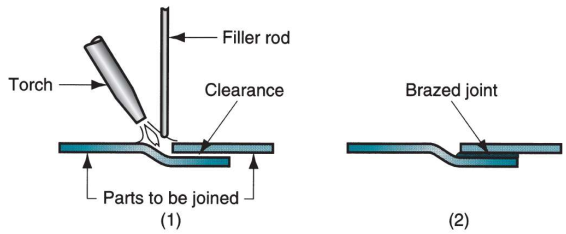
Brazing Filler Metal

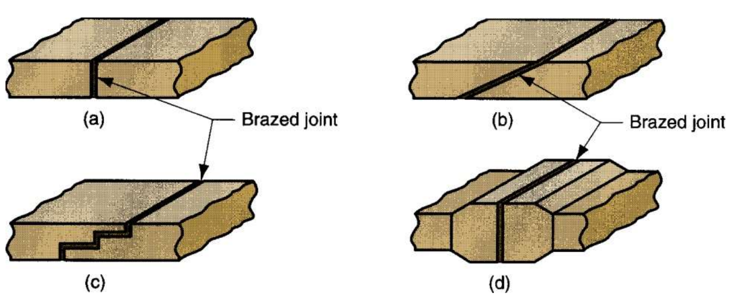


- T_m less than the base metal(s) to be joined
- Capillary action draws molten filler metal into joint

Base metal(s)	Filler metal(s)
Aluminum	Aluminum - silicon
Steel, cast iron	Copper - zinc
Stainless steel	Gold or silver

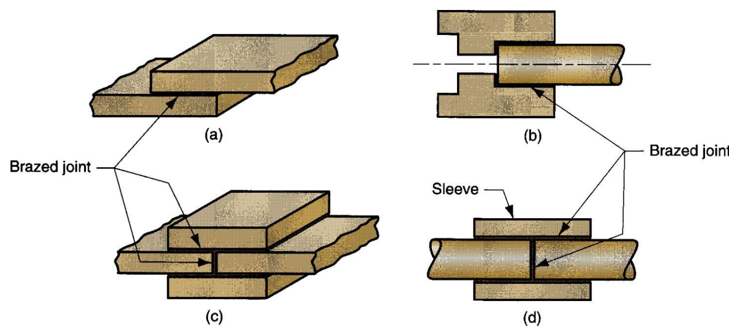
Butt Joint Design for Brazing

(a) Conventional butt joint, and adaptations for brazing: (b) scarf joint, (c) stepped butt joint, (d) increased cross section at the joint



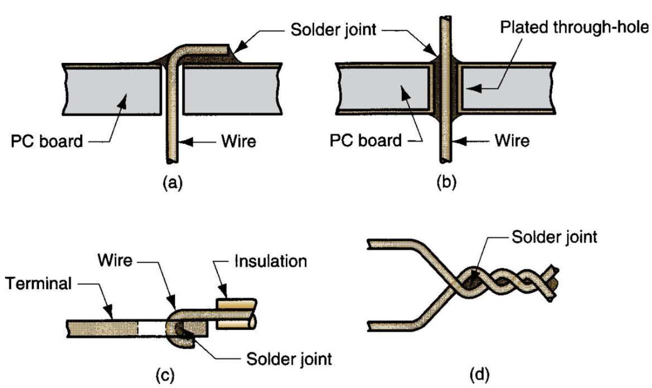
Lap Joints for Brazing

(a) Conventional lap joint, and adaptations for brazing: (b) cylindrical parts, (c) sandwiched parts, and (d) use of sleeve to convert butt joint into lap joint



Typical Solder Joints

(a) Crimped lead wire on PC board; (b) plated through-hole on PC board to increase solder contact surface; (c) hooked wire on flat terminal; and (d) twisted wires

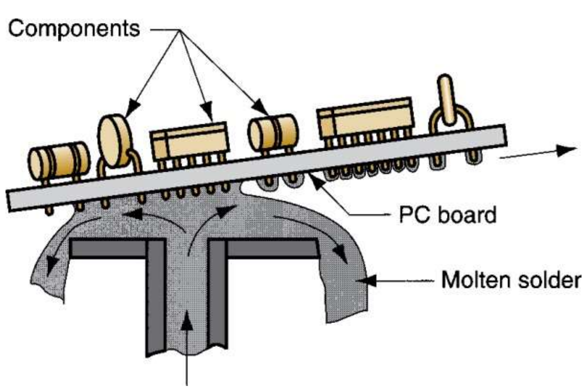


Functions of Brazing and Soldering Fluxes

- Remove oxide films and tarnish from base part surfaces
- Prevent oxidation during process
- Promote wetting of faying surfaces
- Be readily displaced by molten metal during process
- Most fumes are dangerous to very dangerous, you must use ventilation or a fume hood

Wave Soldering

- Molten solder is delivered up through a narrow slot onto the underside of a PCB to connect the component lead wires



Welding Classifications

No filler metal added

Solid state welding

- Friction welding

Filler metal added or parts melted together

Fusion welding

- **Electromagnetic**
  - Laser beam welding
  - Electron Beam welding
- **Electrical energy (aka arc welding)**
  - **Consumable electrode**
    - Stick
    - MIG
  - **Non-consumable electrode**
    - TIG
    - Resistance Welding
- **Chemical energy**
  - Thermit welding
  - Oxyfuel welding

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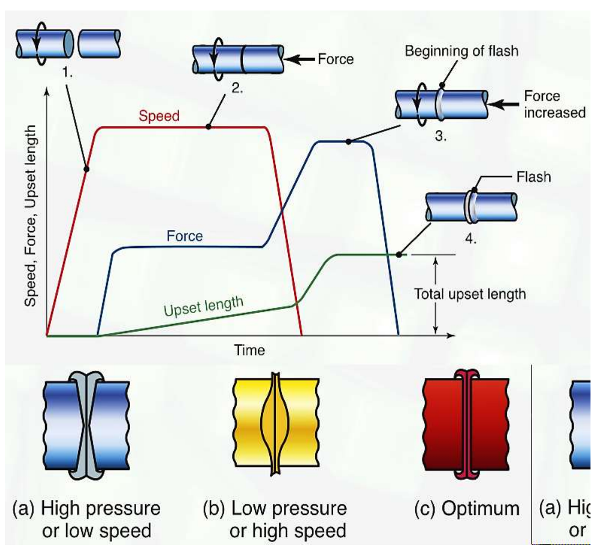
Friction Welding



https://www.youtube.com/watch?v=51Zs8iaydt0 start 0:40 end 2:20

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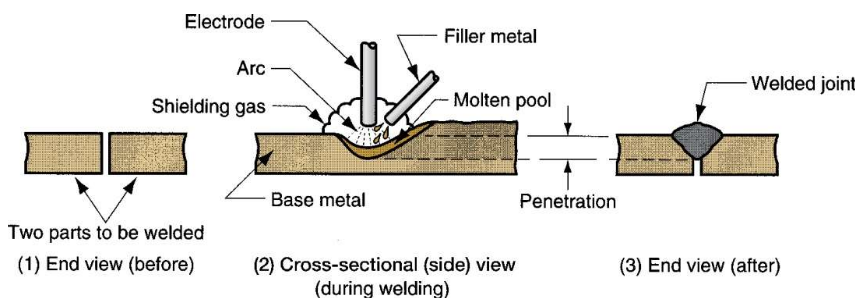
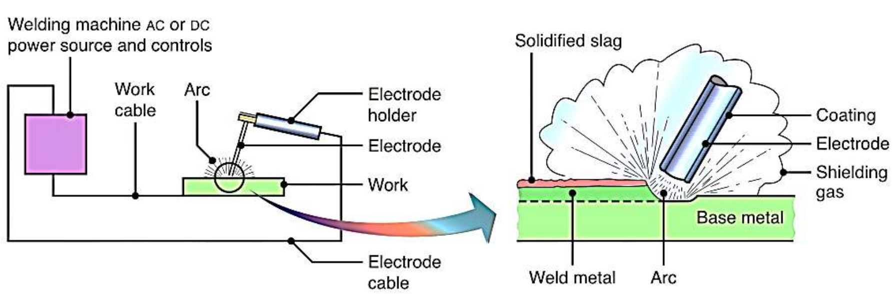
Electric Arc Welding

Basics of arc welding: (1) before the weld; (2) during the weld, the base metal is melted and filler metal is added to molten pool; and (3) the completed weldment



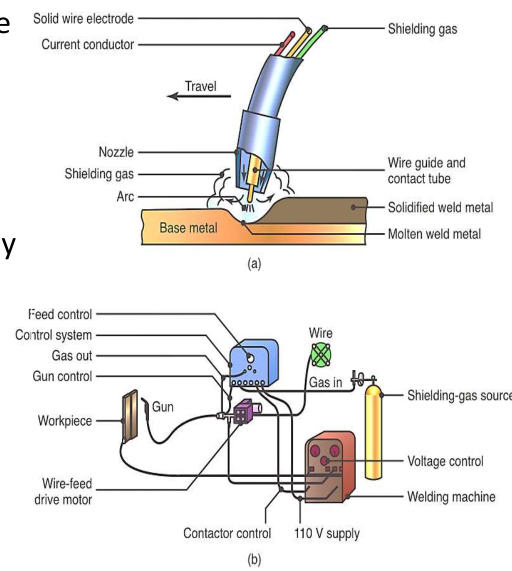
Shielded Metal Arc (SMAW, or Stick)

- An electric arc between a coated electrode and the parent metal
- The coated electrode carries the electric current to form the arc, produces a gas to control the atmosphere and provides filler metal for the weld bead
- Electric current may be AC or DC



Gas Metal Arc Welding (GMAW, or MIG)

- Uses a consumable electrode (filler wire made of the base metal)
- Inert gas is typically Argon
- Most widely used in manufacturing industry today



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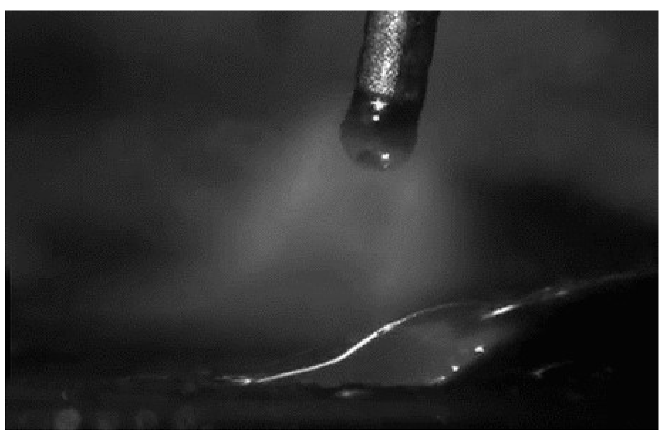
MIG gif



Current arcs between the filler rod and the part surface carrying charged molten metal droplets with it. Filler rod has inert gas flowing around it at all times.

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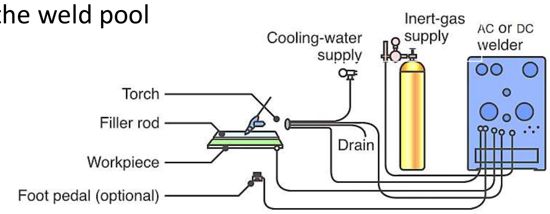
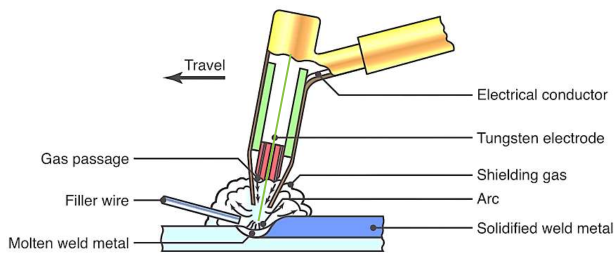
Gas Tungsten Car Welding (GTAW, or TIG)

- Tungsten electrode acts as a cathode
- A plasma is produced between the tungsten cathode and the base metal which heats the base metal to its melting point
- Filler metal can be added to the weld pool





(a)

TIG gif

Tungsten electrode is on the left and stays out of the molten pool. Filler rod is on right and goes in and out of molten pool. Direction is to the right.

Advantages and Disadvantages

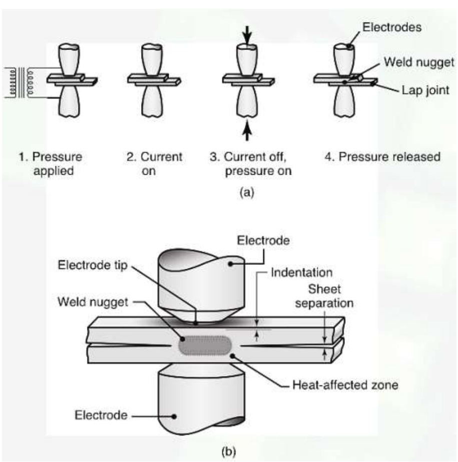
Pro:
- Faster welding
- Easier to learn

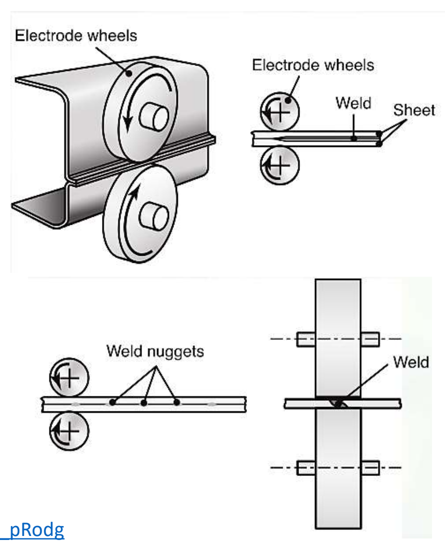
Con:
- Weld splatter
- Greater part distortion

Pro:
- Precision welding (smaller spot size)
- Can do thinner parts

Con:
- More dexterity required
- Slower process

ElectricaResistance Spot/Seam Welding

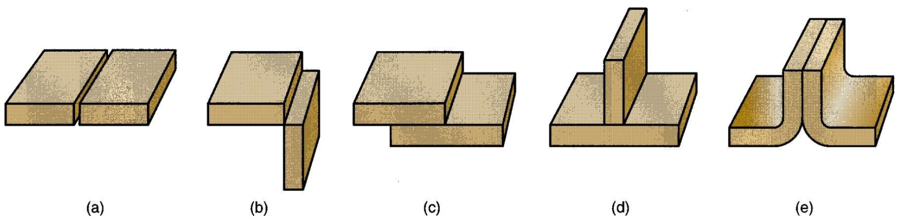




https://www.youtube.com/watch?v=zsin-_pRodg
https://www.youtube.com/watch?v=AwL1CAg43PU
https://www.youtube.com/watch?v=pnQAkq80XaY

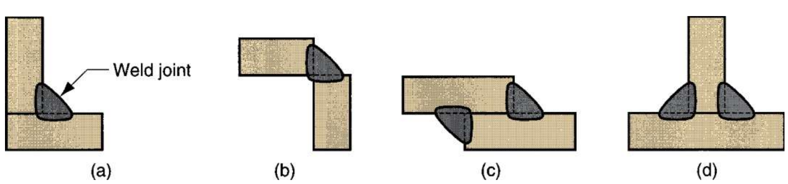
Five Types of Welding Joints

(a) Butt joint, (b) corner joint, (c) lap joint, (d) tee joint, and (e) edge joint



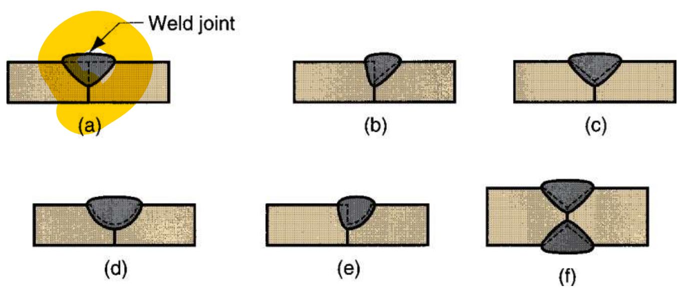
Fillet Welds

(a) Inside single fillet corner joint; (b) outside single fillet corner joint; (c) double fillet lap joint; (d) double fillet tee joint (dashed lines show the original part edges)



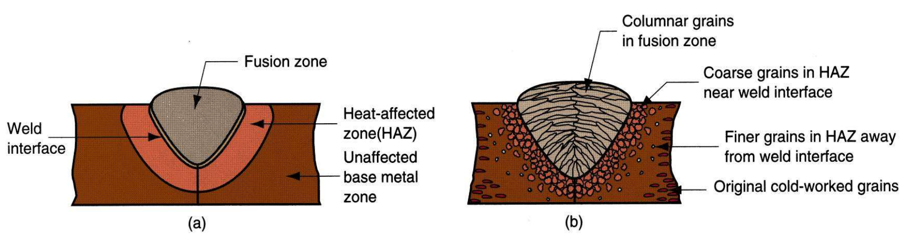
Groove Welds

(a) Square groove weld, one side; (b) single bevel groove weld; (c) single V-groove weld; (d) single U-groove weld; (e) single J-groove weld; (f) double V-groove weld for thicker sections (dashed lines show original part edges)



Thermal Changes and Weld Defects

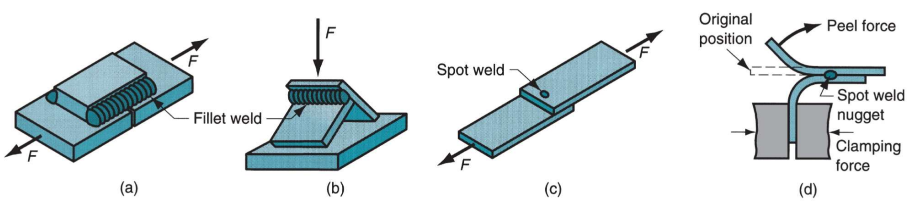
Cross section of a typical fusion welded joint: (a) principal zones in the joint, and (b) typical grain structure.



Mechanical properties are generally weaker in the HAZ (Heat Affected Zone), and this is

Weld Inspection and Testing

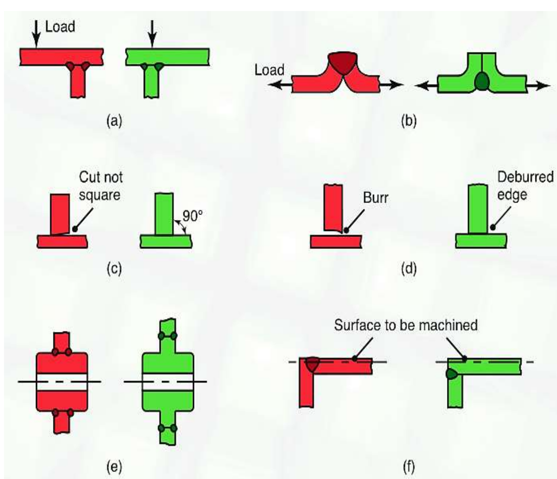
- Inspection methods – generally non-destructive
  - Visual inspection of surface for cracks and inclusions.
  - Ultrasound or x-rays to look for cracks and voids below the surface.
- Testing – generally destructive
  - Common tensile and shear tests:

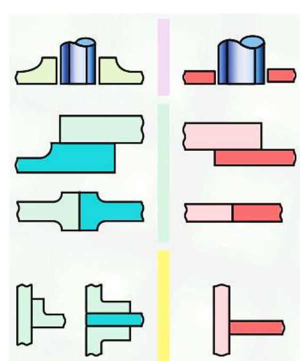


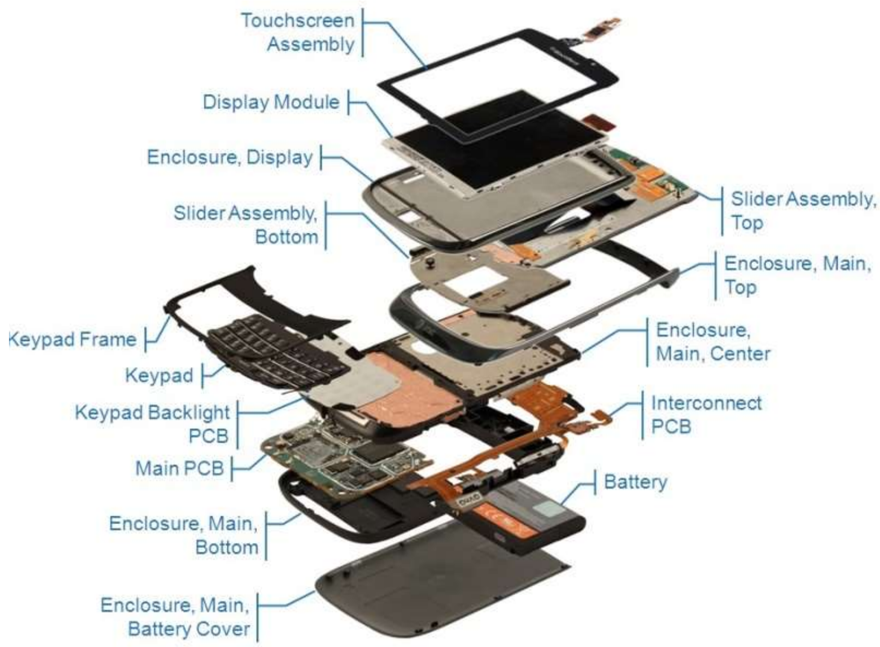
Design Advisor

(i.e. green/blue is good, red is bad)

Welding **Brazing / Solder**







Production Volume → Assembly Choice

1. Manual Bench Assembly: human operators assembling parts on a *bench or fixed location* bringing parts from bins or storage locations to a single station.
2. Manual Assembly Line: human operators assembling parts on a *moving line* picking parts from line-side bins or storage racks; using manual or power assisted tools to assembly parts together.
3. Robotic Assembly: *robotic devices* in the place of human operators performing all or part of the assembly operations.
4. Special Purpose Transfer Machine Assembly: fully automated *assembly machines* designed and built specifically to assemble a mass produced product.

Permanent Mold Casting Processes

Design for Assembly

1. Design the product with a goal of overall ease of assembly.
2. Design each component for ease of assembly to its neighbors.
3. Improve the ease by which parts are joined or assembled together.

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ME 270
Design for Manufacturability

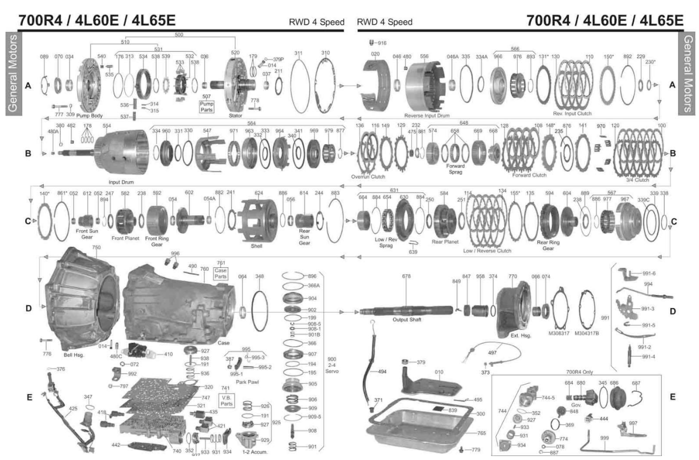
Timothy H. Lee, PhD
Professor Bruce Flachsbart

Fall 2021

Lecture 21 – Design for Assembly

ME 270 – Lecture 11 – DFA

- DFA introduction & tabulation tables
- Minimum Part Number & Assembly Efficiency
- Improving Product and Part Designs



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Design for Assembly:

1. By knowing part information and manufacturing method – DFA programs can quantify:
   1.
   2.
2. The purpose of DFA programs are to provide a guidance and methodology to:

- Assembly typically occupies between **40%** and **60%** of the total production period (manufacture time).

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Assembly Software

Assembly software programs are based upon years of industrial data to accurately determine:

1.
2.

Software can propose alternative designs and which parts are candidates for elimination or simplification

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Handling & Alignment Times

- Handling time depends upon:
  - Grasping method (tweezers, tool, one hand, two hands, two person, etc.)
  - Presentation (fetching distance, entanglement potential if in a bin with similar parts, conveyor, automated dispense, tray, slide feeder, etc.)
  - Size (smaller parts take longer, and large parts take longer than “medium” or “ideal” sized parts)
  - Part symmetry, if rotation or orientation is needed for alignment

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Insertion & Secure Times

- Insertion time depends upon difficulties:
  - Insertion tolerance / hole size
  - Access or view obstructed
  - Insertion force, depth, etc.
  - Having to “hold” the part while securing
- Secure time depends upon method:
  - Thread, bolt, or screw
  - Snap,
  - Rivet (solid, tubular, blind, two part)
  - Press fit (interference fit),
  - Crimp, etc.

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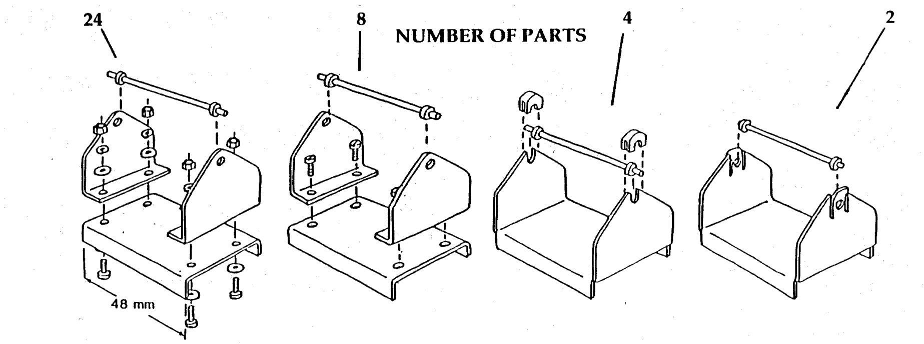
Example Problem

- Can we estimate and compare the assembly time for these parts?



- First we need to learn terminology and what assumptions to make

DFA Part Symmetry - α

<u>α symmetry:</u> rotational symmetry about an axis perpendicular to the axis of insertion

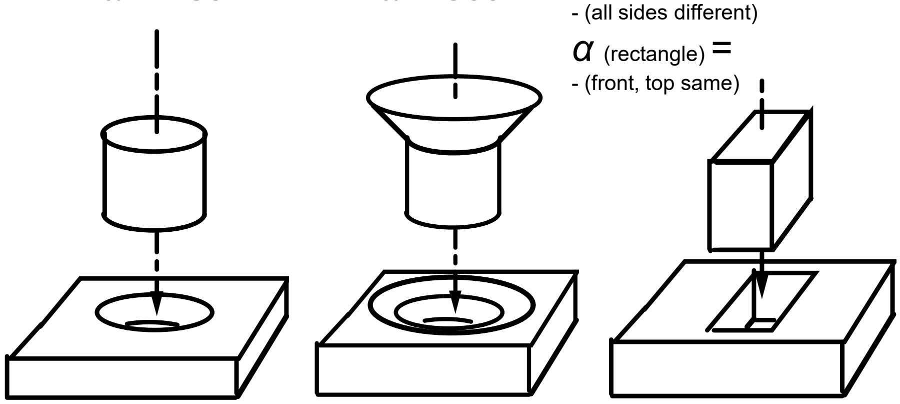
α (cube) =

α (rectangle) =
- (all sides different)

α (rectangle) =
- (front, top same)

α = 180°

α = 360°



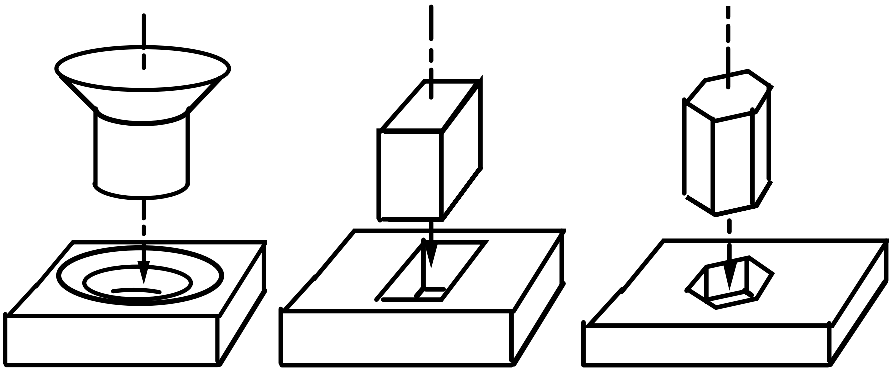
DFA Part Symmetry - β

β symmetry: rotational symmetry about the axis of insertion

β = 0°

β (cube) =
β (rectangle) =
- (all sides different)

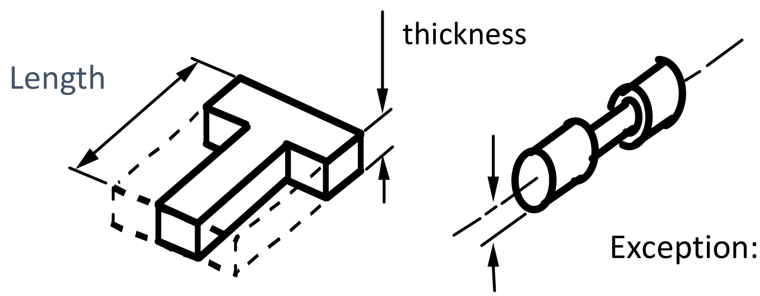
β =



DFA Part Handling – program inputs

Length: length of the longest side of the smallest rectangular prism that can enclose the part.

Aspect ratio: ratio between the longest and shortest lengths of that rectangular prism



General Rule

DFA Part Handling Difficulties

- Slippery: easily slip from fingers or tool
- Fragile or Delicate: require careful handling
- Nest or tangle: but can be separated one handed
- Sharp: or present other hazards to operator
- Stick together: e.g. magnetic force or grease
- Parts that Severely Nest or Tangle: Those that interlock & require two hands to separate
- Flexible Parts: Those that require two hands to manipulate, i.e. <u>large</u> gaskets, belts, bands etc.

DFA – Tabulation Approximations 1

- Software programs use very accurate algorithms (these are simplified assumptions to give you an idea how they work):
- Using tabulation tables similar to this were how DFA started in the 1970s.
- Use these assumptions for homework, the lab, and the Final.
- Handling & Alignment:
  - Part fetch time: 0.5s / 0.5m distance (0.5s minimum)
  - Symmetry: add $(\alpha + \beta) / 360$ seconds
  - Part size: small ($L < 2\ cm$) add 0.5s, large ($L > 20\ cm$) add 0.3s
  - For each handling difficulty (sharp, tangle, flexible, etc.) add 0.4s
  - Aspect ratio > 20 add 0.1s, aspect ration > 40 add 0.3s

DFA – Tabulation Approximations 2

- Insert & Secure:
  - General placement: 0.5s
  - Align to small hole (<2mm) add 0.7s, align to a medium hole (2 < hole < 4mm) add 0.3s,
  - Align to pin (opposite of a "hole"), small (<2mm) add 0.4s, medim (2 < pin diameter < 4mm) add 0.1s.
  - Requiring a grasping aid (tweezer, special gloves, magnifying glass) add 1.4s.
  - Turning insertion (e.g. starting a nut or screw) add 1s.
  - Snap: add 0.3s, Crimp: add 0.8s
  - Final tightening of a screw/nut, add 2s (one sided) or 7s (two sided).
  - For each insertion difficulty (view, force, spring, hold (2 hands), tight tolerance etc.) add 0.4s
  - Rotate base (i.e. turning the assembly over): 1.8s

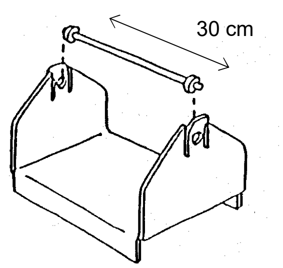
Tray Example 1:

(assume base is presented correctly via conveyor)

Part Symmetry for handle assembly:

α =

β =



Difficulties – Handling *(diameter is 2 cm):*

Difficulties – Insertion *(hole is not small)*:

1) Handling & alignment time: *(assume handle is within 0.5m)*

2) Insert & secure time: *(assume hole is not "small")*

Total time:

Tray Example 2:

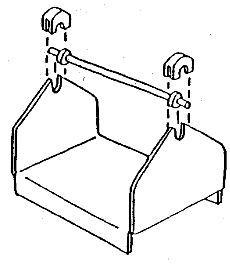
Part Symmetry for handle & crimp brackets:

α = α =

β = β =

Handling difficulties (brackets not small):

Insertion difficulties (crimping takes 2 hands):



1) Handling & alignment time (everything within 0.5m):

2) Insertion & secure time:

Total time:

Tray Example 3:

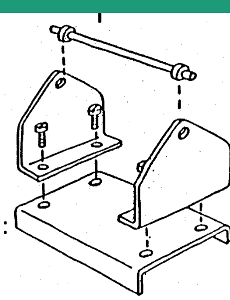
Part Symmetry for handle, side plate, & screw:

α = α = α =

β = β = β =

Handling difficulties (screws small but not sharp):

Insertion difficulties (handle “forced” into hole + 2 hands):



1) Handling & alignment time (everything within 0.5m):

2) Insertion & secure time (hole size is medium, screws are tapered):

Total time:

Tray Example 4:

Part Symmetry for bolt, washer, lock washer, & nut:

α = α = α = α =

β = β = β = β =

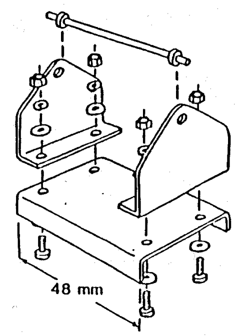
Handling difficulties (only washers and nuts are small):

Insertion difficulties:

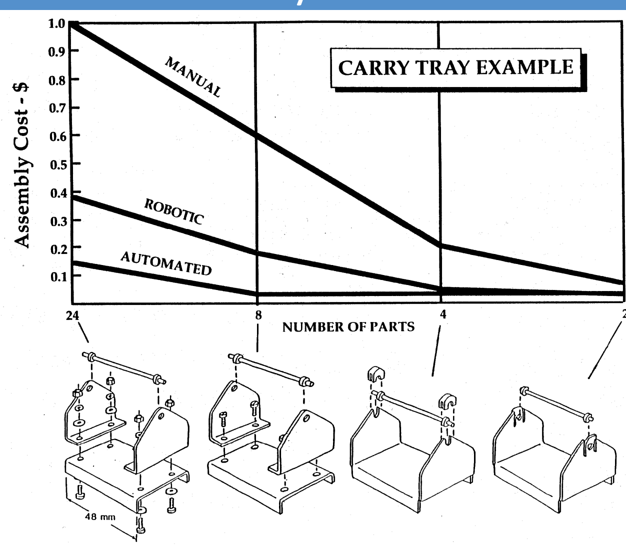
1) Handling & alignment time:

2) Insertion & secure (med hole, bolt 4xhold, washer & nut align to med pin):

Total time: 4 x (bolt, 2 washers, lock washer, & nut) + 11.7s (handle and sides)



Improved Assembly → Enables Automation



Parts:	24	8	4	2
Time(s):	96	35	9	3

DFA Analysis – "The Three Questions":

1. Does a part *move simultaneously* (direction doesn't matter) with another part?
2. Can the part be the *same material* as this other part?
3. Can the *manufacturing method and tolerance* be the same for these parts (e.g. casting, sheet metal, injection molding, similar tolerance, etc.)?

All "**yes**" (comparing 2 parts) indicates parts could be combined (but, just a suggestion).

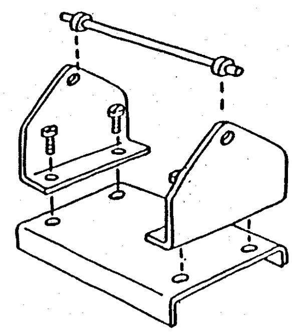
Determining Assembly Efficiency

- DFA Efficiency =
  - Where NM is the theoretical minimum number of parts, only parts that "pass" the "Three Questions."
  - TM is the time to assemble the product (total "assembly time")
  - This assumes, an "ideal" assembly of roughly *3 seconds* per part

Tray Example 3:

DFA analysis: side panel & bottom

1. Move Simultaneously?
2. Same Material?
3. Same Mfg Method and tol?



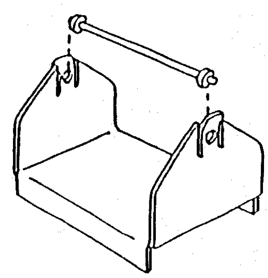
Assembly efficiency

- Total assembly time:
- Efficiency =

Tray Example 1:

DFA analysis: handle & bottom

1. Move Simultaneously?
2. Same Material?
3. Same Mfg Method and tol?



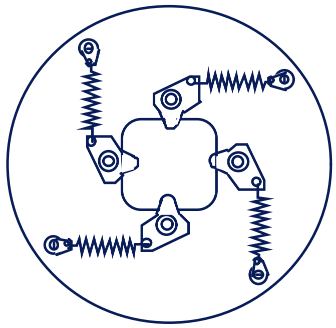
Assembly efficiency

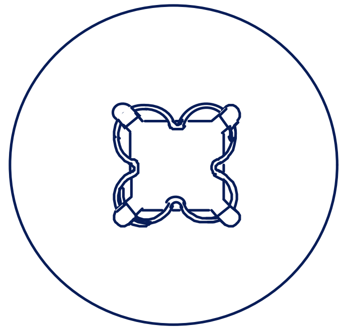
- Total assembly time:
- Efficiency =

Example – shaft indexer:

DFA analysis questions for **indent tooth**:

1. Same Material?
2. Move Simultaneously?
3. Same Mfg Method?





Old design = 24 parts

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University of Illinois at Urbana-Champaign - Zhejiang University Partnership

ME 270
Design for Manufacturability

Timothy H. Lee, PhD

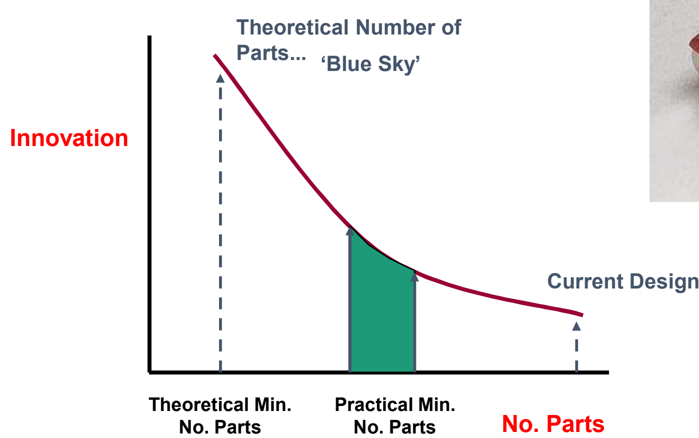
Professor Bruce Flachsbart

Fall 2021

Lecture 22 – Design for Assembly

Creativity & Innovation

- Team assessment of practical changes
- Trade-offs between part cost and assembly cost

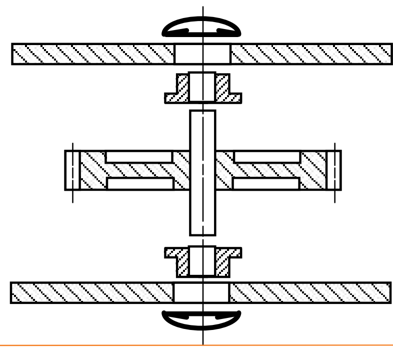


Mechanical Science & Engineering

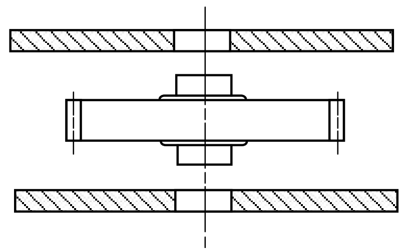
'Product' DFA - Principle #1

1. Design for minimum number of parts:
   - Are all components essential or can their functions be achieved by modifying an existing component?
   - Can components be combined into an integral multifunctional component?

Old design = 8 parts



New design =



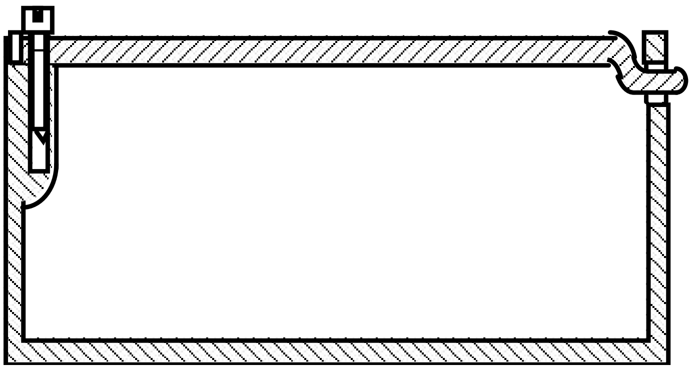
'Product' Principle #1 – focus on fasteners

- Minimize number of fasteners for components
  - Use snap fits where possible
  - Use press fits where disassembly is not required
  - Consider molded hinges, straps, or hook-unders
  - Rationalize fasteners - types, lengths etc.
  - Use one piece fasteners with lead in pilots
  - Design geometry for automatic alignment

Ex. Applications of Principle #1

Hook-under design to minimize

number of fasteners

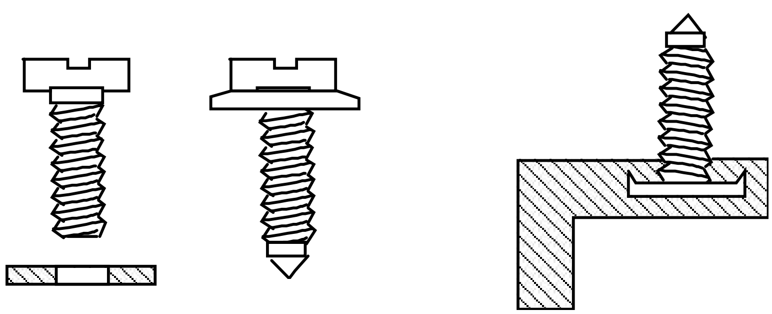


Ex. Applications of Principle #1

Use single-piece fasteners,

with guide pilots

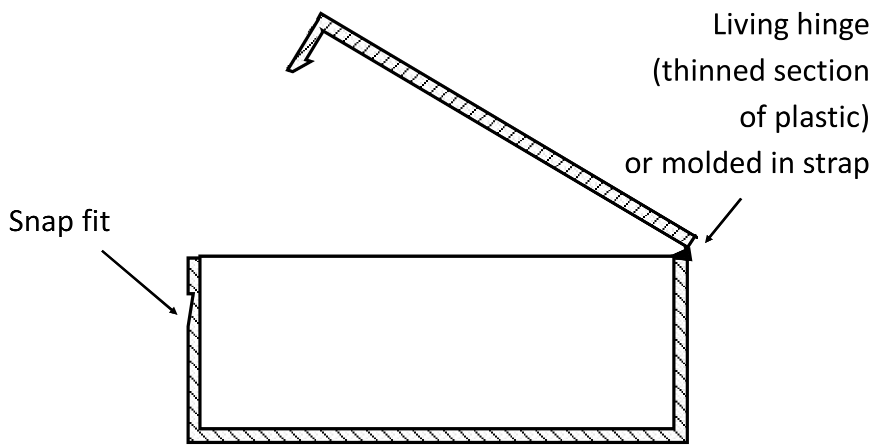
or inserts



lead in pilot

Ex. Applications of Principle #1

Hinges, straps and/or snap fits:



'Product' DFA - Principle #2

- Design the product for assembly from one direction
  - Where possible assemblies should be designed so that a base piece is established, and remaining parts assembled from one, ideally vertical (Z) direction.
  - It is difficult to feed components in from the side.
- The Sony walkman is an excellent example: parts were inserted in straight-down moves only. This enabled a simple robotic system to be used for the entire assembly.

'Product' Principle #2 – especially don't flip

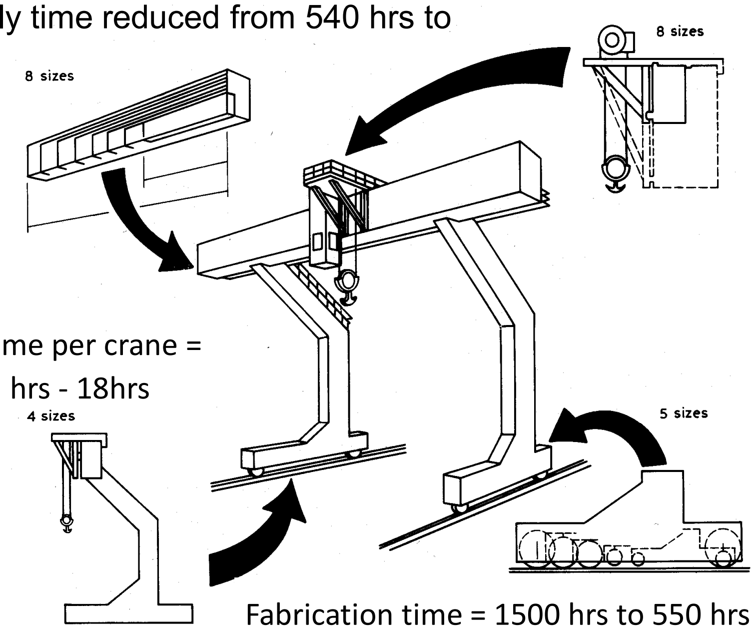
- Avoid the need to turn the assembly over
  - If previously placed components have not been fastened, they may move out of position.
  - Datum and location points change, and complicate the assembly process, which leads to jamming and assembly failure.

'Product' DFA - Principle #3.

- Standardize parts and Modularize assembly. Parts, especially fasteners can be difficult to differentiate, particularly small similar shaped ones.
  - It is relatively common for feeders to become jammed because wrong parts have been fed in by operators.
  - Considerable savings in storage, inventory, ordering etc.
  - Modular sub-assemblies may be built and tested by specialist teams (higher quality).

Modular Design

Assembly time reduced from 540 hrs to 180 hrs



Design time per crane = 350 man hrs - 18hrs

Fabrication time = 1500 hrs to 550 hrs

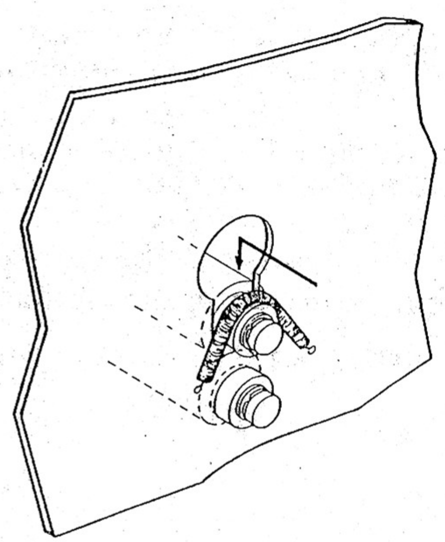
'Product' DFA - Principle #4

- Location and use of datum surfaces:
  - Try to ensures a common location, for as many parts as possible, to be used as a reference for part placement tolerance (e.g. common base).
  - Avoid tolerance build-up (the positional tolerance of one part depending upon the positional tolerance of other parts) as much as possible.

'Product' DFA - Principle #5

Avoid the need for assembly adjustments

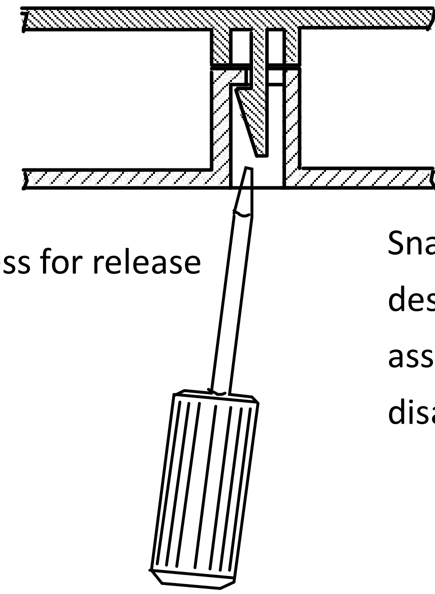
- Equipment going out of adjustment is one of the biggest causes of customer dissatisfaction.
- Spring loading can be used to avoid assembly adjustment and to eliminate adjustment for wear.



'Product' DFA Principle #6

- Consider ease of disassembly for maintenance, service, repair, and recycling
  - Integral snap fits, press fits, and retaining clips (circlips) allow compact designs, but if care is not taken, result in impossible disassembly
  - Disassembly is frequently necessary due to the need to service/repair, and now the requirement to recycle

Ex. Applications of Principle #6



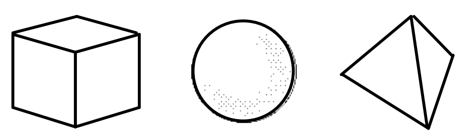
Recess for release of snap

Snap fits - can be designed for ease of assembly & disassembly

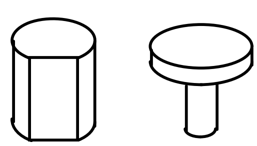
'Part' DFA - Principle #1

- Components should be symmetrical or have exaggerated asymmetry

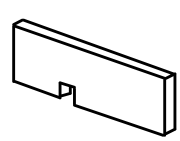
Symmetrical shapes have a predictable rest aspect ⇒



Non-symmetrical shapes have an unpredictable resting aspect ⇒

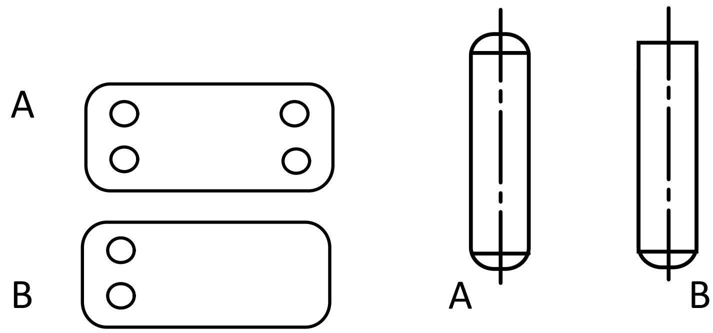


With exaggerated asymmetry part falls on one of its flat faces ⇒



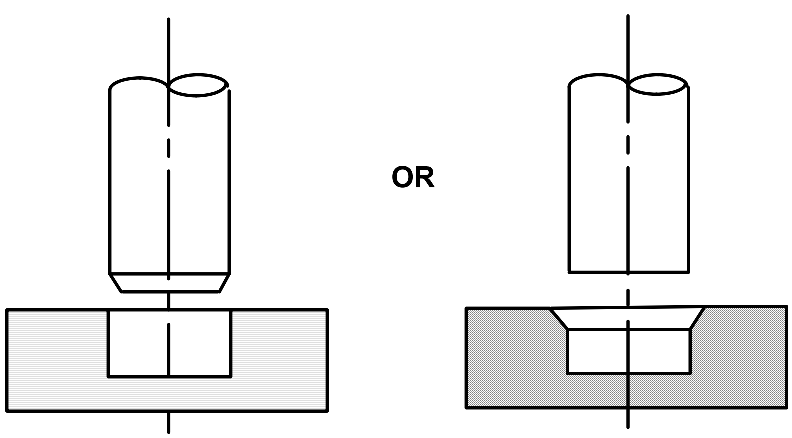
'Part' Principle #1 – adding features?

- Components should have the least number of important directions
- Increases the probability of correct feeding and positioning



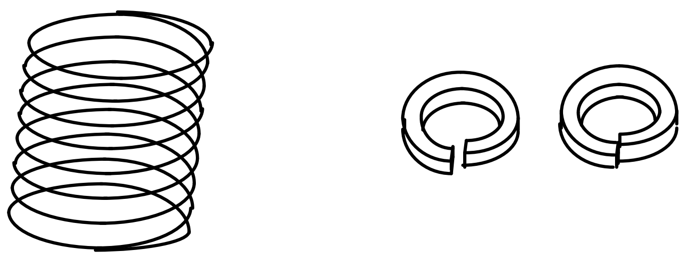
'Part' DFA - Principle #2

- Provide Lead-in or Chamfers
  - Where possible make chamfers and lead-in angles generous, and avoid sharp corners, to avoid jamming:



‘Part’ DFA - Principle #3

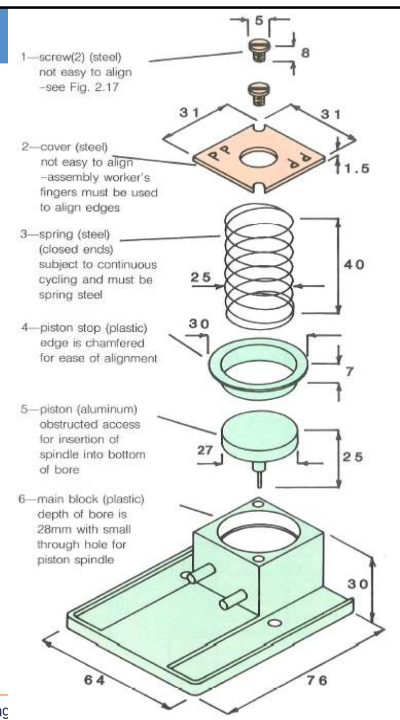
- Design parts to prevent tangling:
  - Often a small design change can eliminate the tendency of components to tangle. Close ends and keep material thickness greater than gaps and slots:



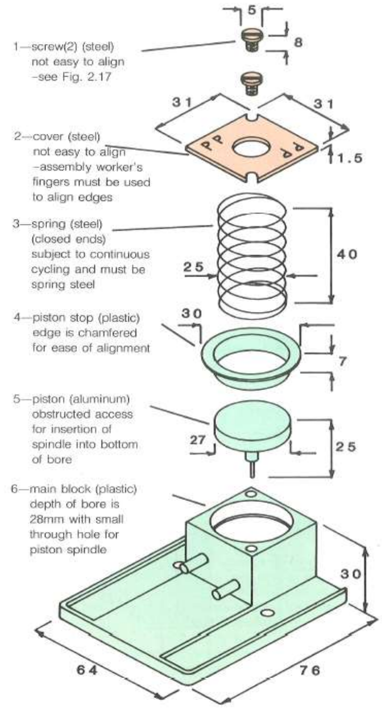
Mechanical Science & Engineering

Analysis: air pump

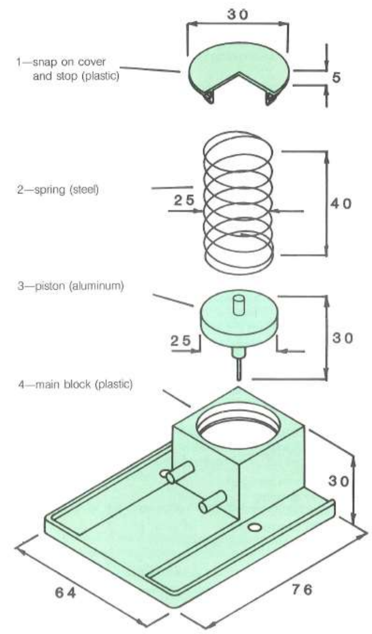
- Which parts (or functions) are functionally necessary?
  - •spring,piston,main block
- Which parts might not be necessary?
  - •cover, piston stop,screw
- Which parts can be improved?
  - •increase bore depth in main block and add chamfer to simplify piston alignment
  - •change cap to snap fit



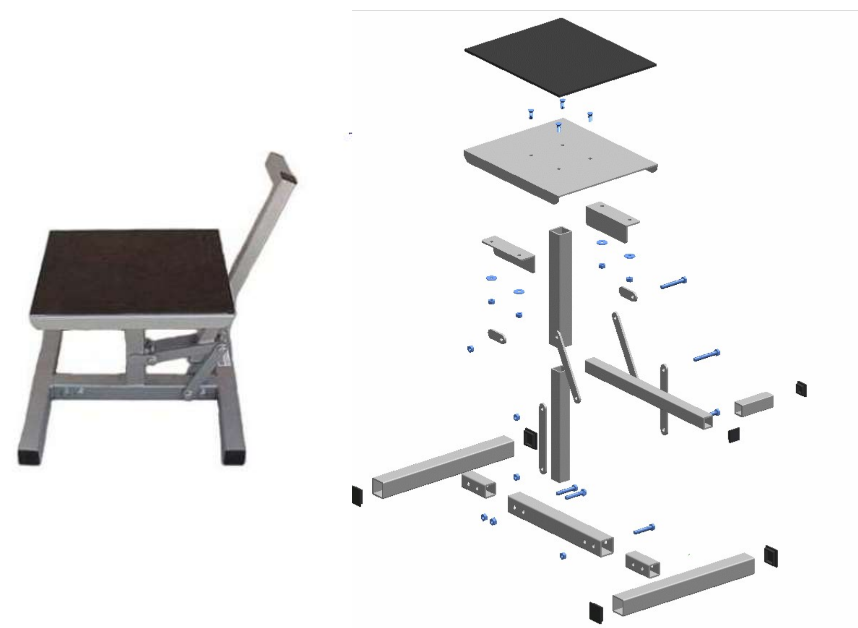
Mechanical Science & Eng



Re-Design using DFA



DFA Analysis – motorcycle lift



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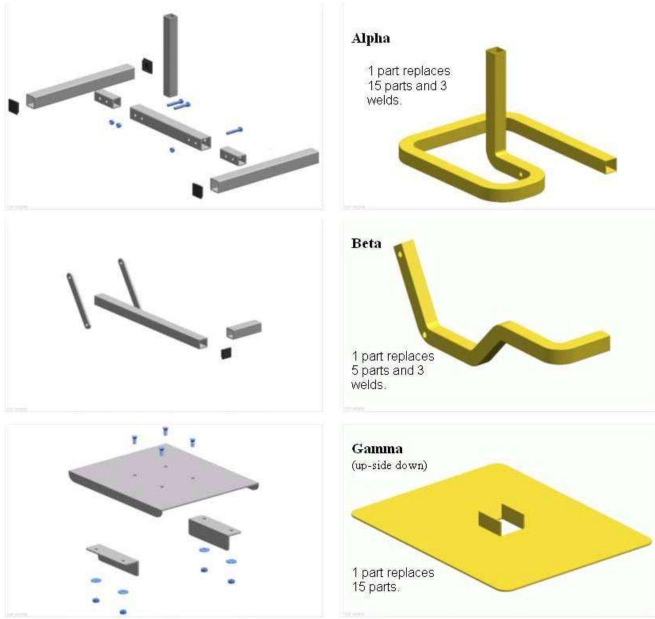
Combining parts that function together:



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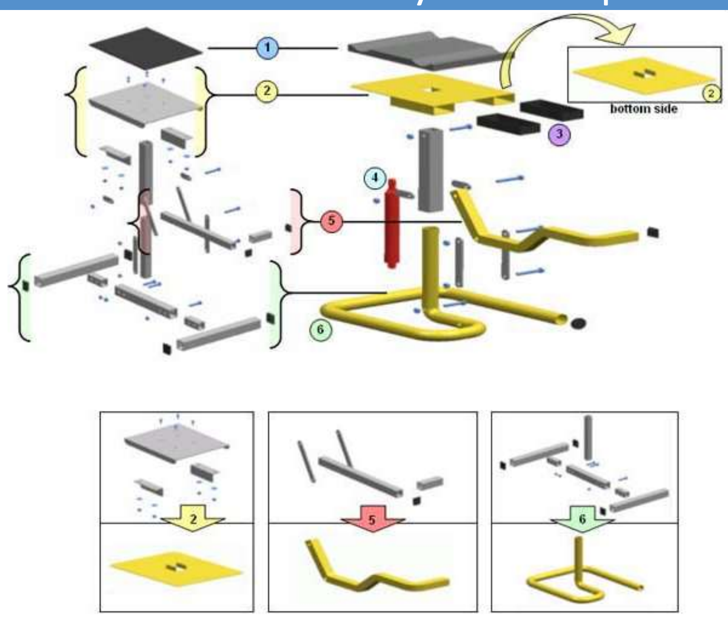
Each Subassembly was Simplified



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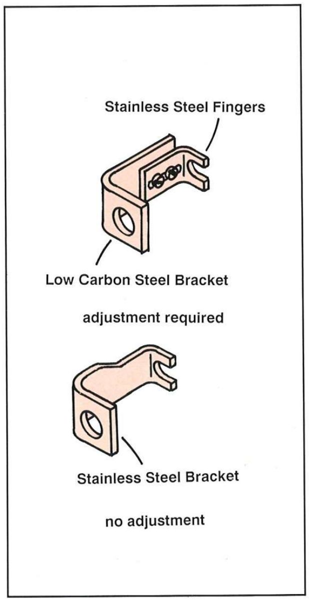
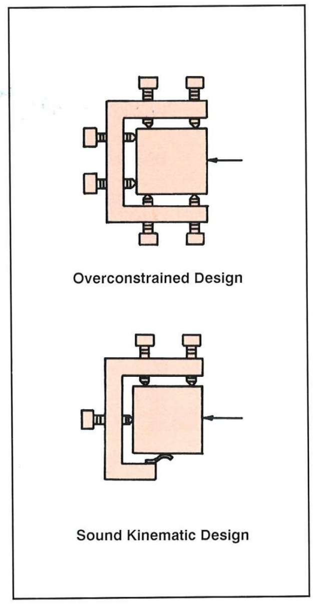
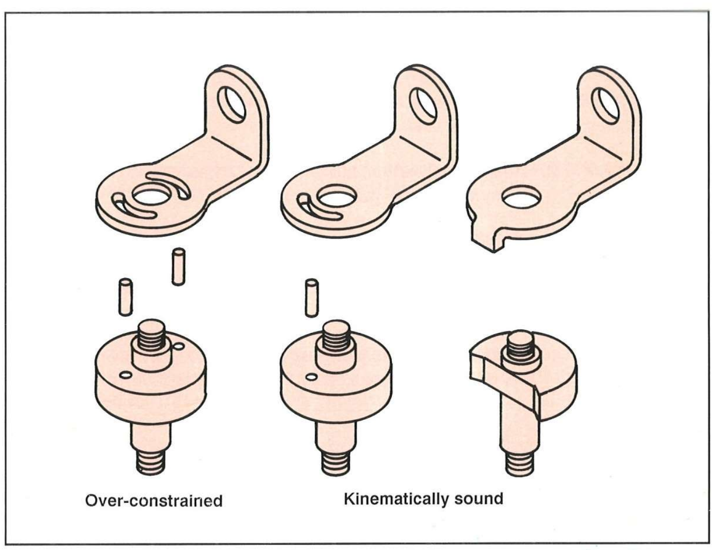
Eliminate Adjustment & Overcontraints

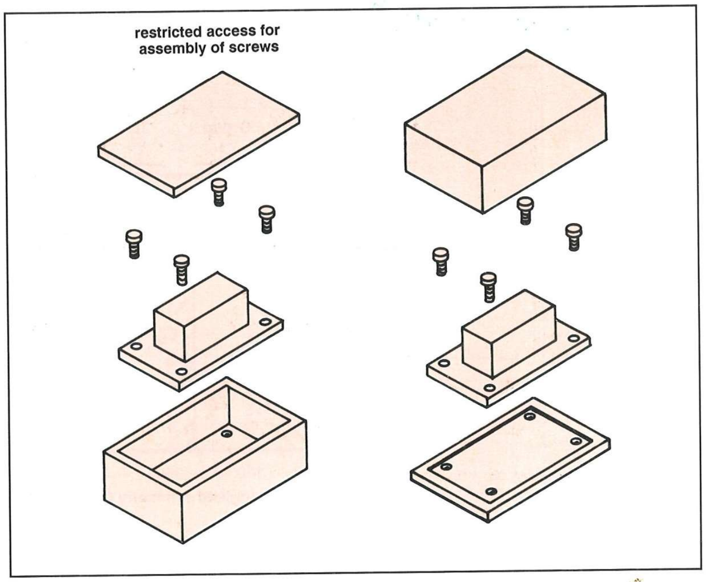




Reduce Parts by Changing Design



Ease Assembly



Boothroyd Early Tabulation Tables:

MANUAL HANDLING—ESTIMATED TIMES (seconds)

Key: ONE HAND; ONE HAND with GRASPING AIDS; TWO HANDS for MANIPULATION; TWO HANDS required for LARGE SIZE

		parts are easy to grasp and manipulate; thickness > 2 mm; size >15 mm	parts are easy to grasp and manipulate; thickness > 2 mm; 6 mm ≤ size ≤15 mm	parts are easy to grasp and manipulate; thickness > 2 mm; size <6 mm	parts are easy to grasp and manipulate; thickness ≤ 2 mm; size >6 mm	parts are easy to grasp and manipulate; thickness ≤ 2 mm; size ≤6 mm	parts present handling difficulties (1); thickness > 2 mm; size >15 mm	parts present handling difficulties (1); thickness > 2 mm; 6 mm ≤ size ≤15 mm	parts present handling difficulties (1); thickness > 2 mm; size <6 mm	parts present handling difficulties (1); thickness ≤ 2 mm; size >6 mm	parts present handling difficulties (1); thickness ≤ 2 mm; size ≤6 mm
		0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand without the aid of grasping tools; $(\alpha+\beta) < 360°$	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
$360° \leq (\alpha+\beta) < 540°$	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
$540° \leq (\alpha+\beta) < 720°$	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
$(\alpha+\beta) = 720°$	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

		parts need tweezers for grasping and manipulation; parts can be manipulated without optical magnification; parts are easy to grasp and manipulate; thickness >0.25 mm	…; parts are easy to grasp and manipulate; thickness ≤0.25 mm	…without optical magnification; parts present handling difficulties (1); thickness >0.25 mm	…; parts present handling difficulties (1); thickness ≤0.25 mm	parts require optical magnification for manipulation; parts are easy to grasp and manipulate; thickness >0.25 mm	…; parts are easy to grasp and manipulate; thickness ≤0.25 mm	parts require optical magnification for manipulation; parts present handling difficulties (1); thickness >0.25 mm	…; parts present handling difficulties (1); thickness ≤0.25 mm	parts need standard tools other than tweezers	parts need special tools for grasping and manipulation
		0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand but only with the use of grasping tools; $\alpha \leq 180°$; $0 \leq \beta \leq 180°$	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
$\alpha \leq 180°$; $\beta = 360°$	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
$\alpha = 360°$; $0 \leq \beta \leq 180°$	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
$\alpha = 360°$; $\beta = 360°$	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

		parts present no additional handling difficulties; $\alpha \leq 180°$; size > 15 mm	…; $\alpha \leq 180°$; 6 mm ≤ size ≤ 15 mm	…; $\alpha \leq 180°$; size < 6 mm	…; $\alpha = 360°$; size > 6 mm	…; $\alpha = 360°$; size ≤ 6 mm	parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1); $\alpha \leq 180°$; size > 15 mm	…; $\alpha \leq 180°$; 6 mm ≤ size ≤ 15 mm	…; $\alpha \leq 180°$; size < 6 mm	…; $\alpha = 360°$; size > 6 mm	…; $\alpha = 360°$; size ≤ 6 mm
		0	1	2	3	4	5	6	7	8	9
parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2)	8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

		parts can be handled by one person without mechanical assistance; parts do not severely nest or tangle and are not flexible; part weight < 10 lb; parts are easy to grasp and manipulate; $\alpha \leq 180°$	…; part weight < 10 lb; parts are easy to grasp and manipulate; $\alpha = 360°$	…; part weight < 10 lb; parts present other handling difficulties (1); $\alpha \leq 180°$	…; part weight < 10 lb; parts present other handling difficulties (1); $\alpha = 360°$	…; parts are heavy (> 10 lb); parts are easy to grasp and manipulate; $\alpha \leq 180°$	…; parts are heavy (> 10 lb); parts are easy to grasp and manipulate; $\alpha = 360°$	…; parts are heavy (> 10 lb); parts present other handling difficulties (1); $\alpha \leq 180°$	…; parts are heavy (> 10 lb); parts present other handling difficulties (1); $\alpha = 360°$	parts severely nest or tangle or are flexible (2)	parts need special tools for grasping and manipulation
		0	1	2	3	4	5	6	7	8	9
two hands required for grasping and transporting parts	9	2	3	2	3	3	4	4	5	7	9

CHART 2-1

MANUAL INSERTION—ESTIMATED TIMES (seconds)

Key: PART ADDED but NOT SECURED; PART SECURED IMMEDIATELY; SEPARATE OPERATION

		after assembly no holding down required to maintain orientation and location (3); easy to align and position during assembly (4); no resistance to insertion	…; easy to align and position during assembly (4); resistance to insertion (5)	…; not easy to align or position during assembly; no resistance to insertion	…; not easy to align or position during assembly; resistance to insertion (5)	holding down required during subsequent processes to maintain orientation or location (3); easy to align and position during assembly (4); no resistance to insertion	…; easy to align and position during assembly (4); resistance to insertion (5)	…; not easy to align or position during assembly; no resistance to insertion	…; not easy to align or position during assembly; resistance to insertion (5)
		0	1	2	3	6	7	8	9
addition of any part (1) where neither the part itself nor any other part is finally secured immediately; part and associated tool (including hands) can easily reach the desired location	0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
part and associated tool (including hands) cannot easily reach the desired location; due to obstructed access or restricted vision (2)	1	4	5	5	6	8	9	9	10
due to obstructed access and restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

		no screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.); easy to align and position with no resistance to insertion (4)	…; not easy to align or position during assembly and/or resistance to insertion (5)	plastic deformation immediately after insertion; plastic bending or torsion; easy to align and position during assembly (4)	…; plastic bending or torsion; not easy to align or position during assembly; no resistance to insertion	…; plastic bending or torsion; not easy to align or position during assembly; resistance to insertion (5)	…; rivetting or similar operation; easy to align and position during assembly (4)	…; rivetting or similar operation; not easy to align or position during assembly; no resistance to insertion	…; rivetting or similar operation; not easy to align or position during assembly; resistance to insertion (5)	screw tightening immediately after insertion (6); easy to align and position with no torsional resistance (4)	…; not easy to align or position and/or torsional resistance (5)
		0	1	2	3	4	5	6	7	8	9
addition of any part (1) where the part itself and/or other parts are being finally secured immediately; part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily	3	2	5	4	5	6	7	8	9	6	8
part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily; due to obstructed access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
due to obstructed access and restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

		mechanical fastening processes (part(s) already in place but not secured immediately after insertion); none or localized plastic deformation; bending or similar processes	…; none or localized plastic deformation; rivetting or similar processes	…; none or localized plastic deformation; screw tightening (6) or other processes	…; snap fit, snap clip, press fit, etc.	non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion); metallurgical processes; no additional material required (e.g. resistance, friction welding, etc.)	…; metallurgical processes; additional material required; soldering processes	…; metallurgical processes; additional material required; weld/braze processes	…; chemical processes (e.g. adhesive bonding, etc.)	non-fastening processes; manipulation of parts or sub-assembly (e.g. orienting, fitting or adjustment of part(s), etc.)	…; other processes (e.g. liquid insertion, etc.)
		0	1	2	3	4	5	6	7	8	9
assembly processes where all solid parts are in place	9	4	7	5	3.5	7	8	12	12	9	12

CHART 2-2

2.27

DFA Analysis Summary

- To quickly improve a product design:
  1. Look for parts that move together
  2. Look for fastening mechanisms to simplify
  3. Look for ways to reduce the part count
  4. Look for ways to increase part symmetry

Primary Ways to Improve Designs

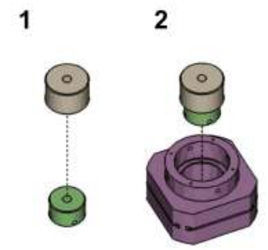
Products:

1. Minimize parts and fasteners
2. Minimize assembly direction
3. Standardize and Modularize
4. Common base to avoid tolerance build-up
5. Self adjustment whenever possible
6. Ease of disassembly and repair

Parts:

1. Symmetry
2. Ease of assembly (chamfers)
3. Parts that won't tangle

DFA Example



- Step 1: assume top & bottom surfaces of both parts are different, diameter is 4 cm, and parts snap together
- Step 2: insertion is a snap fit

Part	α - Sym	β - Sym	Handling Difficulites	Handling & Alignment Time (s)	Insertion Difficulties	Insert & Secure Time (s)	Total Time (seconds)
Step 1a - placement							
Step 1b - snap fit							
Step 2 - snap fit							

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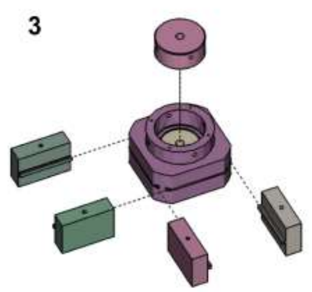
DFA Example



- Step 3: parts must slide into the guides (approximate as a small hole - they will need to be held and force is required), top piece is not symmetrical top to bottom, and small holes must align (easily fits inside so only general placement needed for that).

Part	α - Sym	β - Sym	Handling Difficulites	Handling & Alignment Time (s)	Insertion Difficulties	Insert & Secure Time (s)	Total Time (seconds)
Step 3a - (one) slider							
Step 3b - top inserted							

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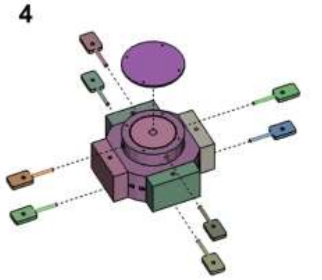
DFA Example

4

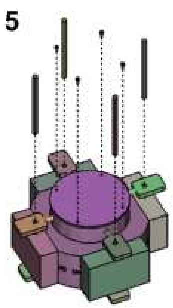


- Step 4: holes are small & pins sharp (insertion force needed to insert pins), top piece is symmetrical top to bottom, and must align with small holes.

Part	α - Sym	β - Sym	Handling Difficulites	Handling & Alignment Time (s)	Insertion Difficulties	Insert & Secure Time (s)	Total Time (seconds)
Step 4a - pins							
Step 4b - top							

DFA Example

5



- Step 5: pins have a large aspect ratio and insertion force is needed to insert symmetric pins into small holes. Lid must be “held” while each (small) screw is attached.

Part	α - Sym	β - Sym	Handling Difficulites	Handling & Alignment Time (s)	Insertion Difficulties	Insert & Secure Time (s)	Total Time (seconds)
Step 5a - (one) pin							
Step 5b - (one) screw							

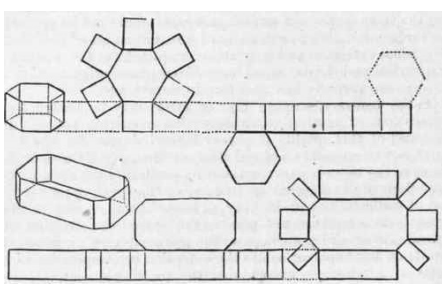
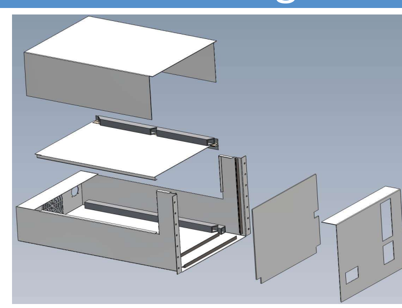
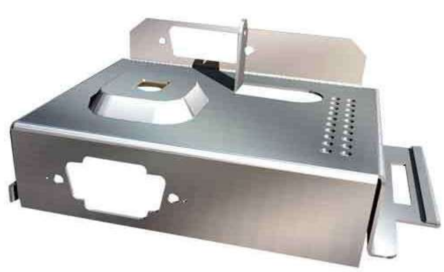
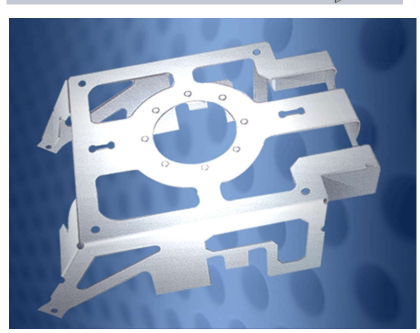
UIUC-ZJU PARTNERSHIP

University of Illinois at Urbana-Champaign - Zhejiang University Partnership

ME 270
Design for Manufacturability

Timothy H. Lee, PhD
Professor Bruce Flachsbart
Fall 2021
Lecture 23 – Sheet Metal

ME 270 – Ch 3 Sheet Metalworking

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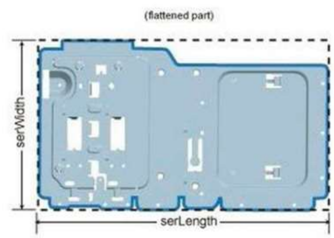
What are Advantages of Sheet Metalwork?

- Inepen
- Ductile, easily formed.
- Bending and shaping to form 3-D object, instead of cutting or adding material.
- Very fast new technologies to bend, shape, stretch, cut, seam, and weld.

UNCOILER AND LEVELLER



Sheet Metal Classification

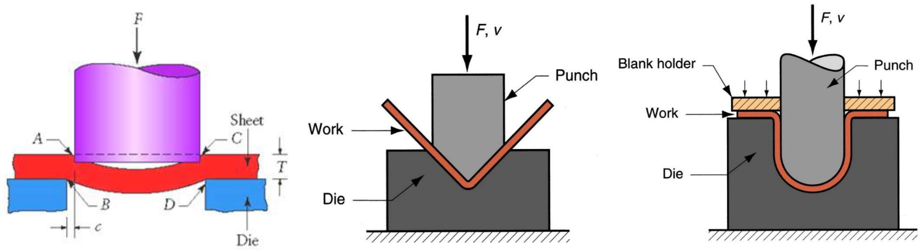
Thickness:

- Between $^{1}/_{64}$” - $^{1}/_{4}$” (~0.4 – 6.0 mm) thick
- Thinner is considered “ foil”
- Thicker is generally considered “ plate”, but sheet metalworking processes have been used on material up to 6” thick.

Material:

- *Low carbon steel* (good formability)
- Aluminum (2nd most popular)
- Stainless Steel, Brass, Copper, Tin, Nickel, etc.

Basic Operations of Sheet Metalwork

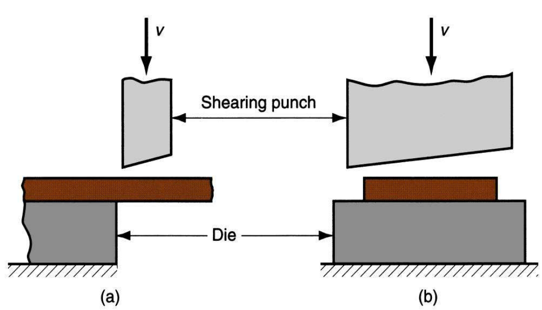


cutting bending drawing/forming

- Good dimensional accuracy
- Good surface finish
- Cold working, stretching, and bending can improve strength

Cutting – Method 1: Shearing

- Sheet metal cutting operation along a ***straight line*** between two cutting edges
- Typically used to cut large sheets

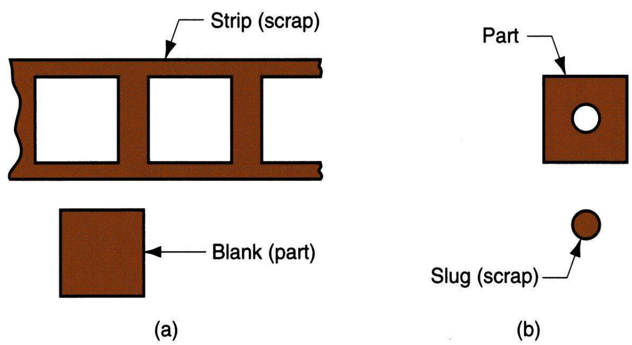


(a) side view of the shearing operation; (b) front view of power shears equipped with inclined upper cutting blade.

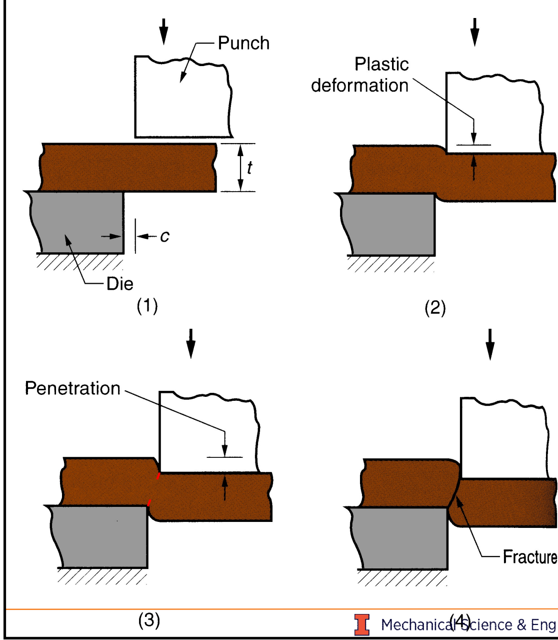
Cutting – Method 2: Blanking and Punching

Blanking - sheet metal cutting to separate piece (called a *blank*) from surrounding stock

Punching - similar to blanking except cut piece is scrap, called a



Cutting Fundamentals



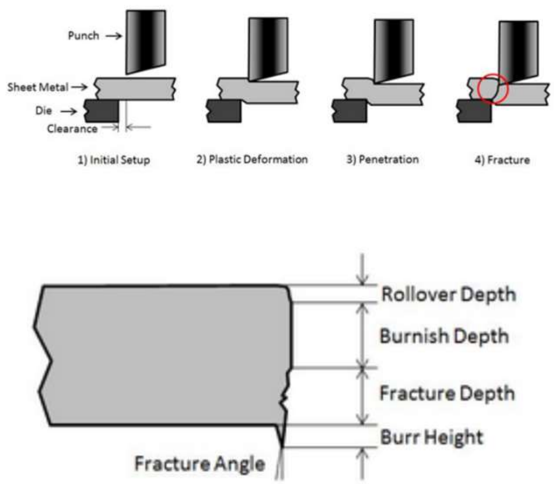
(1) punch before contact, clearance '*c*' between punch and die

(2) punch *plastically deforms material to its yield limit.*

(3) fractures starts at edges of top and bottom blade.

(4) if clearance is set appropriately, fracture lines meet.

Side Profile – Regions after Cutting



- The "*Rollover*" depth is formed during the plastic deformation stage.
- The "*Burnish*" depth, is a smooth region, formed as the blade *penetrates* the metal.
- The "*Fracture*" depth, the roughest region, is quickly formed with the "*Burr*" after shearing force is achieved.

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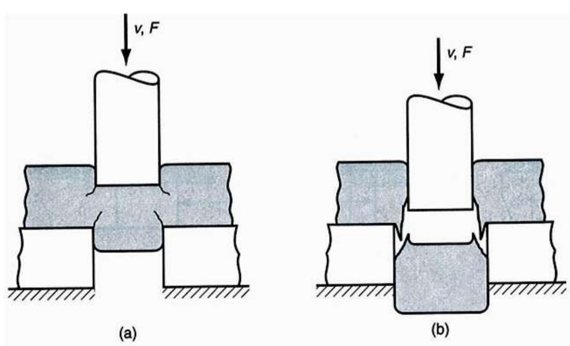
Clearance in Sheet Metal Cutting

- Distance between punch cutting edge and die cutting edge (typically 4 - 8% of thickness)
  - If clearance too small (a), fracture lines pass each other, causing double burnishing and larger force
  - If clearance too large (b), metal is pinched between cutting edges and excessive burr results



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Clearance in Sheet Metal Cutting

- Recommended clearance is calculated by:

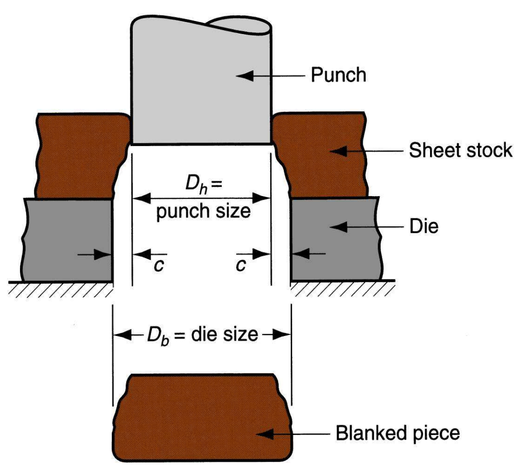
where c = clearance;
a = allowance;
t = stock thickness

- Allowance is determined according to type of metal:

Metal group	a
aluminum alloys (1100, 5052)	0.045
aluminum alloys (2024 and 6061); brass, *soft* cold rolled steel, *soft* stainless steel	0.060
cold rolled steel, stainless steel, (hard & half-hard)	0.075

Punch and Die Sizes

- For a round *blank* of dia. D_b and clearance c:
  - Blanking punch diameter = D_b-2*c
  - Blanking die diameter = D_b
- For a round *hole* of dia. D_h and clearance c:
  - Hole punch diameter = D_h
  - Hole die diameter = D_h+2*c



Angular Clearance

Purpose: allows slug or blank to drop through die

- Typical values: 0.25° to 1.5° on each side

Cutting Force:

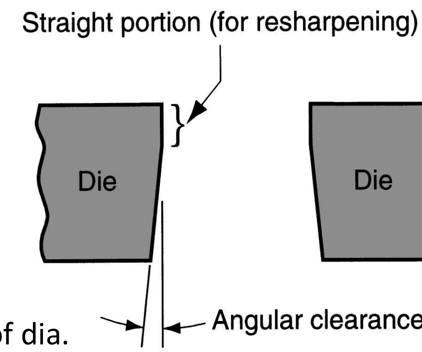
F=S*t*L

where *S* = shear strength;

t = stock thickness,

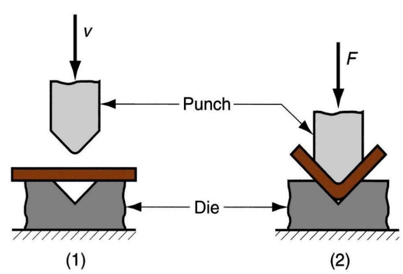
L = length of cut: i.e. circumference of dia. (not punch dia.)

1 ton ≈ 8896 N

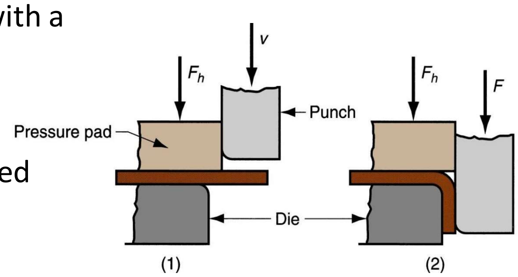


Types of Sheet Metal Bending

- V-bending - performed with a *V-shaped* die
  - Performed on a *press brake*
  - V-dies are simple and inexpensive



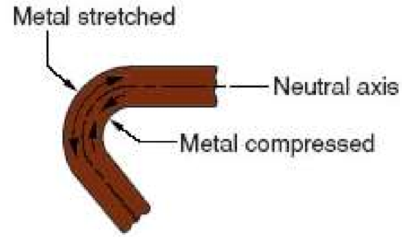
- Edge bending - performed with a *wiping* die
  - Pressure pad required
  - Dies are more complicated and costly



http://featurebasedcosting.com/DFMeBook/eBook_mp4s/bendBrake.mp4

Stretching during Bending

- If bend radius is ***small*** relative to stock thickness, metal tends to stretch during bending
- Important to estimate amount of stretching, so final part length = specified dimension
- A_b is the neutral axis length of the bend only.
- α is not internal angle



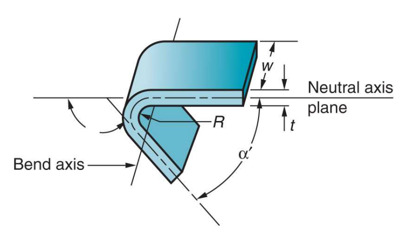
$$A_b = 2\pi \frac{\alpha}{360} (R + K_{Ba} t)$$

A_b = bend allowance (mm)
α = bend angle (degrees)
R = bend radius (mm)
t = Stock thickness
K = Constant:
0.33 if R<2t
0.5 if R>=2t

Bend Allowance Example

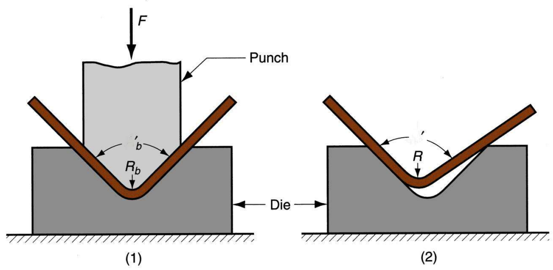
A bending operation is performed on 5 mm thick cold-rolled steel, 35 mm wide. The part is bent to have an interior angle of 40° at a bend radius of 8.5mm. If this bracket needs 40 mm of length after the bend (both sides), determine the blank size required.

-
-
-
-



Springback

- After bending the part partially recovers original shape.
  - When bending pressure is removed, elastic energy remains in bent part,
  - Must overbend the part to so the springback resorts to the needed radius/angle



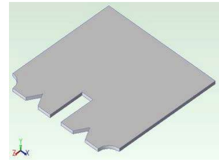
(1) during bending, the work is forced to take radius R_b and included angle α_b' of the bending tool, (2) after punch is removed, the work springs back to radius R and angle α'.

Stamping Operations

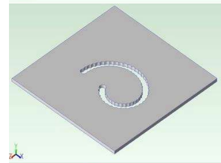
- Removing Material
  - Blanking, Notching, Nibbling, Parting and Perforating
- Deforming Material
  - Bending, Lansing, Cut off, Embossing, Drawing, and Ironing
    - Does not remove any material

Stamping Processes – material is removed

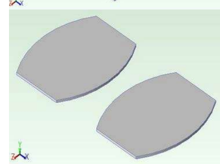
- Notching
  - Cutting process on the edge of the part



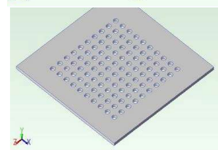
- Nibbling
  - A series of small, overlapping slits/holes used to cutout a larger complex shape
  - Alternative to using a custom punch



- Parting
  - A cut used to separate two parts that aren’t nested together
  - Results in scrap material

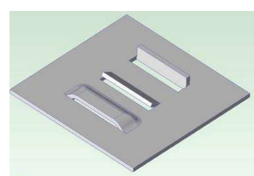


- Perforating
  - A single operation to punch multiple patterned holes

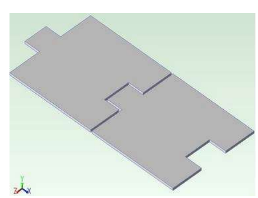


Stamping Processes – no material removed

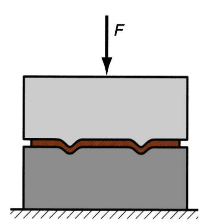
- Lancing
  - A cut hole without any material removed
  - Leftover material is bent in a future process

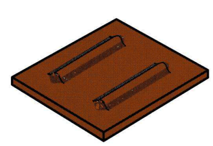


- Cut Off
  - A non-linear cut used to separate two parts/blanks that are nested together



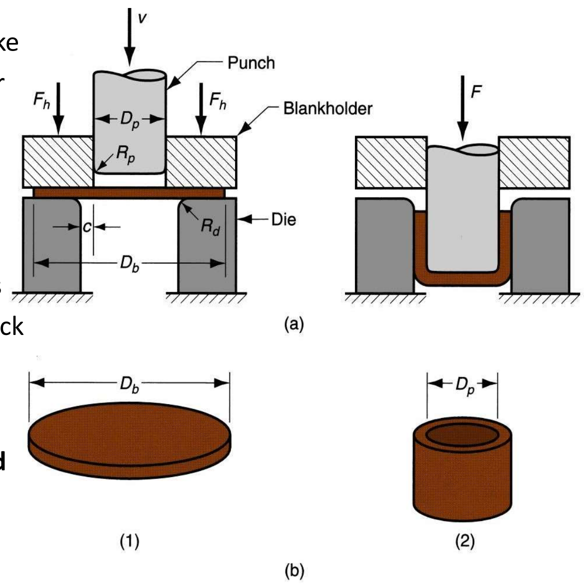
- Embossing
  - Creates indentations or





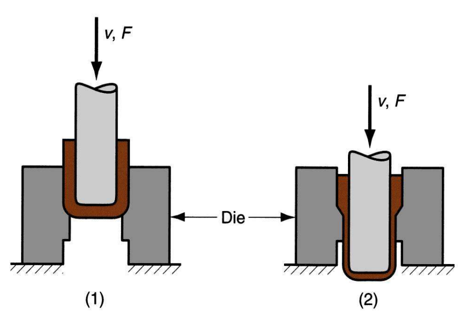
Drawing

- Sheet metal forming to make cup-shaped, box-shaped, or other hollow-shaped parts
- clearance $c = 1.1\ t$
- where t = stock thickness
- In other words, clearance is about 10% greater than stock thickness
- Excess material is often left over. Part must be **Trimmed** using normal shearing or punching processes



Ironing

- Makes wall thickness of cylindrical cup more uniform



Ironing to achieve more uniform wall thickness in a drawn cup: (1) start of process; (2) during process. Note thinning and elongation of walls.

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ME 270
Design for Manufacturability

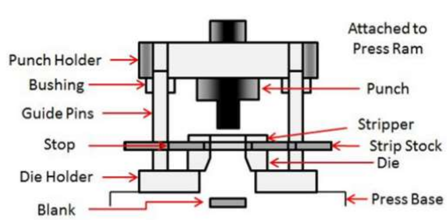
Timothy H. Lee, PhD
Professor Bruce Flachsbart

Fall 2021

Lecture 24 – Sheet Metal

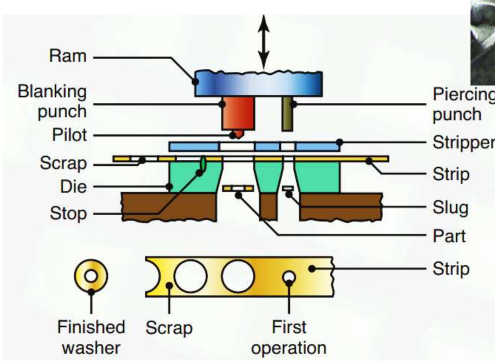
Stamping

- Stamping utilizes a press and die to cut or bend sheet metal
- Multiple dies are used in succession to complete a part with multiple features
- Stamping is used in large production volumes due to high tooling cost



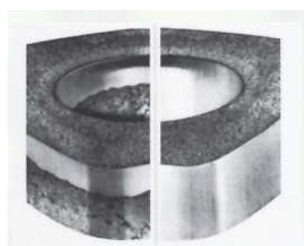
Progressive Die

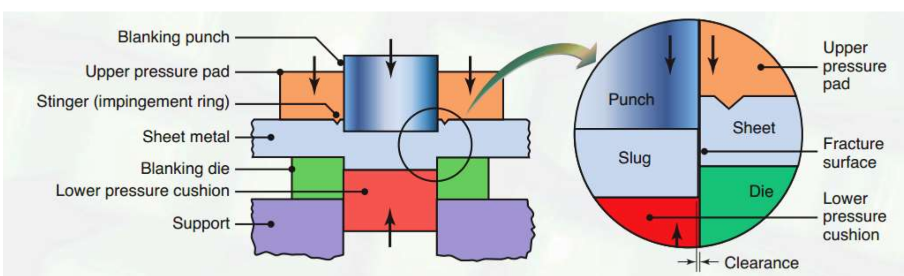
- Geometry and dimensions are reached gradually
- Usually incorporates several punching, shearing, bending, and blanking steps



Fine Blanking – Process Improvements

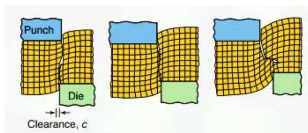
- Upper pressure pad: material plastic flow constraint
- Lower pad: maintain uniform pressure across slug surface

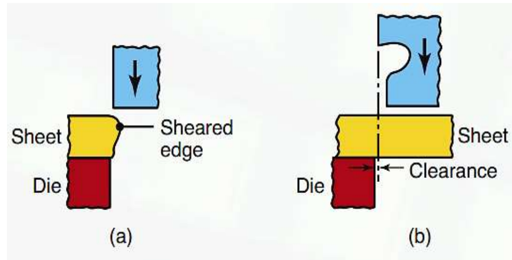




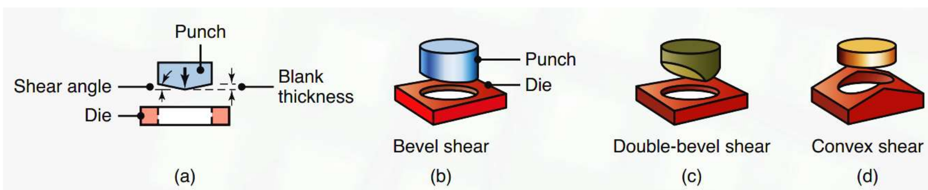
Shaving & Beveled Tooling - Improvements

- Shaving: finishing process providing surface finish and dimensional accuracy





- Beveled Tooling: reducing cutting forces



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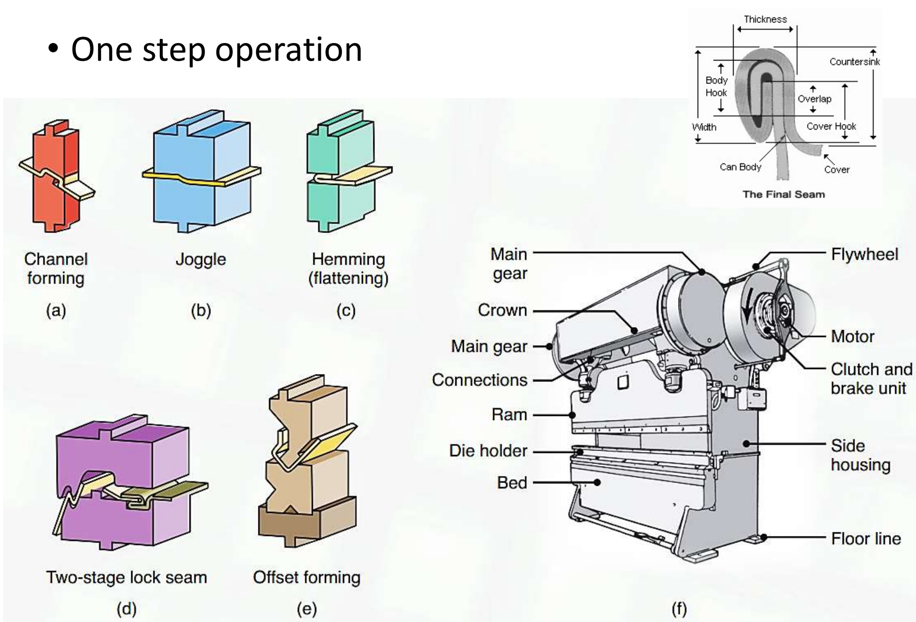
Press-Brake Operations

- One step operation



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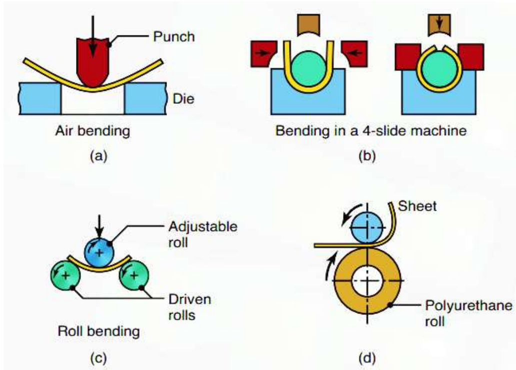
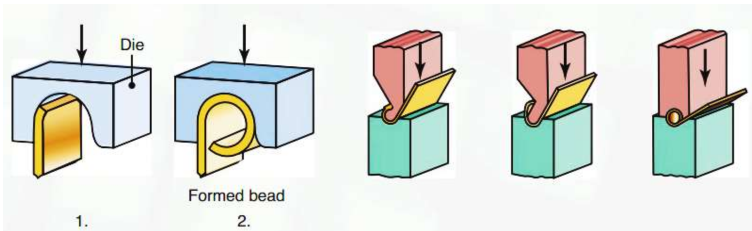
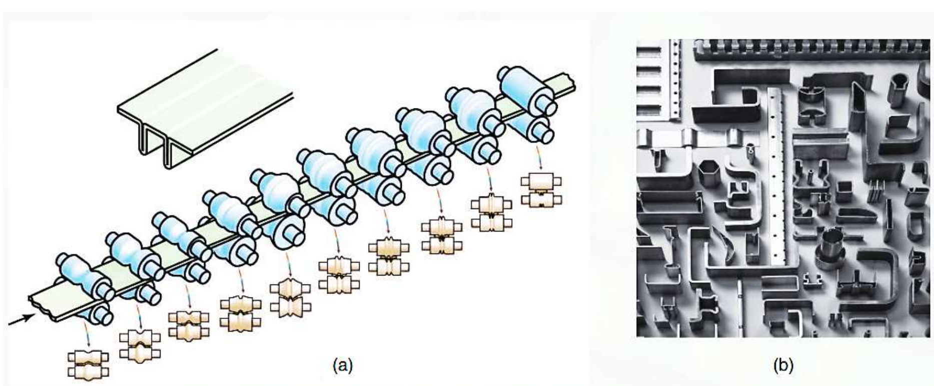
Other Bending Operations





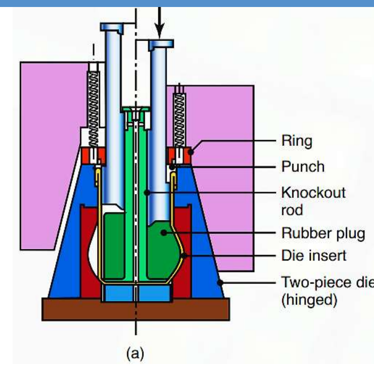
Roll Forming

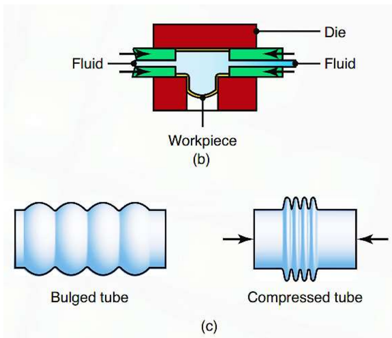
- Forms products similar to extrusion
- Higher equipment cost
- Joining processes need for closed hollow structures



Bulging

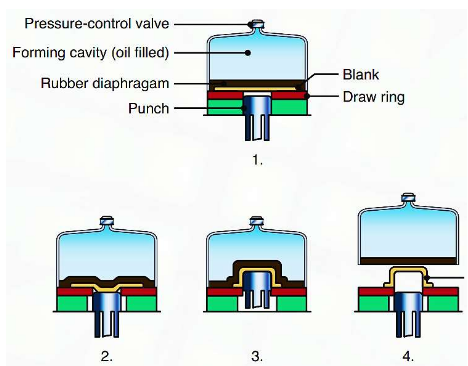
- Hydrostatic pressure used expand portions of a tube

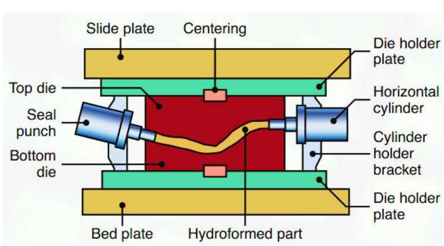




Hydroforming

- Hydrostatic pressure used to applied uniform forming forces on surface of complex workpart
- Extreme pressures!
  - ~30,000psi
  - E, t, r dependence

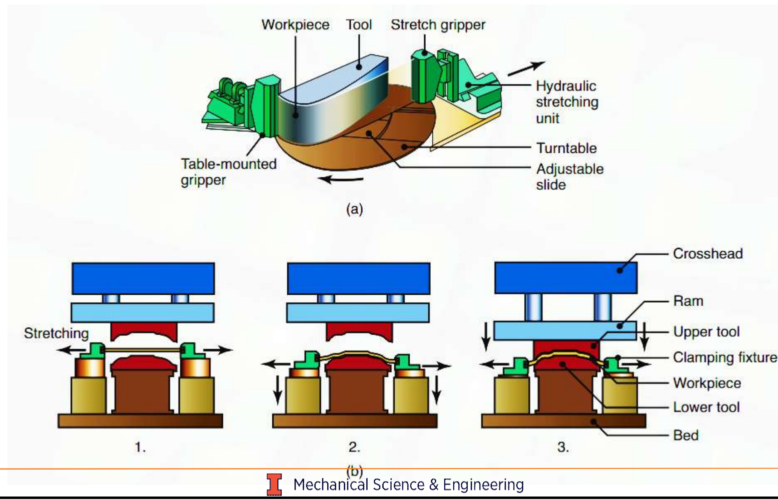




Stretch Forming

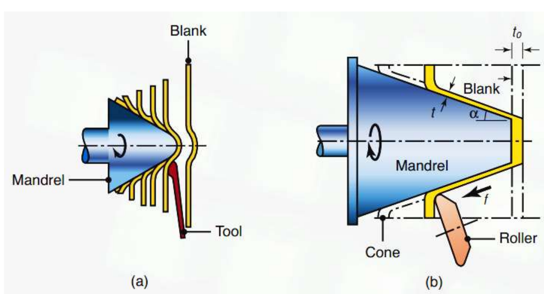
- Sheet stock is only stretch in one direction
- Stretch Force:

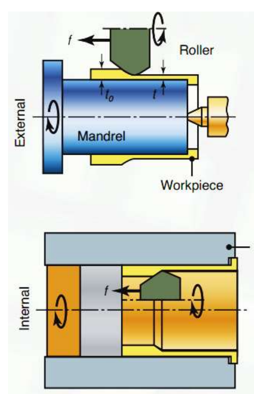
$$F = L \cdot t \cdot Y_f$$



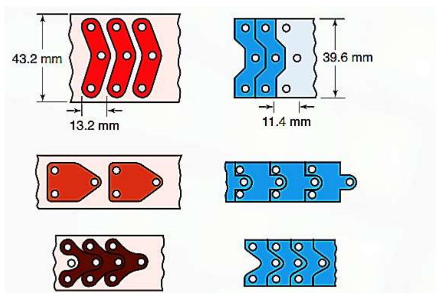
Metal Spinning Process

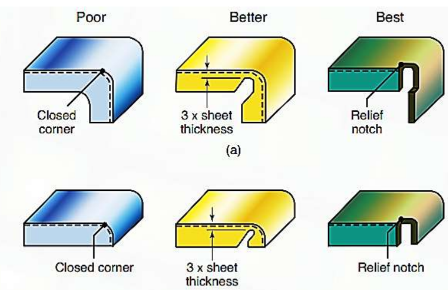
- Conv. Spinning v.s. shear spinning

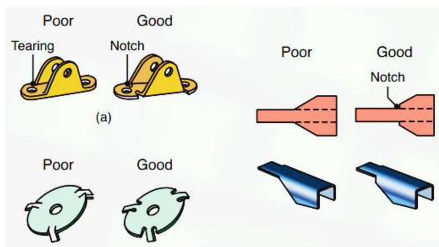


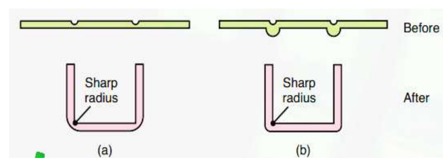


Design Considerations – Cutting/Bending









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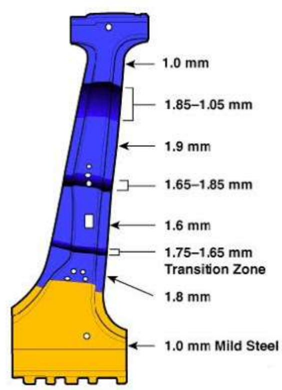
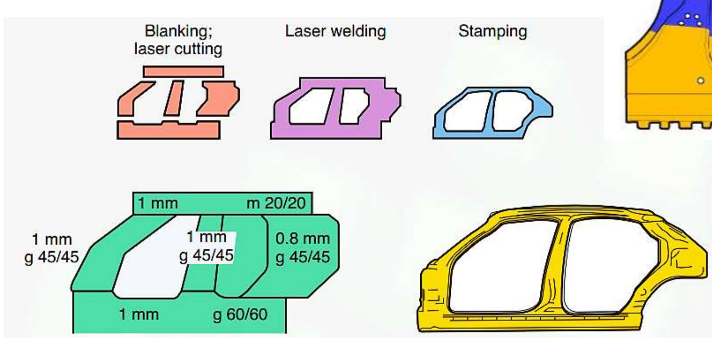
Combined Manufacturing – ex. Car Frames

- Laser cutting
- Laser welding
- Stamping, bending, and drawing
- Hydroforming





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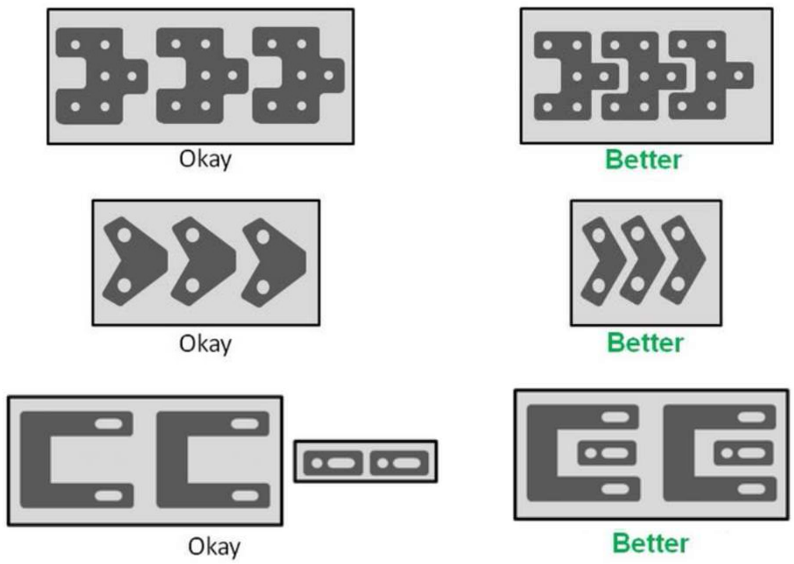
Design Advisor – Nesting Parts



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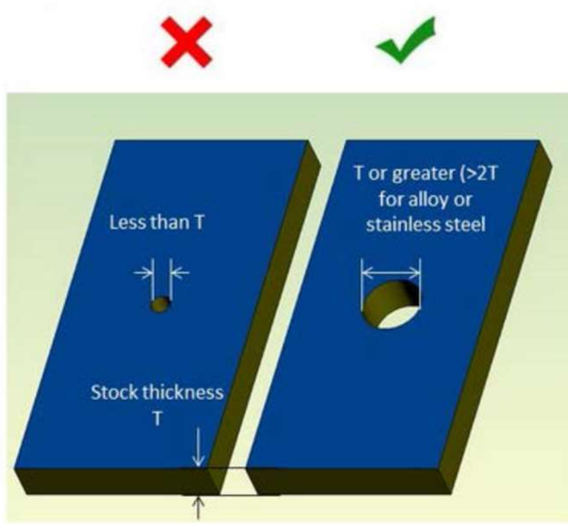
Design Advisor – Hole Size



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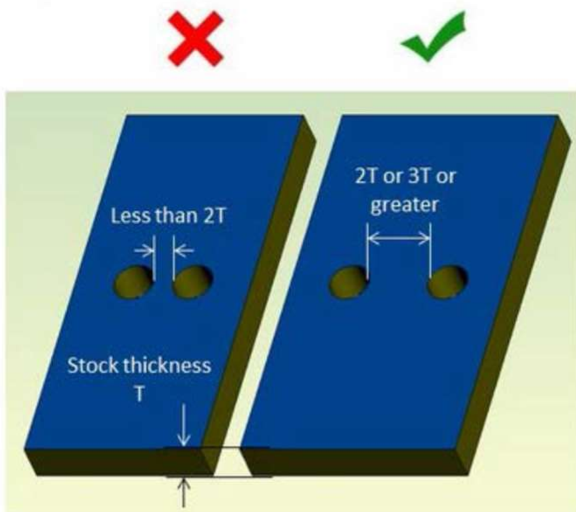
Design Advisor – Holes Together



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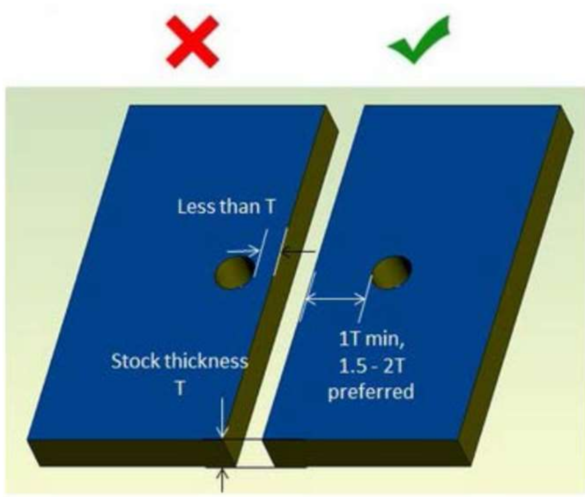
Design Advisor – Hole near Edge



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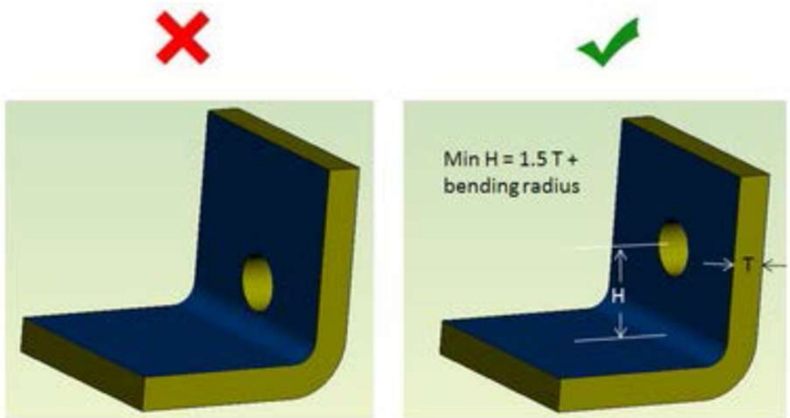
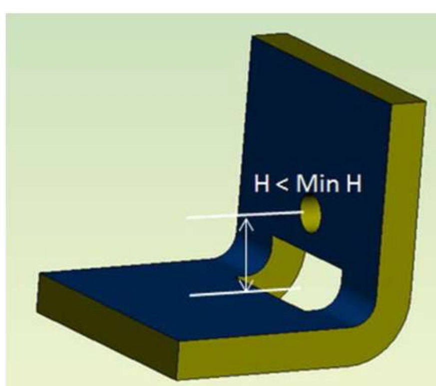
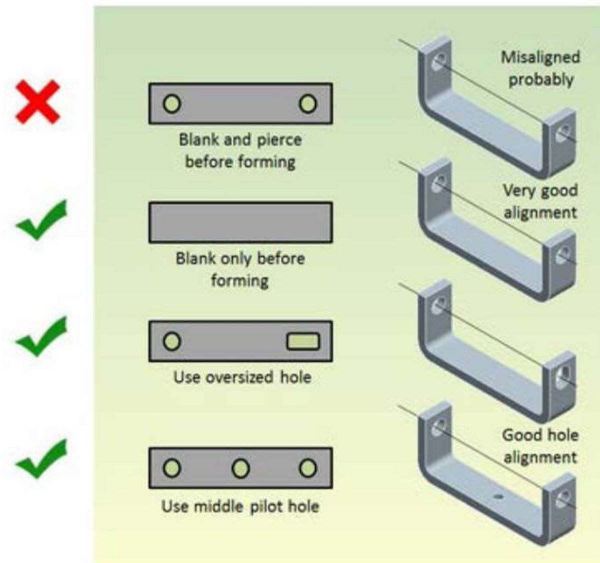
Design Advisor – Hole near Corner



Design Advisor – Hole Close to Bend



Design Advisor – Hole Alignment



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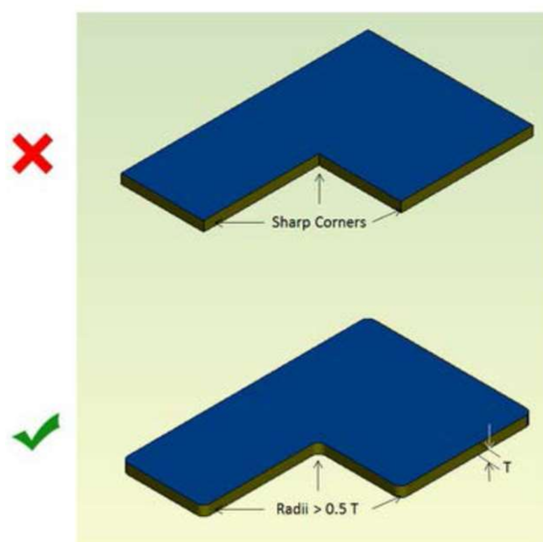
Design Advisor – Sharp Corners



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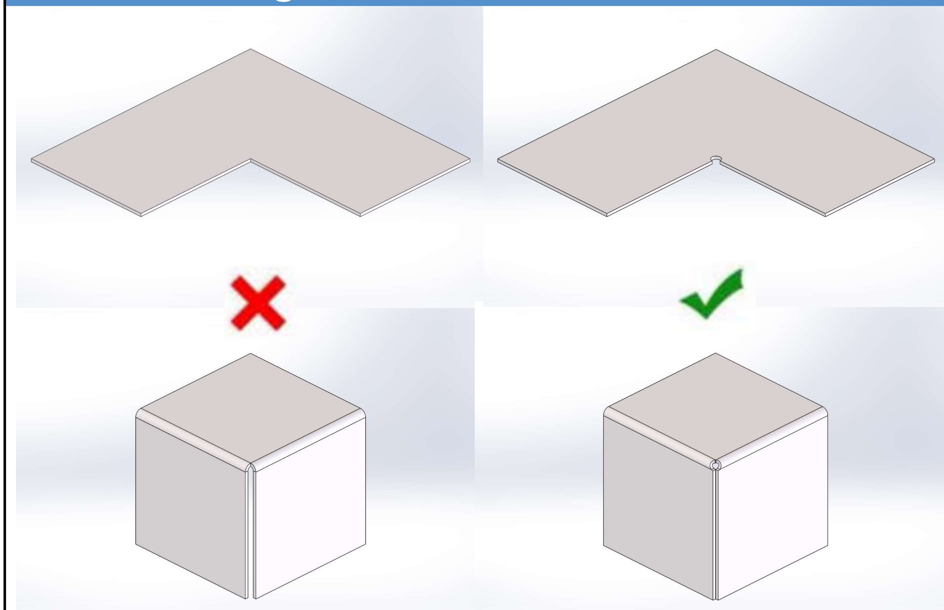
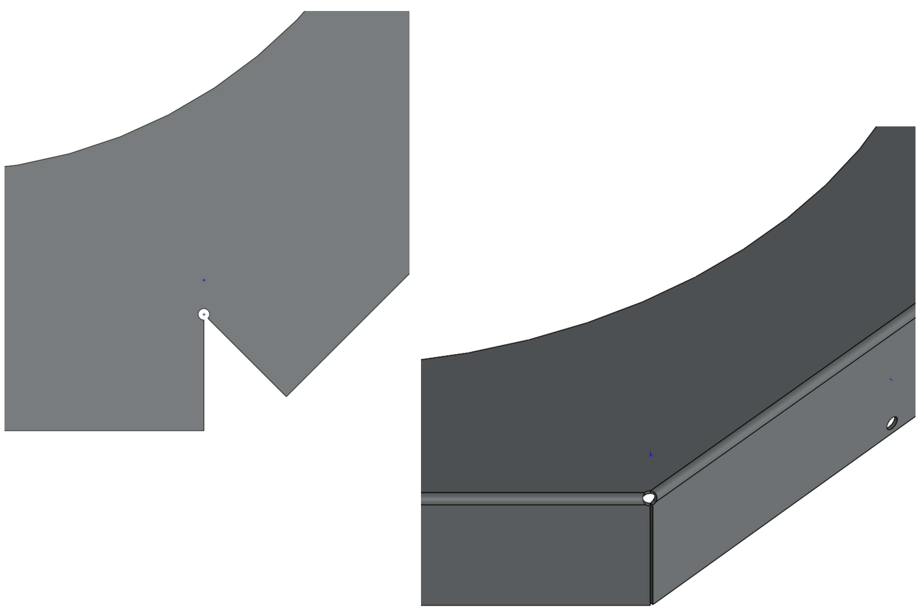
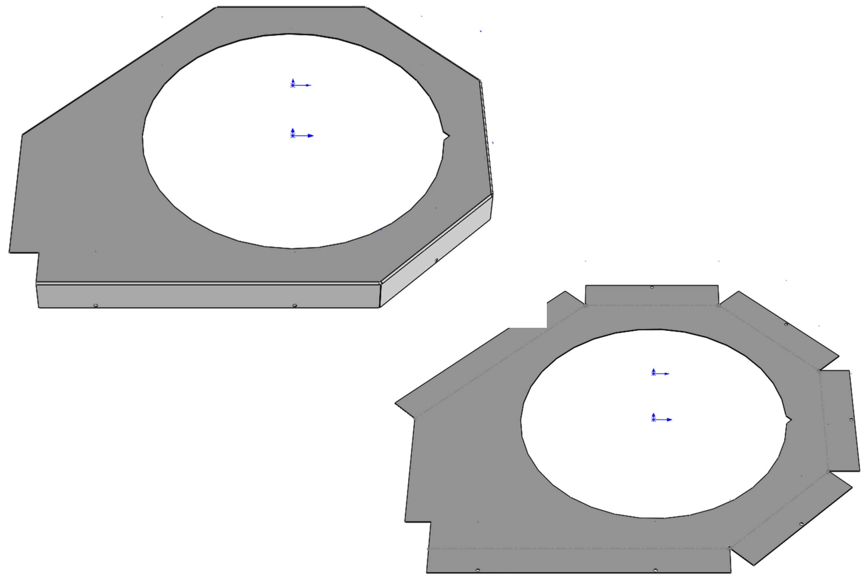
Design Advisor – Corner Relief



Design Advisor – Corner Relief



Design Advisor – Final Part



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ME 270
Design for Manufacturability

Timothy H. Lee, PhD
Professor Bruce Flachsbart

Fall 2021

Lecture 25: Metal Working

ME 270 – Chapters 4, 6 & 11

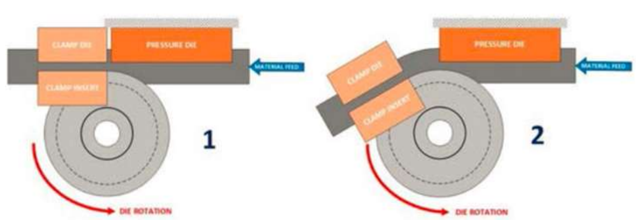
FUNDAMENTALS OF METAL FORMING AND FORGING

Metal Forming

- Plastic deformation to shape a metal workpiece using a tool, called a die, by applying a stress that exceeds the metal's:
- Compressive methods:
  - Forging, Extrusion
- Tensile method:
  - Drawing (wires and bars)
- Tensile and compressive method:
  - Bending, Rolling

Tube Bending

- Round (or square) tube stock can be bent to a limited radius depending on material
- A ball mandrel can be used to help prevent the tube from collapsing and create a tighter bend

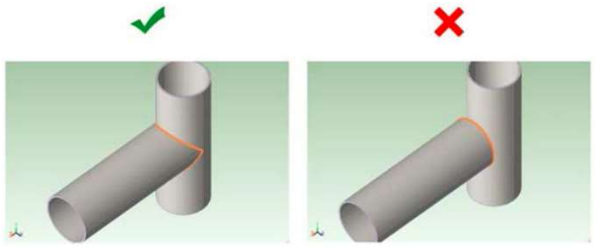


[aPriori Tube Bending video 1]

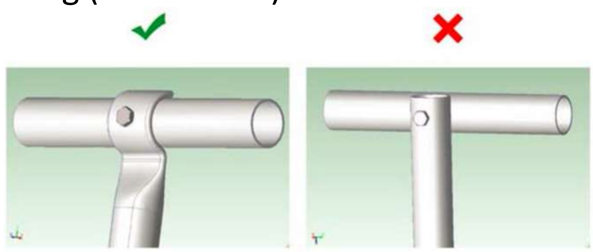
[aPriori Tube Bending video 2]

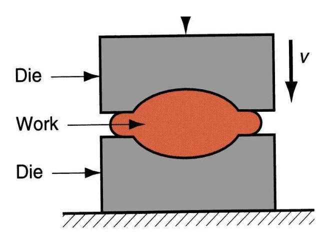
Tube Joining

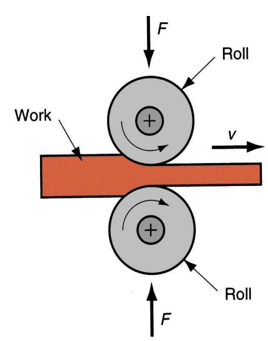
- Welding (most common)

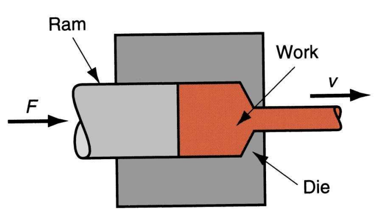


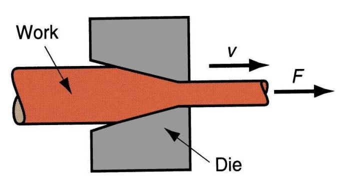
- Fastening (flatten first)



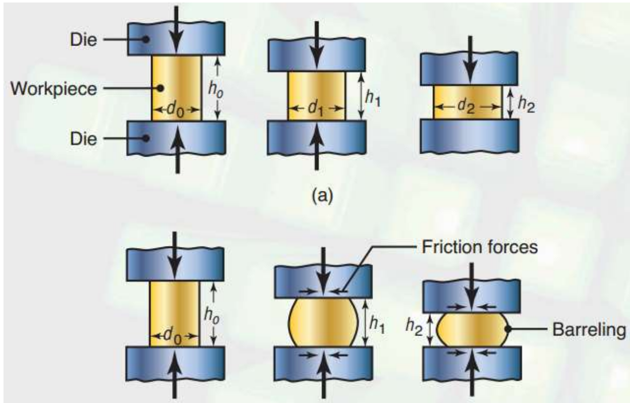


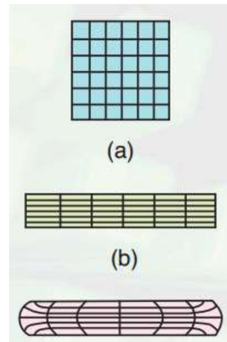






Upsetting (aka open die forging)

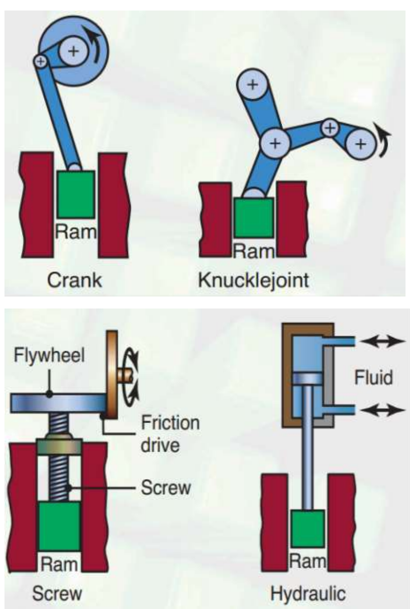




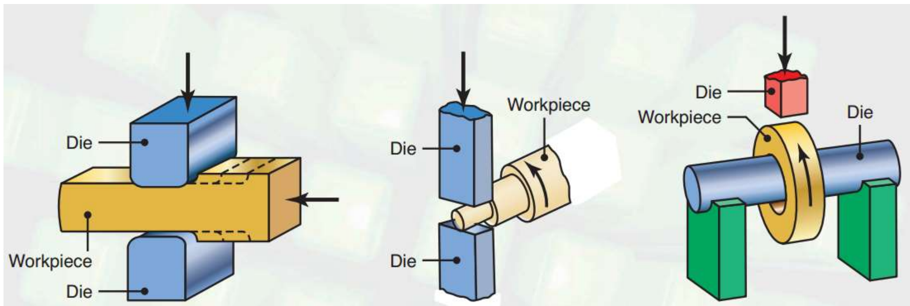
- Virtually any metal can be open die forged
- Shapes need to be simple
- Limited by the amount the material can plastically deform

[Open Die Forging Movie]

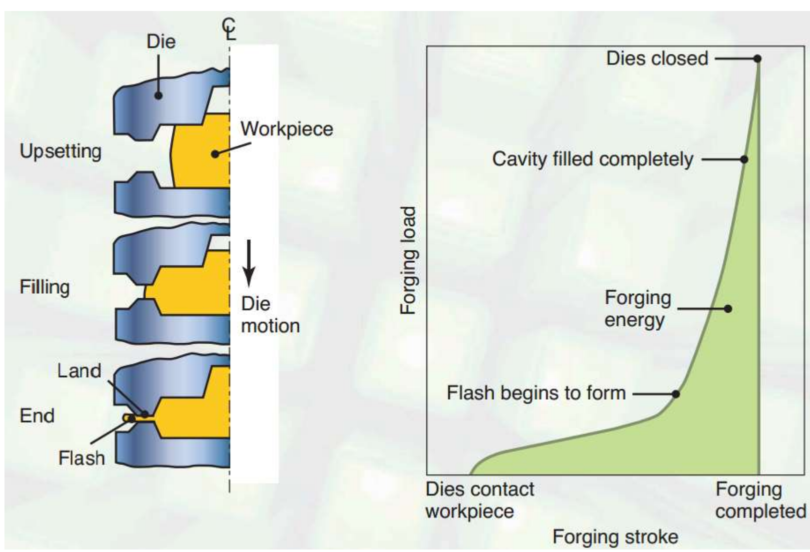
Forging Equipment



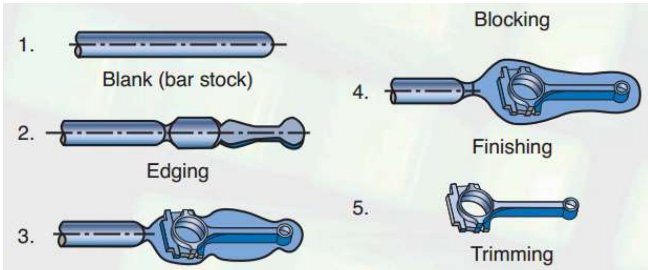
Circular Parts Open Die Forged: Swaging



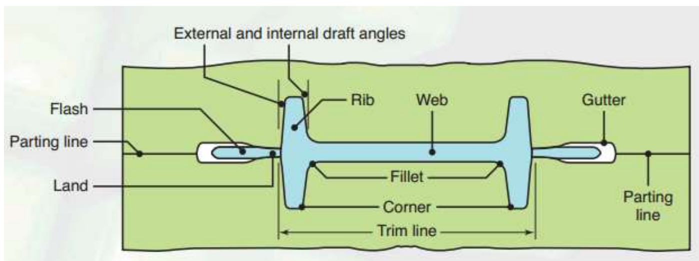
Impression Die Forging (aka closed-die)



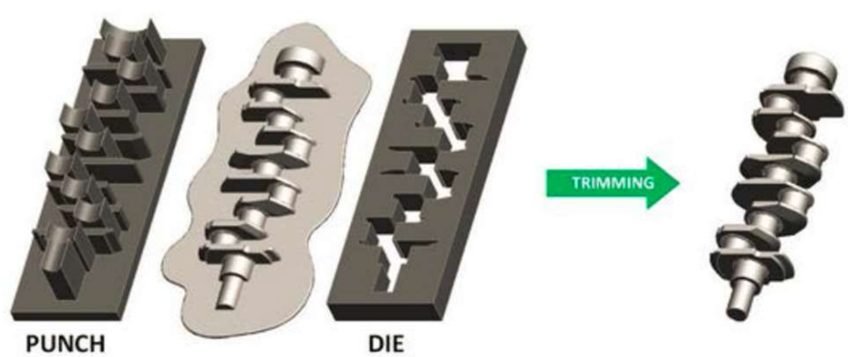
Multiple Forging Dies to make Part



[Impression Die Forging Movie]



Flash Trimming

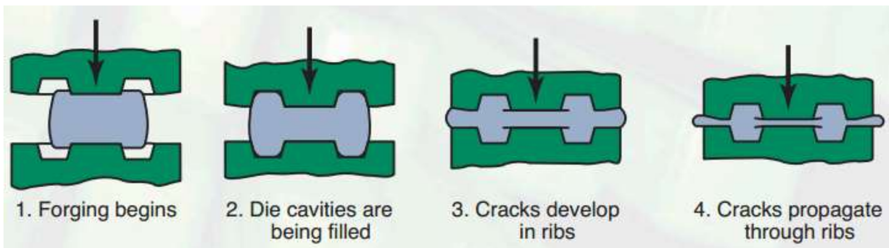


- Easier when workpart is still hot (less force needed)
- More precise when workpart has cooled

Impression Die Forging Defects

Oversized Starting Billet:

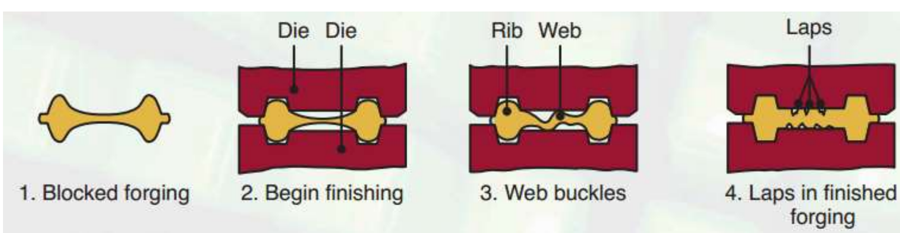
- cavities fill before flashing forms
- material flows from center without flashing there to creates cracks
- forging force could also be too high



Impression Die Forging Defects

Undersized Starting Billet:

- flashing forms before cavity center fills
- center region buckles.

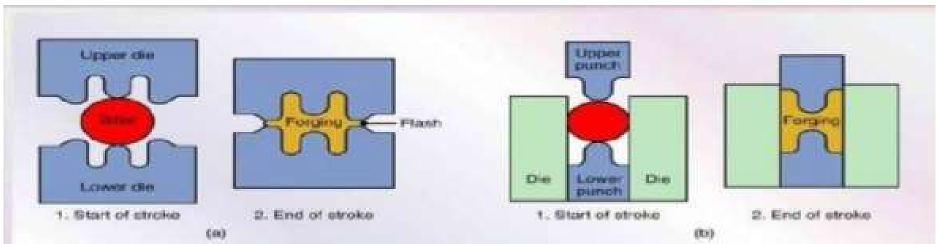


To avoid the most common forging defects:

- Limit material flow distance
- Time the flashing precisely
- Avoid sharp corners

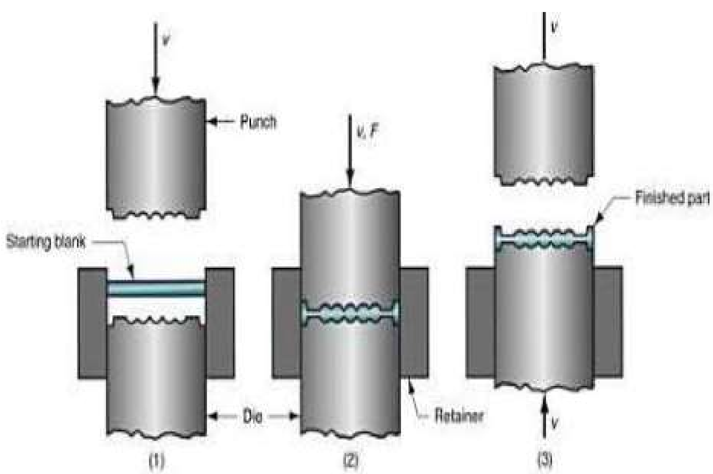
Flashless Forging

- Almost always carried out on a heated workpiece
- Higher pressures used and higher tolerances for the starting blank than impression die forging.
- Shapes must be simple



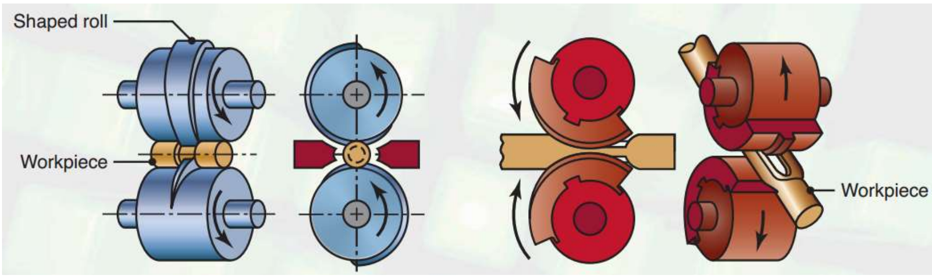
Flashless Forging: "Coining"

- Typically limited to a surface process (not bulk)



Roll Forging

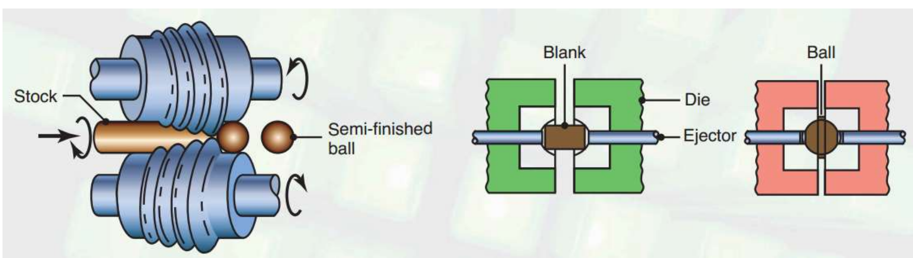
- Combination of rolling, forging, and piercing
- More complex "rolls" (aka the die) than simple rolling
- Less mechanical energy required than impression forging



[Roll Forging]

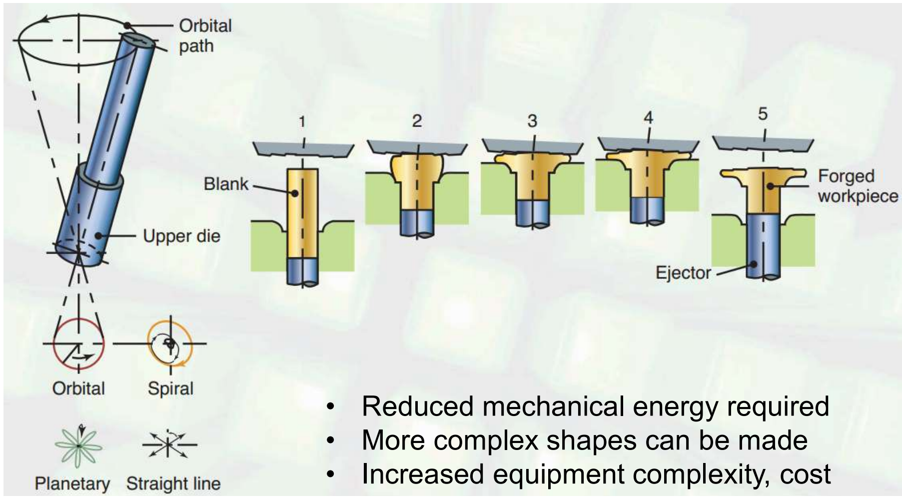
Ball Bearing Production

- Made by either Roll Forming or Die Forging and grinding



[How ball bearings are made]

Orbital-Forging

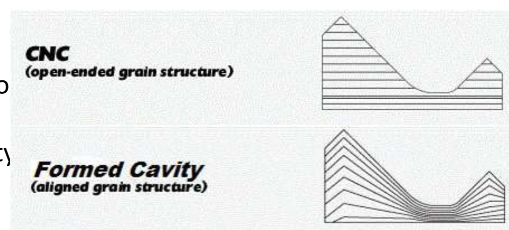


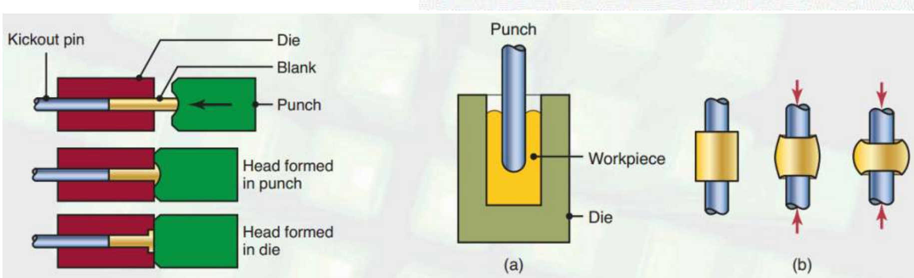
- Reduced mechanical energy required
- More complex shapes can be made
- Increased equipment complexity, cost

Heading and Piercing

Heading:
- Very common method for pro

Piercing (creating a hole or cavity
- Alternative to drilling



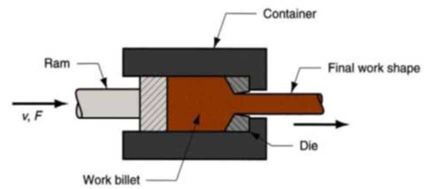


Bolt heading animation

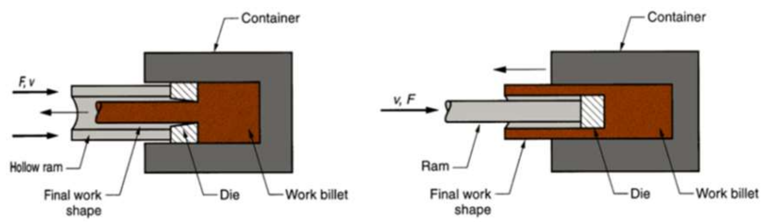
How bolts are made

Metal Extrusion

- Forward or "Direct" Extrusion (rods and bars only)



- Backward or "Indirect" Extrusion (tubes or solids)



Three Temperature Ranges

- Cold working:
  - Better accuracy, closer tolerances, directional properties
  - Due to strain hardening, strength and hardness are:
  - Metal may not be ductile enough for large deformations
  - Higher deformation forces and power
- Warm working: $T_{room} < T_{working} < T_{recrystalization}$
  - Lower forces and power than cold working
  - More intricate work geometries possible
- Hot Working: $T_{working} \geq T_{recrystalization}$
  - Larger deformations possible,
  - Lower dimensional accuracy, higher total energy required, poorer surface finish (work surface oxidized i.e.scale), shorter tool (die) life

ME 270
Design for Manufacturability

Timothy H. Lee, PhD
Professor Bruce Flachsbart

Fall 2021

Lecture 26 – Non-traditional Machining

ME 270 –Chapter 13

NONTRADITIONAL MACHINING PROCESSES

1. Mechanical Energy Processes (USM, WJC, AJM)

   - *high velocity stream of abrasives or fluid (or both)*

   - *example: Water Jet Cutting (WJC)*

2. Electrochemical Processes (ECM)

   - *reverse of electroplating*

3. Thermal Processes (EDM, Wire EDM, EBM, LBM, PAC)

   - *vaporizing of a small area of work surface*

   - *example:* Wire Electric Discharge Machining (*EDM)*

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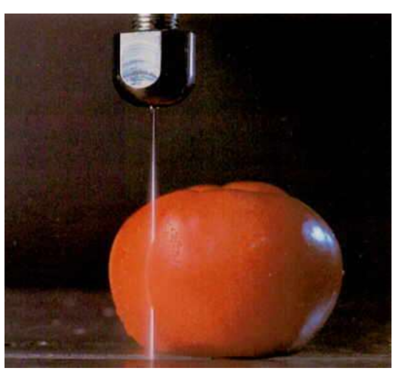
Nontraditional Processes Used When:

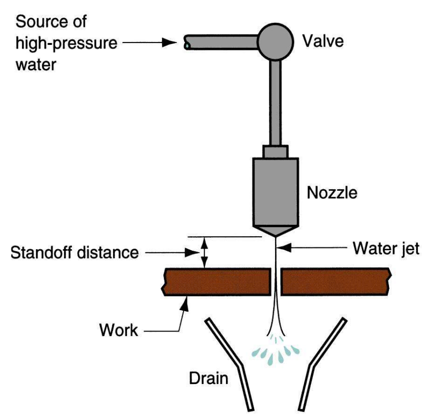
Nontraditional machining is characterized by material removal that:

1. Material is either very hard, brittle or both; or material is very ductile:
2. Part geometry is complex or geometric requirements impossible with conventional methods:
3. Need to avoid surface damage or contamination that often accompanies conventional machining:

1) Water Jet Cutting (WJC)

- Uses high pressure, high velocity stream of water directed at work surface for cutting





1) WJC Applications

- Usually automated using CNC or industrial robots
- Best used to cut narrow slits in flat stock such as: *plastic, textiles, composites, tile, and cardboard*
- Not suitable for:
- When used on metals, you need to add to the water stream:
- Smallest kerf width about 0.4 mm for metals, and 0.1mm for plastics and non-metals.
- More info: http://www.waterjets.org

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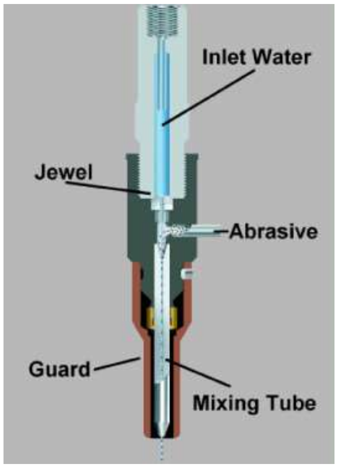
1) WJC Advantages

- No crushing or burning of work surface
- Minimum material loss
- No environmental pollution
- Ease of automation



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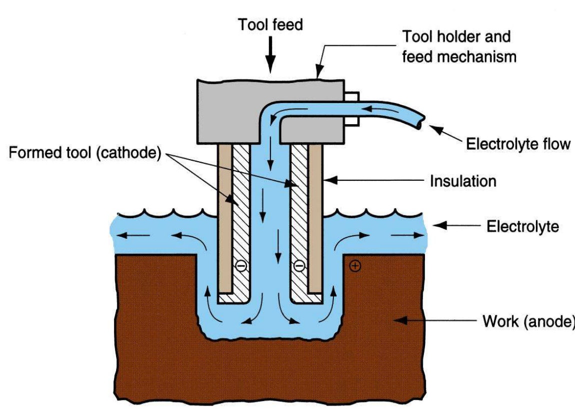
2) Electrochemical Machining Processes

- Electrical energy used in combination with chemical reactions to remove material
- Reverse of:
- Work material must be a:
- Feature dimensions down to about *10 μm*

Courtesy of AEG-Elotherm-Germany

2) Electrochemical Machining (ECM)

Material removal by anodic dissolution, using electrode (tool) in close proximity to work but separated by a rapidly flowing electrolyte



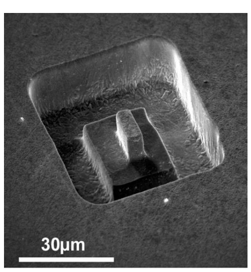
2) ECM Operation

Material is deplated from anode workpiece (*positive* pole) and transported to a cathode tool (*negative* pole) in an electrolyte bath

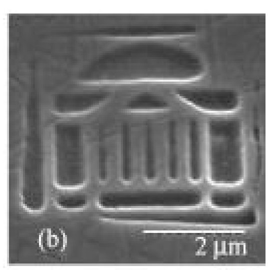
- Electrolyte flows rapidly between two poles to carry off deplated material, so it does not:
- Electrode materials: Cu, brass, or stainless steel
- Tool shape is the:
  - Tool size must allow for the gap

2) ECM Applications

- Die sinking - irregular shapes and contours for forging dies, plastic molds, and other tools
- Multiple hole drilling - many holes can be drilled simultaneously with ECM
- No burrs created – no residual stress



Schuster et al, Science 2000



Trimmer et al, APL 2003

Material Removal Rate of ECM

- Based on *Faraday's First Law*: rate of metal dissolved is proportional to the current

$$M_{RR} = Af_r = \eta CI$$

where I = current; A = *frontal area of the electrode (mm²),* f_r = *feed rate (mm/s), and η = efficiency coefficient*

$$C = \frac{M}{n\rho F}$$ = specific removal rate with work material;

M = atomic weight of metal (kg/mol)
ρ = density of metal (kg/m³),
F = Faraday constant (Coulomb)
n = valency of the ion;

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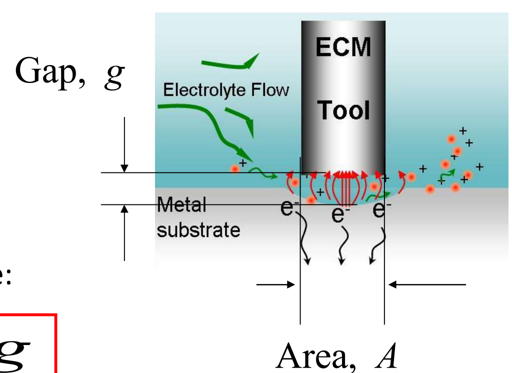
Equations for ECM



- Resistance of Electrode:

$$\boxed{R = r\frac{g}{A}}$$

r is the resistivity of the electrolyte fluid (Ohm·m)

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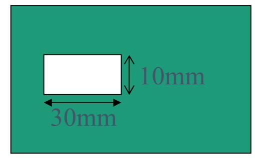
Example: ECM through a plate

Rectangular hole cut in 12 mm thick Al plate;

current I = 1200 amps, 95% efficiency,

$C_{Al} = 3.44\times10^{-2}$ mm^3/amp·s. How long?



3) Thermal Energy Processes - Overview

- Very high temperatures, but only:
  - Material is removed by:
- Problems and concerns:
  - Redeposition of vaporized metal
  - Surface damage and metallurgical damage to the new work surface
  - In some cases, resulting finish is so poor that subsequent processing is required

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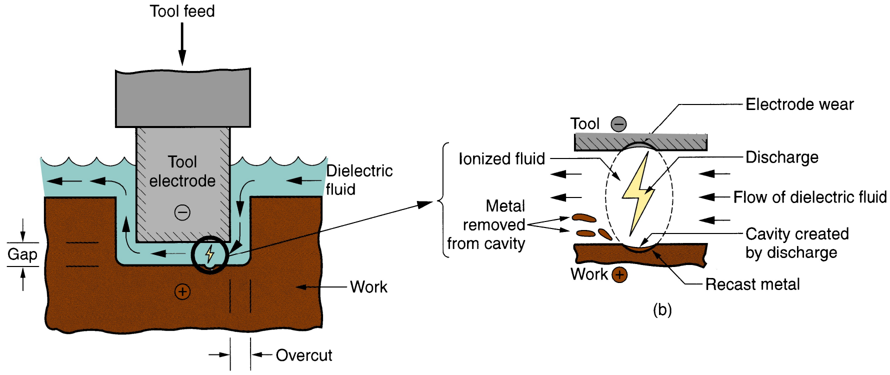
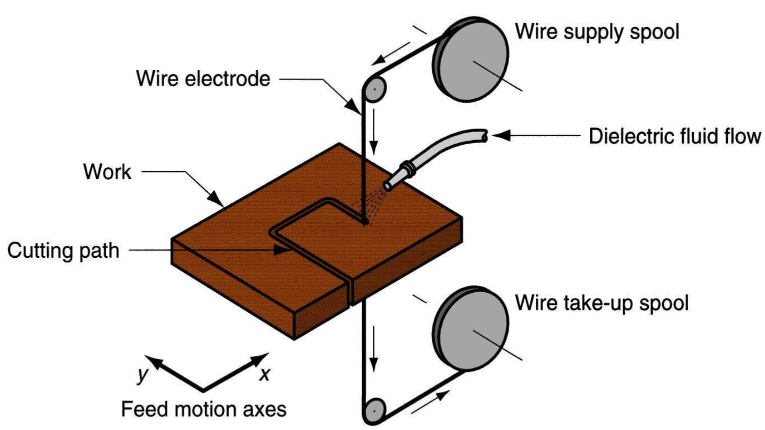
3) Electric Discharge Machining (EDM)



- One of the most widely used nontraditional processes
- Shape of finished work is inverse of tool shape
- Sparks occur across a small gap between tool and work
- Holes as small as 0.3mm can be made with feature sizes (radius etc.) down to ~2μm

3) Wire EDM

- EDM uses small diameter wire as electrode to cut a narrow kerf in work – similar to a:



3) Material Removal Rate of EDM

- Weller Equation (Empirical);

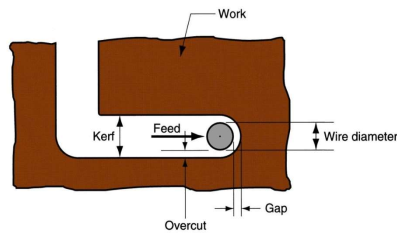
  Maximum rate: $M_{RR} = \frac{KI}{T_m^{1.23}}$

  where K = 664 (°C$^{1.23}$·mm^3/amp·s); I = discharge current; T_m = melt temp of work material **(°C)**

- Actual material removal rate:

  $$M_{RR} = v_f \cdot h \cdot w_{kerf}$$

  where v_f = feed rate; h = workpiece thickness; w_{kerf} = kerf width



While cutting, wire is continuously advanced between supply spool and take-up spool to:

3) Wire EDM Applications

- Ideal for stamp and die components
  - Since kerf is so narrow, it is often possible to fabricate punch and die in a single cut
- Other tools and parts with intricate outline shapes, such as lathe form tools, extrusion dies, and flat templates

UIUC-ZJU PARTNERSHIP

University of Illinois at Urbana-Champaign - Zhejiang University Partnership

ME 270
Design for Manufacturability

Timothy H. Lee, PhD
Professor Bruce Flachsbart

Fall 2021

Lecture 27 – Review and EDO

ME 270 – Lecture 15 – Review & EDO

What is Design for Manufacturability?

Ideation
- Brainstorming
- Creativity
- Group Organization
- Idea Refinement
- Design Process

Manufacturing
- aPriori
- RP
- Machining
- Casting
- Plastic Processing
- Composites
- Sheet Metalwork
- Forming & Forging

Optimization
- Metrology
- Quality Control
- DOE
- DFA
- Evolutionary Design Theory

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Why is "Team Project Learning" so Important?

- *Retention* of engineering knowledge and skills are much *better*.
- *Motivation* (and enjoyment) about engineering is *improved*.
- Seeing the usefulness & *application* of their knowledge base → students *value their education* more.

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Project Based Learning in Groups – Why?

- Companies are increasingly developing products and ***solving problems*** using "teams"
- Improve ***"soft" skills***: better at compromise, motivating others, dealing with failure, resolving disputes, etc.
- Improve ***"hard" engineering skills***: learn failure analysis, how to apply engineering concepts from classes, better understanding of trade-offs and limitation of various approaches, etc.

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Benefits of Group Work

- Improve creativity and work quality
- Learn to appreciate people from different disciplines and with different life experiences
- Learn how to have constructive dialog
- Increase motivation by drawing from the energy of team members
- Keeps you focused since you are accountable
- Build lasting friendships
- Better prepare you for the workplace

Groups increase productivity and fun!

Final Exam

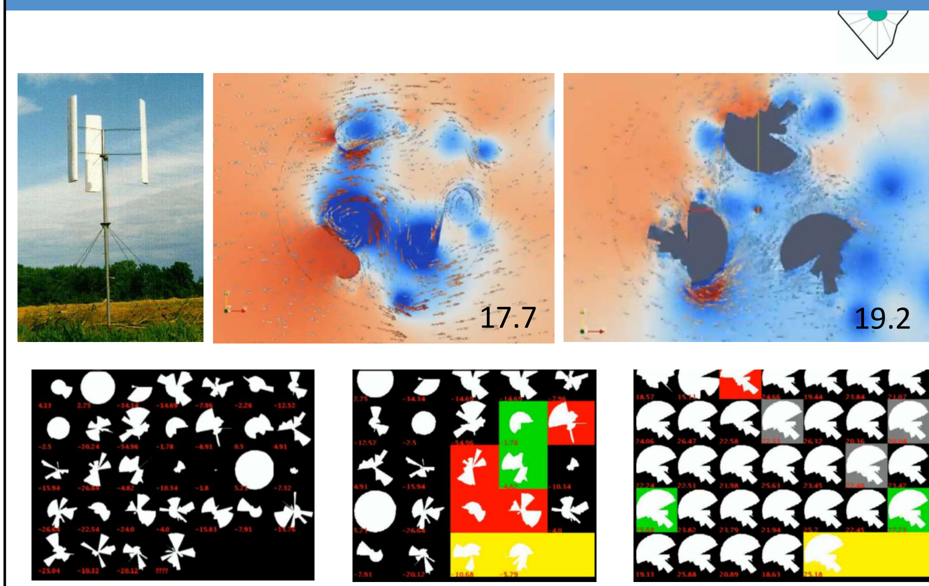
- Cumulative – worth 25% of your final grade
- Roughly equally covering all the material, about 2 hours long.
- Very similar to past homeworks – same format

Genetic Algorithm and Design Theory

Evolutionary Design Optimization (EDO):

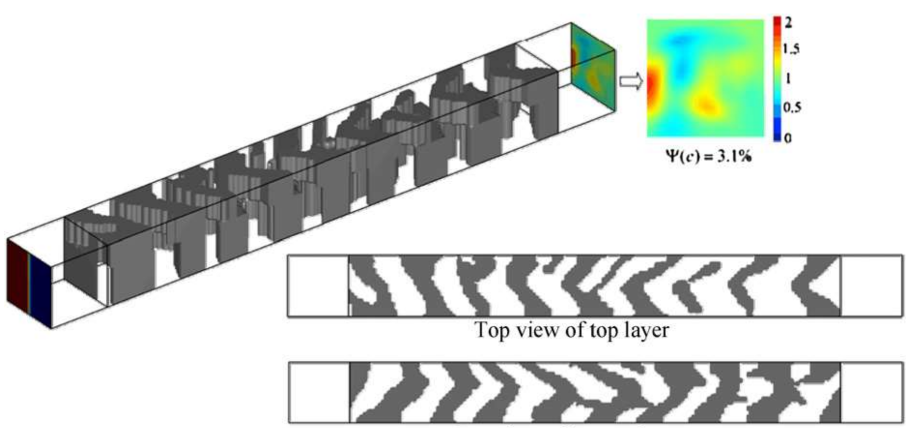
1. In a computer-world "**parent designs**" → "**mate**" and have →"**offspring**"
2. "**Survival**" of designs depends on **beating out** other designs based upon a selected computer **algorithm**

EDO a Better Wind Turbine?



http://www.youtube.com/watch?v=YZUNRmwoijw

Micromixer Design Example:

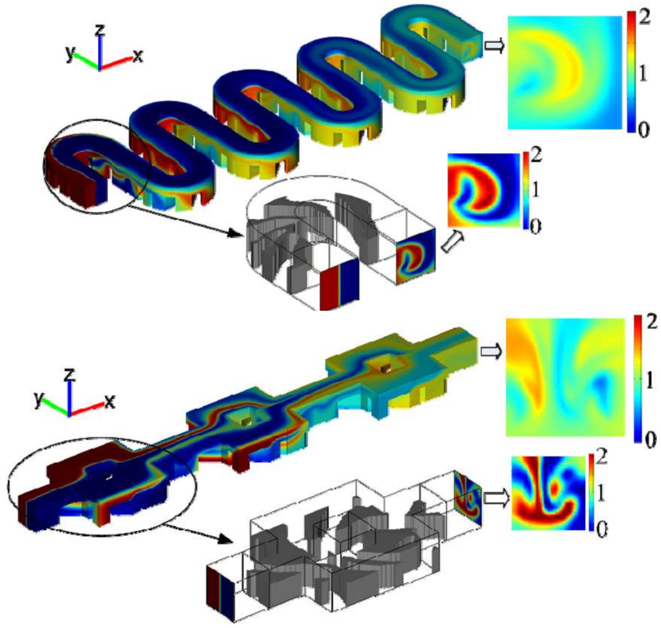


- Yongshun Liu, "Experimental investigation of passive micromixers conceptual design using the layout optimization method," J. Micromech. Microeng. 23 (2013)

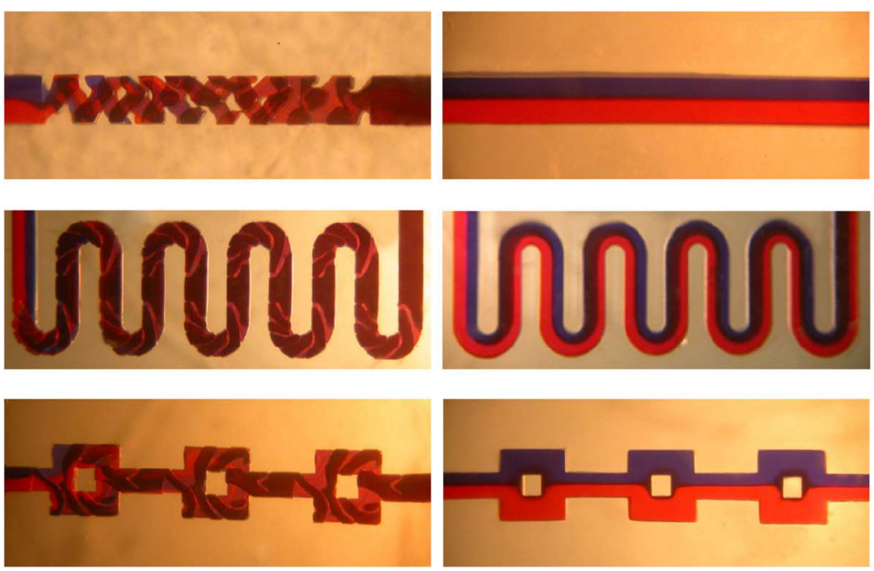
Micromixer

Just the bottom layer has a serpentine pattern:

Split and Combine mixer:

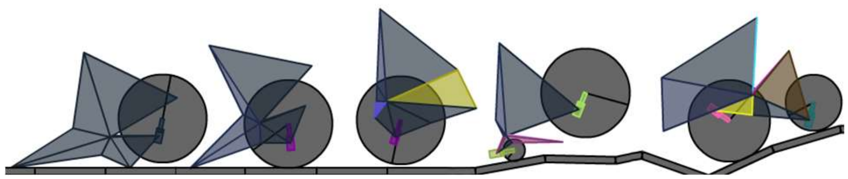


Mixer Results:



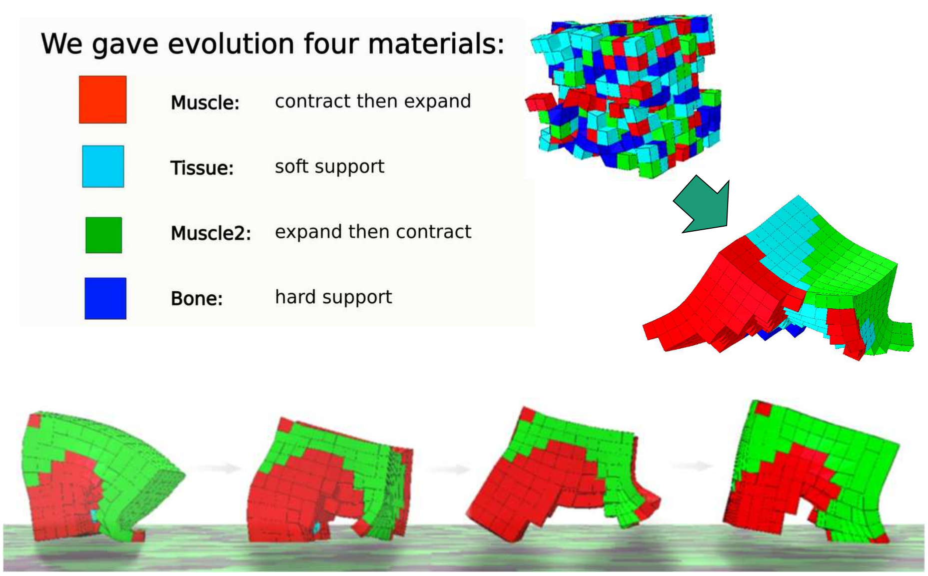
Designing a “Car” through Evolution?

- Starts with 20 randomly generated “car” shapes.
- Cars that go the furthest reproduce more offspring for the next generation.
- Car “bodies” are 8 randomly chosen vector lengths and directions.
- 1-3 random vectors have wheels (3 sizes)
- http://rednuht.org/genetic_cars_2/



http://boxcar2d.com/faq.html#a1.0

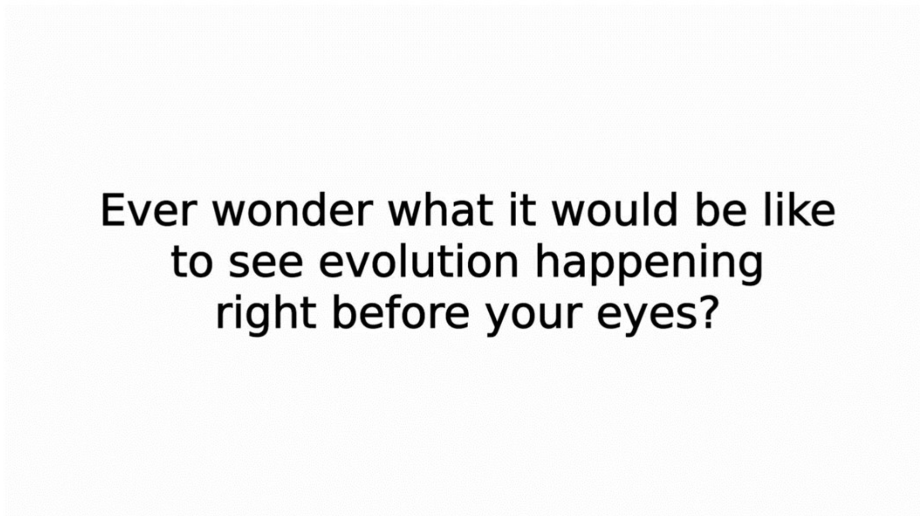
Evolution of Animal Locomotion?



Unshackling Evolution: Evolving Soft Robots with Multiple Materials Nick Cheney, Robert MacCurdy, Jeff Clune, Hod Lipson

Soft tissue locomotion

Soft tissue evolving locomotion



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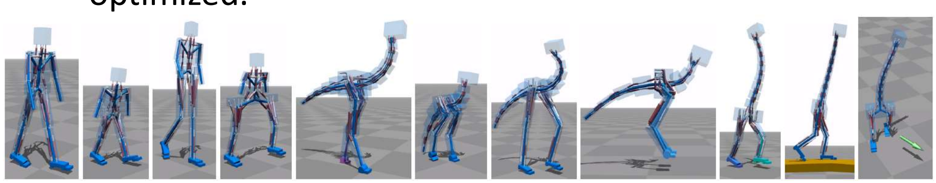
Simulated Bipedal Locomotion

- Both muscle routing and control parameters are optimized.



Longer version video:
https://www.youtube.com/watch?v=pgaEE27nsQw

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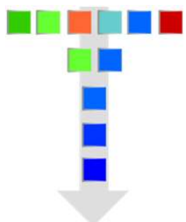
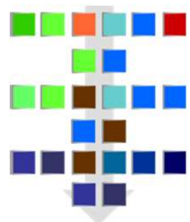
Evolutionary Design Optimization

Typical Design:



EDO:



- Process depends heavily on the computer program's ability to "model *reality* accurately"
- As computer models of 3D world get better so will EDO.