General Introduction

I.1 What Is Manufacturing?

As you begin to read this chapter, take a few moments to inspect various objects around you: mechanical pencil, light fixture, chair, cell phone, and computer. You soon will note that all these objects, and their numerous individual components, are made from a variety of materials and have been produced and assembled into the items that you now see. You also will note that some objects, such as a paper clip, nail, spoon, and door key, are made of a single component. However, as shown in Table I.1, the vast majority of objects around us consist of numerous individual pieces that are built and assembled by a combination of processes called **manufacturing**.

The word *manufacture* first appeared in English in 1567 and is derived from the Latin *manu factus*, meaning "made by hand." The word *manufacturing* first appeared in 1683, and the word *production*, which is often used interchangeably with the word *manufacturing*, first appeared sometime during the 15th century.

Manufacturing is concerned with making products. A manufactured product may itself be used to make other products, such as (a) a large press, to shape flat sheet metal into automobile bodies, (b) a drill, for producing holes, (c) industrial sawing machines, for making clothing at high rates, and (d) numerous pieces of machinery, to produce an endless variety of individual items, ranging from thin wire for guitars and electric motors to crankshafts and connecting rods for automotive engines (Fig. I.1).

Note that items such as bolts, nuts, and paper clips are *discrete products*, meaning individual items. By contrast, a roll of aluminum foil, a spool of wire, and metal or plastic tubing are *continuous products*, which are then cut into individual pieces of various lengths for specific purposes.

Because a manufactured item typically starts with raw materials, which are then subjected to a sequence of processes to make individual products, it has a certain *value*. For example, clay has some value as mined, but when it is made into a product such as cookware, pottery, an electrical insulator, or a cutting tool, value is *added* to the clay. Similarly, a nail has a value over and above the cost of the short piece of wire or rod from which it is made. Products such as computer chips, electric motors, and professional athletic shoes are known as *high-value-added* products.

A Brief History of Manufacturing. Manufacturing dates back to the period 5000–4000 B.C. (Table I.2), and thus, it is older than recorded history, the earliest forms of which were invented by the Sumerians around 3500 B.C. Primitive cave

TABLE I.1

Approximate Number of Parts in Products	
Common pencil	4
Rotary lawn mower	300
Grand piano	12,000
Automobile	15,000
Boeing 747–400	6,000,000

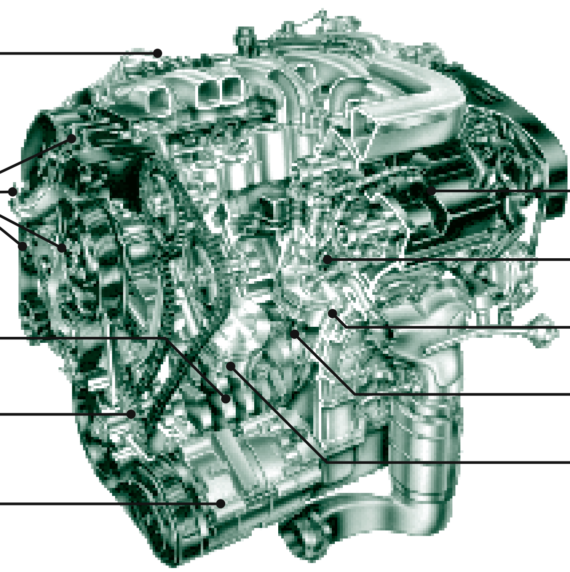


FIGURE I.1 Illustration of an automotive engine (the Duratec V-6), showing various components and the materials used in making them. *Source*: Courtesy of Ford Motor Company. Illustration by D. Kimball.

drawings, as well as markings on clay tablets and stone, needed (1) some form of a brush and some sort of "paint," as in the prehistoric *cave paintings* in Lascaux, France, estimated to be 16,000 years old; (2) some means of scratching the clay tablets and baking them, as in *cuneiform scripts* and *pictograms* of 3000 B.C.; and (3) simple tools for making incisions and carvings on the surfaces of stone, as in the *hieroglyphs* in ancient Egypt.

The manufacture of items for specific uses began with the production of various household artifacts, which were typically made of either wood, stone, or metal. The materials first used in making utensils and ornamental objects included gold, copper, and iron, followed by silver, lead, tin, bronze (an alloy of copper and tin), and brass (an alloy of copper and zinc). The processing methods first employed involved mostly *casting* and *hammering*, because they were relatively easy to perform. Over the centuries, these simple processes gradually began to be developed into more and more complex operations, at increasing rates of production and higher levels of product quality. Note, for example, from Table I.2 that lathes for cutting screw threads already were available during the period from 1600 to 1700, but it was not until some three centuries later that automatic screw machines were developed.

TABLE I.2

Historical Development of Materials, Tools, and Manufacturing Processes

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining, and manufacturing systems
	Before 4000 B.C.	Gold, copper, meteoric iron	Earthenware, glazing, natural fibers	Hammering		Tools of stone, flint, wood, bone, ivory, composite tools
	4000–3000 B.C.	Copper casting, stone and metal molds, lost-wax process, silver, lead, tin, bronze		Stamping, jewelry	Soldering (Cu–Au, Cu–Pb, Pb–Sn)	Corundum (alumina, emery)
Egypt: ~3100 B.C. to ~300 B.C.	3000–2000 B.C.	Bronze casting and drawing, gold leaf	Glass beads, potter's wheel, glass vessels	Wire by slitting sheet metal	Riveting, brazing	Hoe making, hammered axes, tools for ironmaking and carpentry
	2000–1000 B.C.	Wrought iron, brass				
Greece: ~1100 B.C. to 146 B.C.; Roman Empire: ~500 B.C. to 476 A.D.	1000–1 B.C.	Cast iron, cast steel	Glass pressing and blowing	Stamping of coins	Forge welding of iron and steel, gluing	Improved chisels, saws, files, woodworking lathes
Middle Ages: ~476 to 1492	1–1000 A.D.	Zinc, steel	Venetian glass	Armor, coining, forging, steel swords		Etching of armor
	1000–1500	Blast furnace, type metals, casting of bells, pewter	Crystal glass	Wire drawing, gold- and silversmith work		Sandpaper, windmill driven saw
Renaissance: 14th to 16th centuries	1500–1600	Cast-iron cannon, tinplate	Cast plate glass, flint glass	Waterpower for metalworking, rolling mill for coinage strips		Hand lathe for wood
	1600–1700	Permanent-mold casting, brass from copper and metallic zinc	Porcelain	Rolling (lead, gold, silver), shape rolling (lead)		Boring, turning, screw-cutting lathe, drill press

(*continued*)

TABLE I.2 *(continued)*

Historical Development of Materials, Tools, and Manufacturing Processes

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining, and manufacturing systems
	1700–1800	Malleable cast iron, crucible steel (iron bars and rods)		Extrusion (lead pipe), deep drawing, rolling		
First Industrial Revolution: ~1780 to 1850	1800–1900	Centrifugal casting, Bessemer process, electrolytic aluminum, nickel steels, babbitt, galvanized steel, powder metallurgy, open-hearth steel	Window glass from slit cylinder, light bulb, vulcanization, rubber processing, polyester, styrene, celluloid, rubber extrusion, molding	Steam hammer, steel rolling, seamless tube, steel-rail rolling, continuous rolling, electroplating		Shaping, milling, copying lathe for gunstocks, turret lathe, universal milling machine, vitrified grinding wheel
WWI	1900–1920		Automatic bottle making, bakelite, borosilicate glass	Tube rolling, hot extrusion	Oxyacetylene; arc, electrical-resistance, and thermit welding	Geared lathe, automatic screw machine, hobbing, high-speed-steel tools, aluminum oxide and silicon carbide (synthetic)
	1920–1940	Die casting	Development of plastics, casting, molding, polyvinyl chloride, cellulose acetate, polyethylene, glass fibers	Tungsten wire from metal powder	Coated electrodes	Tungsten carbide, mass production, transfer machines
WWII	1940–1950	Lost-wax process for engineering parts	Acrylics, synthetic rubber, epoxies, photosensitive glass	Extrusion (steel), swaging, powder metals for engineering parts	Submerged arc welding	Phosphate conversion coatings, total quality control
Second Industrial Revolution: 1947–	1950–1960	Ceramic mold, nodular iron, semiconductors, continuous casting	Acrylonitrile-butadiene-styrene, silicones, fluorocarbons, polyurethane, float glass, tempered glass, glass ceramics	Cold extrusion (steel), explosive forming, thermomechanical processing	Gas metal arc, gas tungsten arc, and electroslag welding; explosion welding	Electrical and chemical machining, automatic control

TABLE I.2

Historical Development of Materials, Tools, and Manufacturing Processes

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining, and manufacturing systems
Space age	1960–1970	Squeeze casting, single-crystal turbine blades	Acetals, polycarbonate, cold forming of plastics, reinforced plastics, filament winding	Hydroforming, hydrostatic extrusion, electroforming	Plasma-arc and electron-beam welding, adhesive bonding	Titanium carbide, synthetic diamond, numerical control, integrated circuit chip
	1970–1990	Compacted graphite, vacuum casting, organically bonded sand, automation of molding and pouring, rapid solidification, metal-matrix composites, semisolid metalworking, amorphous metals, shape-memory alloys (smart materials), computer simulation	Adhesives, composite materials, semiconductors, optical fibers, structural ceramics, ceramic-matrix composites, biodegradable plastics, electrically conducting polymers	Precision forging, isothermal forging, superplastic forming, dies made by computer-aided design and manufacturing, net-shape forging and forming, computer simulation	Laser beam, diffusion bonding (also combined with superplastic forming), surface-mount soldering	Cubic boron nitride, coated tools, diamond turning, ultraprecision machining, computer-integrated manufacturing, industrial robots, machining and turning centers, flexible-manufacturing systems, sensor technology, automated inspection, expert systems, artificial intelligence, computer simulation and optimization
Information age	1990–2000s	Rheocasting, computer-aided design of molds and dies, rapid tooling, TRIP and TWIP steels	Nanophase materials, metal foams, advanced coatings, high-temperature superconductors. machinable ceramics, diamondlike carbon, carbon nanotubes	Rapid prototyping, rapid tooling, environmentally friendly metalworking fluids	Friction stir welding, lead-free solders, laser butt-welded (tailored) sheet-metal blanks, electrically conducting adhesives	Micro- and nano fabrication, LIGA (a German acronym for a process involving lithography, electroplating, and molding), dry etching, linear motor drives, artificial neural networks, six sigma, three-dimensional computer chips

Source: J.A. Schey, C.S. Smith, R.F. Tylecote, T.K. Derry, T.I. Williams, S.R. Schmid, and S. Kalpakjian.

Although ironmaking began in the Middle East in about 1100 B.C., a major milestone was the production of steel in Asia during the period 600–800 A.D. A wide variety of materials continually began to be developed. Today, countless metallic and nonmetallic materials with unique properties are available, including *engineered materials* and various advanced materials. Among the available materials are industrial or high-tech ceramics, reinforced plastics, composite materials, and nanomaterials that are now used in an extensive variety of products, ranging from prosthetic devices and computers to supersonic aircraft.

Until the **Industrial Revolution**, which began in England in the 1750s and is also called the *First Industrial Revolution*, goods had been produced in *batches* and required much reliance on manual labor in all phases of their production. The *Second Industrial Revolution* is regarded by some as having begun in the mid-1900s with the development of solid-state electronic devices and computers (Table I.2). **Mechanization** began in England and other countries of Europe, basically with the development of textile machinery and machine tools for cutting metal. This technology soon moved to the United States, where it continued to be further developed.

A major advance in manufacturing occurred in the early 1800s with the design, production, and use of **interchangeable parts**, conceived by the American manufacturer and inventor Eli Whitney (1765–1825). Prior to the introduction of interchangeable parts, much hand fitting was necessary because no two parts could be made exactly alike. By contrast, it is now taken for granted that a broken bolt can easily be replaced with an identical one produced decades after the original. Further developments soon followed, resulting in countless consumer and industrial products that we now cannot imagine being without.

Beginning in the early 1940s, several milestones were reached in all aspects of manufacturing, as can be observed by a detailed review of Table I.2. Note particularly the progress that has been made during the 20th century, compared with that achieved during the 40-century period from 4000 B.C. to 1 B.C.

For example, in the Roman Empire (~500 B.C. to 476 A.D.), factories were available for the mass production of glassware; however, the methods used were generally very slow, and much manpower was involved in handling the parts and operating the machinery. Today, production methods have advanced to such an extent that (a) aluminum beverage cans are made at rates of more than 500 per minute, with each can costing about four cents to make, (b) holes in sheet metal are punched at rates of 800 holes per minute, and (c) incandescent light bulbs are made at rates of more than 2000 bulbs per minute (see Example I.1), each costing less than one dollar.

EXAMPLE I.1 Incandescent Light Bulbs

The first incandescent lamp was made by T.A. Edison (1847–1931) in New Jersey and was first lit in 1879. A typical bulb then had a life of only about 13.5 hours. Numerous improvements have since been made in both materials and production methods for making light bulbs, with the main purposes being increasing their life and reducing production costs. This example briefly describes the typical sequence of methods used in manufacturing incandescent light bulbs.

The basic components of an incandescent (meaning "glowing with heat") light bulb are shown in Fig. I.2a. The light-emitting component is the filament, which, by the passage of current and due to its electrical resistance, is heated to incandescence to a temperature of 2200°–3000°C (4000°–5400°F). Edison's first successful lamp had a carbon filament, although he and others also had experimented with carbonized paper and metals such as osmium, iridium,

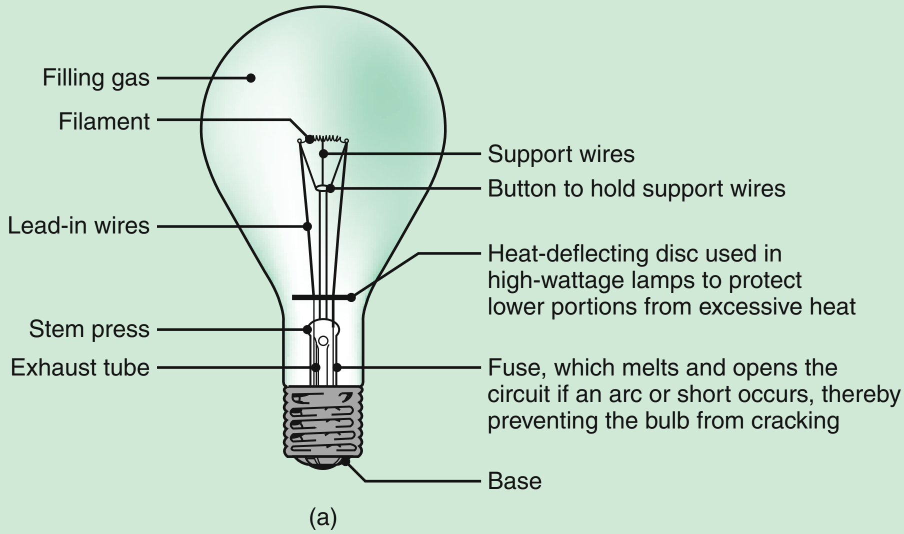


FIGURE I.2a Components of a common incandescent light bulb. *Source*: Courtesy of General Electric Company.

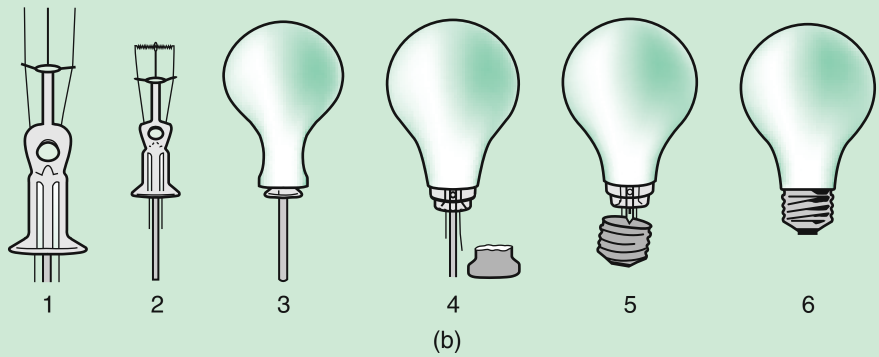


FIGURE I.2b Manufacturing steps in making an incandescent light bulb. *Source*: Courtesy of General Electric Company.

and tantalum. However, none of these materials has the strength, resistance to high temperature, and long life as has tungsten (Section 16.8), which is now the most commonly used filament material.

The first step in manufacturing a light bulb is making the glass stem that supports the lead-in wires and the filament and connects them to the base of the bulb (Fig. I.2b). All these components are positioned, assembled, and sealed while the glass is heated by gas flames. The filament is then attached to the lead-in wires. The filament is made by powder metallurgy techniques (Chapter 17), which involves first pressing tungsten powder into ingots and sintering it (heating it without its melting). Next, the ingot is shaped into round rods by rotary swaging (Section 14.4) and then drawing it through a set of dies into thin wire (Sections 15.8 and 15.10). The wire diameter for a 60-W, 120-V bulb is 0.045 mm (0.0018 in.). The diameter must be controlled precisely, because if it is only 1% less than the diameter specified, the life of the bulb would be reduced by as much as 25% (because of the increased heat due to the higher electrical resistance of the wire).

Note from Fig. I.2a, as well as by direct obsevation of a clear light bulb, that the filament wire is coiled; this is done in order to increase the light-producing capacity of the filament. The spacing between the coils must be precise, so as to prevent a localized buildup of heat that might short the filament during its use.

The completed stem assembly (called the *mount*) is transferred to a machine that lowers a glass bulb over the mount. Gas flames are used to seal the rim of the mount to the neck of the bulb. The air in the bulb is then exhausted through the exhaust tube (which is an integral part of the glass stem), and the bulb is either evacuated or filled with inert gas. For 40-W bulbs and higher, the gas used is typically a mixture of nitrogen and argon. The exhaust tube is then sealed. The filling gas must be pure, as otherwise the inside surfaces of the bulb will blacken. It has been observed that just one drop of water in the gas that is used for half a million bulbs will cause blackening in all of them.

The next step involves attaching the metal base to the glass bulb with a special cement. The machine that performs this operation also solders or welds the lead-in wires to the base, to provide the electrical connection. The lead-in wires are usually made of nickel, copper, or molybdenum, and the support wires are made of molybdenum (Section 6.8). The portion of the lead-in wire that is embedded in the stem is made from an iron–nickel alloy, which has essentially the same coefficient of thermal expansion as that of the glass (Table 3.1), as otherwise the thermal stresses that develop may cause cracking of the glass stem. The bulb base is generally made from aluminum, replacing the more expensive brass base that was used many years ago. To reduce friction and thus allow easy insertion of the bulb into a socket, the metal base is coated with a special compound.

Several types of glasses (Section 8.4) are used, depending on the bulb type. The bulbs are made by blowing molten glass into a mold (Section 18.3.3). The inside of the bulb either is left clear or is frosted (thus making it translucent), to better diffuse the light and to reduce glare.

I.2 Product Design and Concurrent Engineering

Product design involves the creative and systematic prescription of the shape and characteristics of an artifact to achieve specified objectives while simultaneously satisfying several constraints. Design is a critical activity, because it has been estimated that as much as 80% of the cost of product development and manufacture is determined by the decisions made in the *initial* stages of design. The product design process has been studied extensively; it is briefly introduced here because of the strong interactions between manufacturing and design activities.

Innovative approaches are essential in successful product design, as are clearly specified functions and a clear statement of the performance expected of the product, which may be new or a modified version of an existing product. The market for the product and its anticipated use(s) also must be clearly defined; this aspect involves the assistance of market analysts and sales personnel who will bring valuable and timely input to the manufacturer, especially regarding market trends.

The Design Process. Traditionally, design and manufacturing activities have taken place *sequentially*, as shown in Fig. I.3a. This methodology may, at first, appear to be straightforward and logical; in practice, however, it is wasteful of resources. Consider the case of a manufacturing engineer who, for example, determines that, for a variety of reasons, it would be more desirable (a) to use a different material, such as a polymer or a ceramic, instead of a metal or (b) to use the same material, but in a different condition, such as a softer instead of a harder material or a

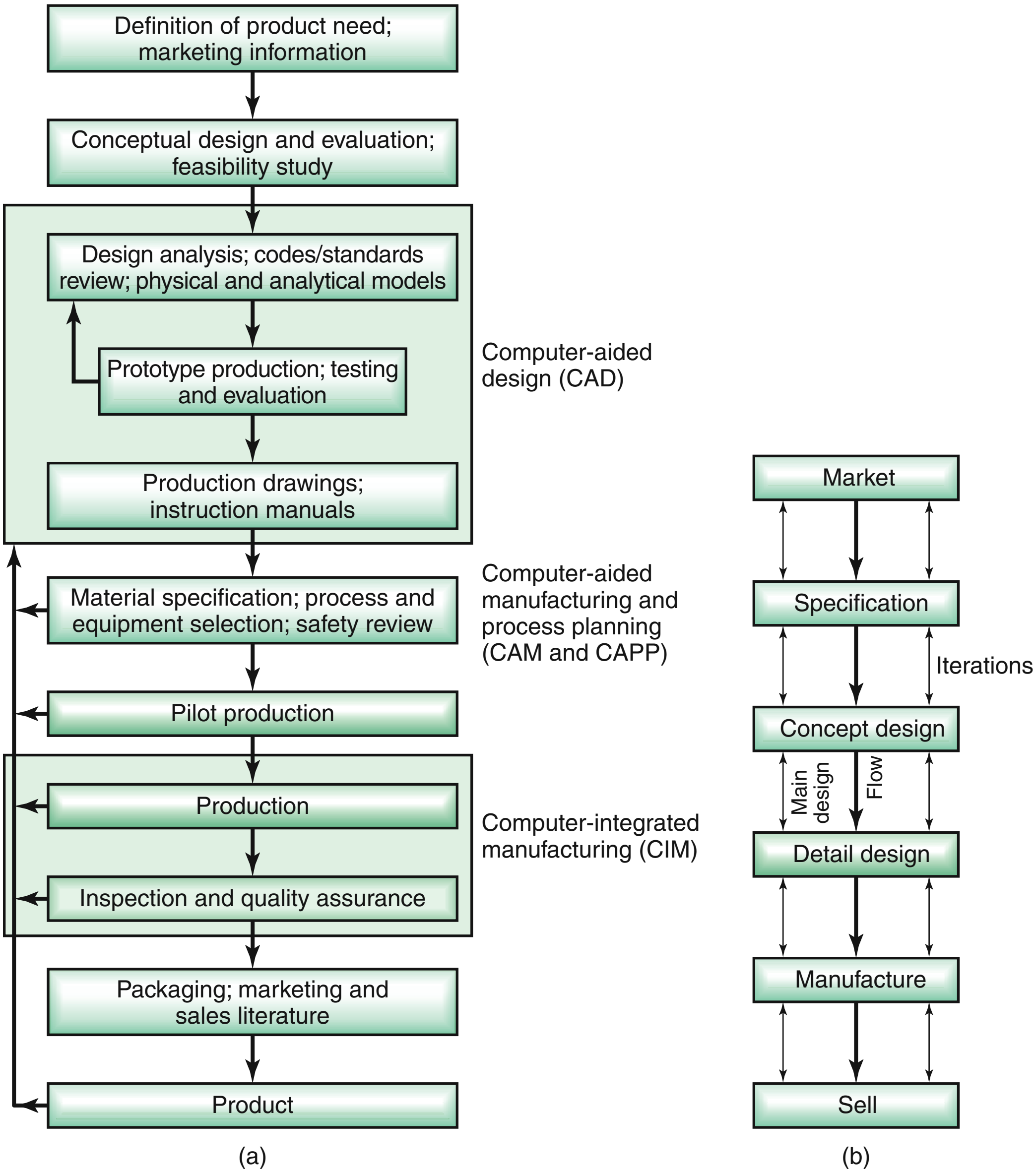


FIGURE I.3 (a) Chart showing various steps involved in *traditional* design and manufacture of a product. Depending on the complexity of the product and the type of materials used, the time span between the original concept and the marketing of the product may range from a few months to several years. (b) Chart showing general product flow in *concurrent engineering*, from market analysis to marketing the product. *Source*: After S. Pugh.

material with a smoother surface finish, or (c) to modify the design of a component in order to make it easier, faster, and less expensive to manufacture. Note that these decisions must take place at the material-specification stage (the sixth box from the top in Fig. I.3a).

Each of the modifications just described will necessitate a repeat of the design analysis stage (the third box from the top in Fig. I.3a) and the subsequent stages, to ensure that the product will still meet all specified requirements and will function satisfactorily. A later change from, say, a forged to a cast component will likewise necessitate a repeat analysis. Such iterations obviously waste both time and the resources of a company.

Concurrent Engineering. Driven primarily by the consumer electronics industry, a continuing trend is taking place to bring products to the marketplace as rapidly as possible, so as to gain a higher percentage share of the market and thus higher profits. An important methodology aimed at achieving this end is *concurrent engineering*, which involves the product-development approach shown in Fig. I.3b. Note that, although this concept, also called **simultaneous engineering**, still has the same general product-flow sequence as in the traditional approach (Fig. I.3a), it now contains several deliberate modifications. From the earliest stages of product design and engineering, *all* relevant disciplines are now *simultaneously* involved. As a result, any iterations that may have to be made will require a smaller effort and thus result in much less wasted time than occurs in the traditional approach to design. It should be apparent that a critical feature of this approach is the recognition of the importance of communication among and within all disciplines.

Concurrent engineering can be implemented in companies large or small, which is particularly significant because 98% of all U.S. manufacturing companies have fewer than 500 employees. Such companies are generally referred to as *small businesses*. As an example of the benefits of concurrent engineering, one automotive company reduced the number of components in one of its engines by 30%, decreased the engine weight by 25%, and reduced its manufacturing time by 50%.

Life Cycle. In concurrent engineering, the design and manufacture of products are integrated with a view toward optimizing all elements involved in the *life cycle* of the product (see Section I.4). The life cycle of a new product generally consists of the following four stages:

1. Product start-up
2. Rapid growth of the product in the marketplace
3. Product maturity
4. Decline.

Consequently, **life-cycle engineering** requires that the *entire life* of a product be considered, beginning with the design stage and on through production, distribution, product use, and, finally, recycling or the disposal of the product.

Role of Computers in Product Design. Typically, product design first requires the preparation of *analytical* and *physical models* of the product for the purposes of visualization and engineering analysis. Although the need for such models depends on product complexity, constructing and studying these models have become highly simplified through the use of **computer-aided design** (CAD) and **computer-aided engineering** (CAE) techniques.

CAD systems are capable of rapid and complete analyses of designs, whether it be a simple shelf bracket or a shaft in large and complex structures. The Boeing 777 passenger airplane, for example, was designed completely by computers in a process known as **paperless design**, with 2000 workstations linked to eight design servers. Unlike previous mock-ups of aircraft, no prototypes or mock-ups were built and the 777 was constructed and assembled *directly* from the CAD/CAM software that had been developed.

Through computer-aided engineering, the performance of structures subjected, for example, to static or fluctuating loads or to temperature gradients also can be simulated, analyzed, and tested, rapidly and accurately. The information developed is stored and can be retrieved, displayed, printed, and transferred anytime and anywhere within a company's organization. Design modifications can be made and optimized (as is often the practice in engineering, especially in the production of large structures) directly, easily, and at any time.

Computer-aided manufacturing involves all phases of manufacturing, by utilizing and processing the large amount of information on materials and processes gathered and stored in the organization's database. Computers greatly assist in organizing the information developed and performing such tasks as (a) programming for numerical-control machines and for robots for material-handling and assembly operations (Chapter 37), (b) designing tools, dies, molds, fixtures, and work-holding devices (Parts II, III, and IV), and (c) maintaining quality control (Chapter 36).

On the basis of the models developed and analyzed in detail, product designers then finalize the geometric features of each of the product's components, including specifying their dimensional tolerances and surface-finish characteristics. Because all components, regardless of their size, eventually have to be assembled into the final product, dimensional tolerances are a major consideration in manufacturing (Chapter 35). Indeed, dimensional tolerances are equally important for small products as well as for car bodies or airplanes. The models developed also allow the specification of the mechanical and physical properties required, which in turn affect the selection of materials. (Section I.5).

Prototypes. A *prototype* is a physical model of an individual component or product. The prototypes developed are carefully reviewed for possible modifications to the original design, materials, or production methods. An important and continuously evolving technology is **rapid prototyping** (RP, see Chapter 20). Using CAD/CAM and various specialized technologies, designers can now make prototypes rapidly and at low cost, from metallic or nonmetallic materials such as plastics and ceramics.

Prototyping new components by means of traditional methods (such as casting, forming, and machining) could cost an automotive company hundreds of millions of dollars a year, with some components requiring a year or more to complete. Rapid prototyping can significantly reduce costs and the associated product-development times. Rapid-prototyping techniques are now advanced to such a level that they also can be used for low-volume (in batches typically of fewer than 100 parts) economical production of a variety of actual and functional parts to be assembled into products.

Virtual Prototyping. *Virtual prototyping* is a software-based method that uses advanced graphics and virtual-reality environments to allow designers to view and examine a part in detail. This technology, also known as **simulation-based design**, uses CAD packages to render a part such that, in a 3-D interactive virtual environment, designers can observe and evaluate the part as it is being drawn and developed. Virtual prototyping has been gaining importance, especially because of the availability of low-cost computers and simulation and analysis tools.

I.3 Design for Manufacture, Assembly, Disassembly, and Service

Design for manufacture (DFM) is a comprehensive approach to integrating the design process with production methods, materials, process planning, assembly, testing, and quality assurance. DFM requires a fundamental understanding of (1) the characteristics, capabilities, and limitations of materials, manufacturing processes, machinery, equipment, and tooling and (2) variability in machine performance, dimensional accuracy and surface finish of the workpiece, processing time, and the effect of processing methods on product quality. Establishing *quantitative* relationships is essential in order to be able to analyze and optimize a design for ease of manufacturing and assembly at minimum product cost.

The concepts of **design for assembly** (DFA), **design for manufacture and assembly** (DFMA), and **design for disassembly** (DFD) are all important aspects of all manufacturing. Methodologies and computer software are now available for design for assembly, utilizing 3-D conceptual designs and solid models. Subassembly, assembly, and disassembly times and costs can now be minimized, while product integrity and performance are maintained. Experience has indicated that a product which is easy to assemble is usually also easy to disassemble.

Assembly is an important phase of manufacturing and requires a consideration of the ease, speed, and cost of putting together the numerous individual components of a product (Fig. I.4). Assembly costs in manufacturing operations can be substantial, typically ranging from 20 to 60% of the total product cost. *Disassembly* of a product is an equally important consideration, for maintenance, servicing and recycling of individual components.

As described in Part VI, there are several methods of assembly of components, including the use of a wide variety of fasteners, adhesives, or joining techniques such as welding, brazing, or soldering. As is the case in all types of manufacturing, each of these operations has its own specific characteristics, assembly times, advantages and limitations, associated costs, and special design considerations. Individual parts may be assembled by hand or by a variety of automatic equipment and industrial robots. The choice depends on factors such as product complexity, the number of components to be assembled, the care and protection required to prevent damage to the surfaces of the parts, and the relative cost of labor compared with the cost of machinery required for automated assembly.

Design for Service. In addition to design for assembly and for disassembly, *design for service* is important in product design. Products often have to be disassembled to varying degrees in order to service and, if necessary, repair them. The design should take into account the concept that, for ease of access, components that are most likely to be in need of servicing be placed, as much as possible, at the outer layers of the product. This methodology can be appreciated by anyone who has had the experience of servicing machinery.

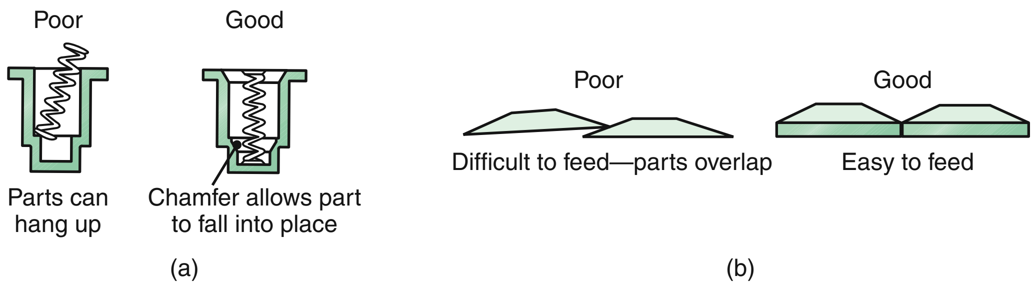


FIGURE I.4 Redesign of parts to facilitate assembly. *Source*: After G. Boothroyd and P. Dewhurst.

I.4 Green Design and Manufacturing

In the United States alone, 9 million passenger cars, 300 million tires, 670 million compact fluorescent lamps, and more than 5 billion kilograms of plastic products are discarded each year. Every three months, industries and consumers discard enough aluminum to rebuild the U.S. commercial air fleet. Note that, as indicated subsequently, the term *discarding* implies that the products have reached the end of their useful life; it does not necessarily mean that they are wasted and dumped into landfills.

The particular manufacturing process and the operation of machinery can each have a significant environmental impact. Manufacturing operations generally produce some waste, such as:

a. Chips from machining and trimmed materials from sheet forming, casting, and molding operations.
b. Slag from foundries and welding operations.
c. Additives in sand used in sand-casting operations.
d. Hazardous waste and toxic materials used in various products.
e. Lubricants and coolants in metalworking and machining operations.
f. Liquids from processes such as heat treating and plating.
g. Solvents from cleaning operations.
h. Smoke and pollutants from furnaces and gases from burning fossil fuels.

The adverse effects of these activities, their damage to our environment and to the Earth's ecosystem, and, ultimately, their effect on the quality of human life are now widely recognized and appreciated. Major concerns involve global warming, greenhouse gases (carbon dioxide, methane, and nitrous oxide), acid rain, ozone depletion, hazardous wastes, water and air pollution, and contaminant seepage into water sources. One measure of the adverse impact of human activities is called the **carbon footprint**, which quantifies the amount of greenhouse gases produced in our daily activities.

The term **green design and manufacturing** is now in common usage in all industrial activities, with a major emphasis on **design for the environment** (DFE). Also called **environmentally conscious design and manufacturing**, this approach considers *all* possible adverse environmental impacts of materials, processes, operations, and products, so that they can all be taken into account at the earliest stages of design and production.

These goals, which increasingly have become global, also have led to the concept of **design for recycling** (DFR). Recycling may involve one of two basic activities:

- *Biological cycle*: Organic materials degrade naturally, and in the simplest version, they lead to new soil that can sustain life. Thus, product design involves the use of (usually) organic materials. The products function well for their intended life and can then be safely discarded.
- *Industrial cycle*: The materials in the product are recycled and reused continuously. For example, aluminum beverage cans are recycled and reused after they have served their intended purpose. To demonstrate the economic benefits of this approach, it has been determined that producing aluminum from scrap, instead of from bauxite ore, reduces production costs by as much as 66% and reduces energy consumption and pollution by more than 90%.

One of the basic principles of design for recycling is the use of materials and product-design features that facilitate biological or industrial recycling. In the U.S. automotive industry, for example, about 75% of automotive parts (mostly metal) are now recycled, and there are continuing plans to recycle the rest as well, including plastics, glass, rubber, and foam. About 100 million of the 300 million discarded automobile tires are reused in various ways.

Cradle-to-cradle Production. A term coined in the 1970s and also called C2C, *cradle-to-cradle* production considers the impact of each stage of a product's life cycle, from the time natural resources are mined and processed into raw materials, through each stage of manufacturing products, their use and, finally, recycling. Certification procedures for companies are now being developed for cradle-to-cradle production, as they have been for quality control (Section 40.4). *Cradle-to-grave* production, also called *womb-to-tomb* production, has a similar approach, but does not necessarily consider or take on the responsibility of recycling.

Cradle-to-cradle production especially emphasizes

1. Sustainable and efficient manufacturing activities, using clean technologies.
2. Waste-free production.
3. Using recyclable and nonhazardous materials.
4. Reducing energy consumption.
5. Using renewable energy, such as wind and solar energy.
6. Maintaining ecosystems by minimizing the environmental impact of all activities.
7. Using materials and energy sources that are locally available, so as to reduce energy use associated with their transport, which, by and large, has an inherently high carbon footprint.
8. Continuously exploring the reuse and recycling of materials, thus perpetually trying to recirculate materials; also included is investigating the composting of materials whenever appropriate or necessary, instead of dumping them into landfills.

Guidelines for Green Design and Manufacturing. In reviewing the various activities described thus far, note that there are overarching relationships among the basic concepts of DFMA, DFD, DFE, and DFR. These relationships can be summarized as guidelines, now rapidly being accepted worldwide:

1. Reduce waste of materials, by refining product design, reducing the amount of materials used in products, and selecting manufacturing processes that minimize scrap (such as forming instead of machining).
2. Reduce the use of hazardous materials in products and processes.
3. Investigate manufacturing technologies that produce environmentally friendly and safe products and by-products.
4. Make improvements in methods of recycling, waste treatment, and reuse of materials.
5. Minimize energy use, and whenever possible, encourage the use of renewable sources of energy.
6. Encourage recycling by using materials that are a part of either industrial or biological cycling, but not both in the same product assembly. Ensure proper handling and disposal of all waste in the case of materials used that are not part of an industrial or biological cycle.

I.5 Selection of Materials

An increasingly wide variety of materials are now available, each type having its own (a) material properties and manufacturing characteristics, (b) advantages and limitations, (c) material and production costs, and (d) consumer and industrial applications (Part I). The selection of materials for products and their components is typically made in consultation with materials engineers, although design engineers may also be sufficiently experienced and qualified to do so. At the forefront of new materials usage are industries such as the aerospace and aircraft, automotive, military equipment, and sporting goods industries.

The general types of materials used, either individually or in combination with other materials, are the following:

- **Ferrous metals:** Carbon, alloy, stainless, and tool and die steels (Chapter 5)
- **Nonferrous metals:** Aluminum, magnesium, copper, nickel, titanium, superalloys, refractory metals, beryllium, zirconium, low-melting-point alloys, and precious metals (Chapter 6)
- **Plastics (polymers):** Thermoplastics, thermosets, and elastomers (Chapter 7)
- **Ceramics, glasses, glass ceramics, graphite, diamond**, and **diamondlike materials** (Chapter 8)
- **Composite materials**: Reinforced plastics and metal-matrix and ceramic-matrix composites (Chapter 9)
- **Nanomaterials** (Section 8.8)
- **Shape-memory alloys** (also called *smart materials*), **amorphous alloys, semiconductors**, and **superconductors** (Chapters 6, 18 and 28).

As new developments continue, the selection of an appropriate material for a particular application becomes even more challenging. Also, there are continously shifting trends in the substitution of materials, driven not only by technological considerations, but also by economics.

Properties of Materials. *Mechanical properties* of interest in manufacturing generally include strength, ductility, hardness, toughness, elasticity, fatigue, and creep resistance (Chapter 2). *Physical properties* are density, specific heat, thermal expansion and conductivity, melting point, and electrical and magnetic properties (Chapter 3). Optimum designs often require a consideration of a combination of mechanical *and* physical properties. A typical example is the strength-to-weight and stiffness-to-weight ratios of materials for minimizing the weight of structural members. Weight minimization is particularly important for aerospace and automotive applications, in order to improve performance and fuel economy.

Chemical properties include oxidation, corrosion, degradation, toxicity, and flammability. These properties play a significant role under both hostile (such as corrosive) and normal environments. *Manufacturing properties* indicate whether a particular material can be cast, formed, machined, joined, and heat treated with relative ease. As Table I.3 illustrates, no one material has the same manufacturing characteristics. Another consideration is *appearance*, which includes such characteristics as color, surface texture, and feel, all of which can play a significant role in a product's acceptance by the public.

Availability. As will be emphasized throughout this book, the economic aspect of material selection is as important as technological considerations (Chapter 40). Thus, the availability of materials is a major concern in manufacturing. Furthermore, if materials are not available in the desired quantities, shapes, dimensions, and surface

TABLE I.3

General Manufacturing Characteristics of Various Materials

Alloy	Castability	Weldability	Machinability
Aluminum	E	F	E–G
Copper	G–F	F	G–F
Gray cast iron	E	D	G
White cast iron	G	VP	VP
Nickel	F	F	F
Steels	F	E	F
Zinc	E	D	E

Note: E, excellent; G, good; F, fair; D, difficult; VP, very poor. The ratings shown depend greatly on the particular material, its alloys, and its processing history.

texture, substitute materials or additional processing of a particular material may well be required, all of which can contribute significantly to product cost.

Reliability of supply is important in order to meet production schedules. In automotive industries, for example, materials must arrive at a plant at appropriate time intervals. (See also *just in time*, Section I.7). Reliability of supply is also important, considering the fact that most countries import numerous raw materials. The United States, for example, imports most of the cobalt, titanium, chromium, aluminum, nickel, natural rubber, and diamond that it needs. Consequently, a country's *self-reliance* on resources, especially energy, is an often-expressed political goal, but is challenging to achieve. Geopolitics (defined briefly as the study of the infuence of a nation's physical geography on its foreign policy) must thus be a consideration, particularly during periods of global hostility.

Service Life. We all have had the experience of a shortened service life of a product, which often can be traced to (a) improper selection of materials, (b) improper selection of production methods, (c) insufficient control of processing variables, (d) defective parts or manufacturing-induced defects, (e) poor maintenance, and (f) improper use of the product. Generally, a product is considered to have failed when it

- Stops functioning, due to the failure of one or more of its components, such as a broken shaft, gear, bolt, or turbine blade or a burned-out electric motor
- Does not function properly or perform within required specifications, due, for example, to worn gears or bearings
- Becomes unreliable or unsafe for further use, as in the erratic behavior of a switch, poor connections in a printed-circuit board, or delamination of a composite material.

Throughout various chapters, this text describes the types of failure of a component or a product resulting, for example, from (a) design deficiencies, (b) improper material selection, (c) incompatibility of materials in contact, which produces friction, wear, and galvanic corrosion, (d) defects in raw materials, (e) defects induced during manufacturing, (f) improper component assembly, and (g) improper product use.

Material Substitution in Products. For a variety of reasons, numerous substitutions are often made in materials, as evidenced by a simple inspection and comparison of common products such as home appliances, sports equipment, or automobiles. As a measure of the challenges faced in material substitution, consider the following examples: (a) metal vs. wooden handle for a hammer, (b) aluminum vs. cast-iron lawn chair, (c) aluminum vs. copper wire, (d) plastic vs. steel car bumper, (e) plastic vs. metal toy, and (f) alloy steel vs. titanium submarine hull.

The two examples that follow give typical details of the major factors involved in material substitution in common products.

EXAMPLE I.2 Baseball Bats

Baseball bats for the major and minor leagues are generally made of wood from the northern white ash tree, a wood that has high dimensional stability, a high elastic modulus and strength-to-weight ratio, and high shock resistance. Wooden bats can, however, break during their use and may cause serious injury. The wooden bats are made on semiautomatic lathes and then subjected to finishing operations for appearance and labeling. The straight uniform grain required for such bats has become increasingly difficult to find, particularly when the best wood comes from ash trees that are at least 45 years old.

For the amateur market and for high school and college players, aluminum bats (top portion of Fig. I.5) have been made since the 1970s as a cost-saving alternative to wood. The bats are made by various metalworking operations, described throughout Part III. Although, at first, their performance was not as good as that of wooden bats, the technology has advanced to a great extent. Metal bats are now made mostly from high-strength aluminum tubing, as well as other metal alloys. The bats are designed to have the same center of percussion (known as the sweet spot, as in tennis racquets) as wooden bats, and are usually filled with polyurethane or cork for improved sound damping and for controlling the balance of the bat.

Metal bats possess such desirable performance characteristics as lower weight than wooden bats, optimum weight distribution along the bat's length, and superior impact dynamics. Also, as documented by scientific studies, there is a general consensus that metal bats outperform wooden bats.

FIGURE I.5 Cross sections of baseball bats made of aluminum (top two) and composite material (bottom two).

Developments in bat materials now include composite materials (Chapter 9) consisting of high-strength graphite and glass fibers embedded in an epoxy resin matrix. The inner woven sleeve (lower portion of Fig. I.5) is made of Kevlar fibers (an aramid), which add strength to the bat and dampen its vibrations. These bats perform and sound much like wooden bats.

Source: Mizuno Sports, Inc.

EXAMPLE I.3 U.S. Pennies

Billions of pennies are produced and put into circulation each year by the U.S. Mint. The materials used have undergone significant changes throughout history, largely because of periodic material shortages and the resulting fluctuating cost of appropriate raw materials. The following table shows the chronological development of material substitutions in pennies:

1793–1837	100% copper
1837–1857	95% copper, 5% tin and zinc
1857–1863	88% copper, 12% nickel
1864–1962	95% copper, 5% tin and zinc
1943 (WW II years)	Steel, plated with zinc
1962–1982	95% copper, 5% zinc
1982–present	97.5% zinc, plated with copper

I.6 Selection of Manufacturing Processes

As will be described throughout this text, there is often more than one method that can be employed to produce a component for a product from a given material. The following broad categories of manufacturing methods are all applicable to metallic as well as nonmetallic materials:

a. **Casting** (Fig. I.6a): Expendable mold and permanent mold (Part II).

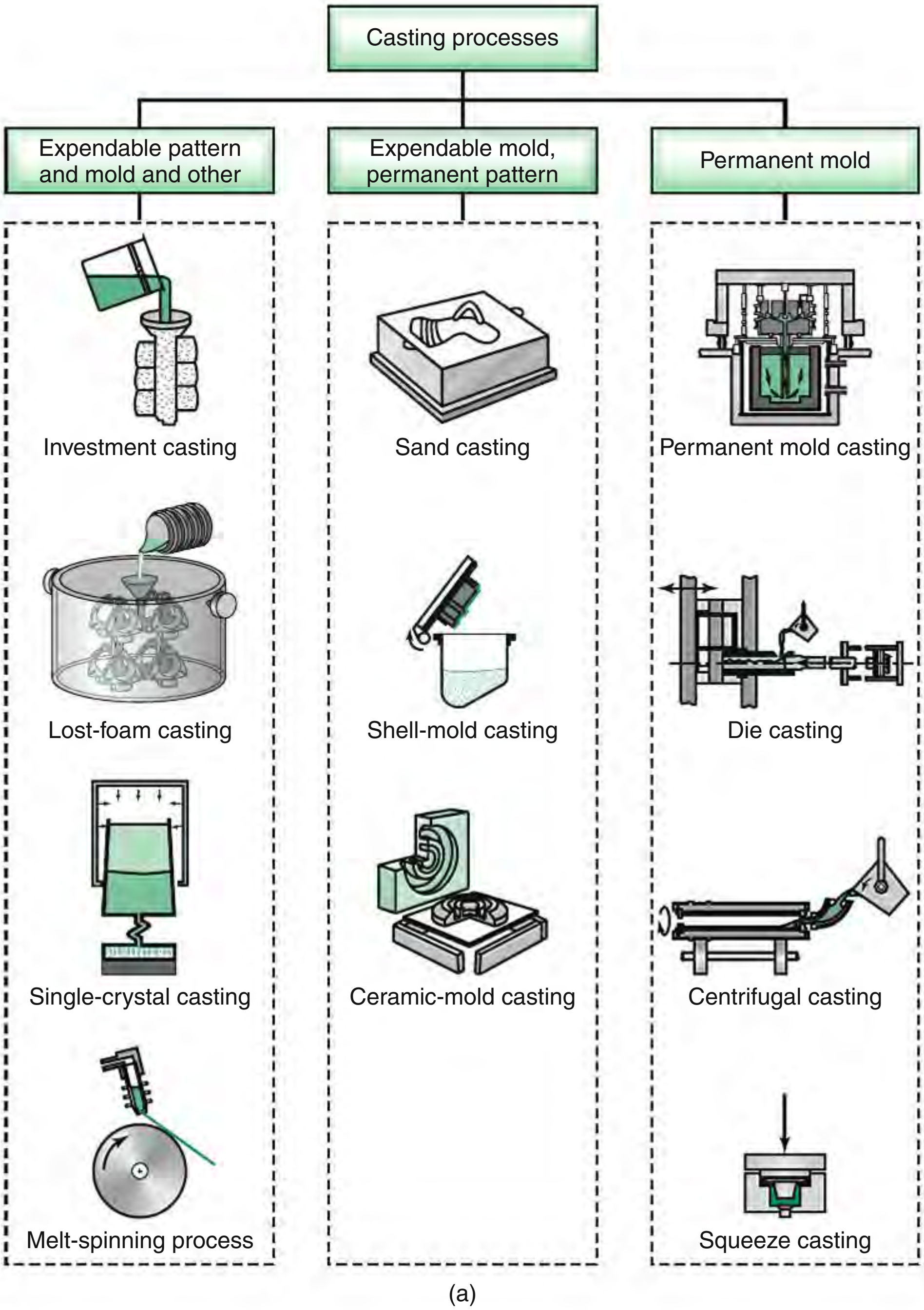


FIGURE I.6a Schematic illustrations of various casting processes.

b. **Forming and shaping** (Figs. I.6b through I.6d): Rolling, forging, extrusion, drawing, sheet forming, powder metallurgy, and molding (Part III).

c. **Machining** (Fig. I.6e): Turning, boring, drilling, milling, planing, shaping, broaching; grinding; ultrasonic machining; chemical, electrical, and electrochemical machining; and high-energy-beam machining (Part IV). This broad category also includes **micromachining** for producing ultraprecision parts (Part V).

d. **Joining** (Fig. I.6f): Welding, brazing, soldering, diffusion bonding, adhesive bonding, and mechanical joining (Part VI).

e. **Finishing:** Honing, lapping, polishing, burnishing, deburring, surface treating, coating, and plating (Chapters 26 and 34).

f. **Microfabrication and nanofabrication:** Technologies that are capable of producing parts with dimensions at the micro (one-millionth of a meter) and nano (one-billionth of a meter) levels; fabrication of microelectromechanical

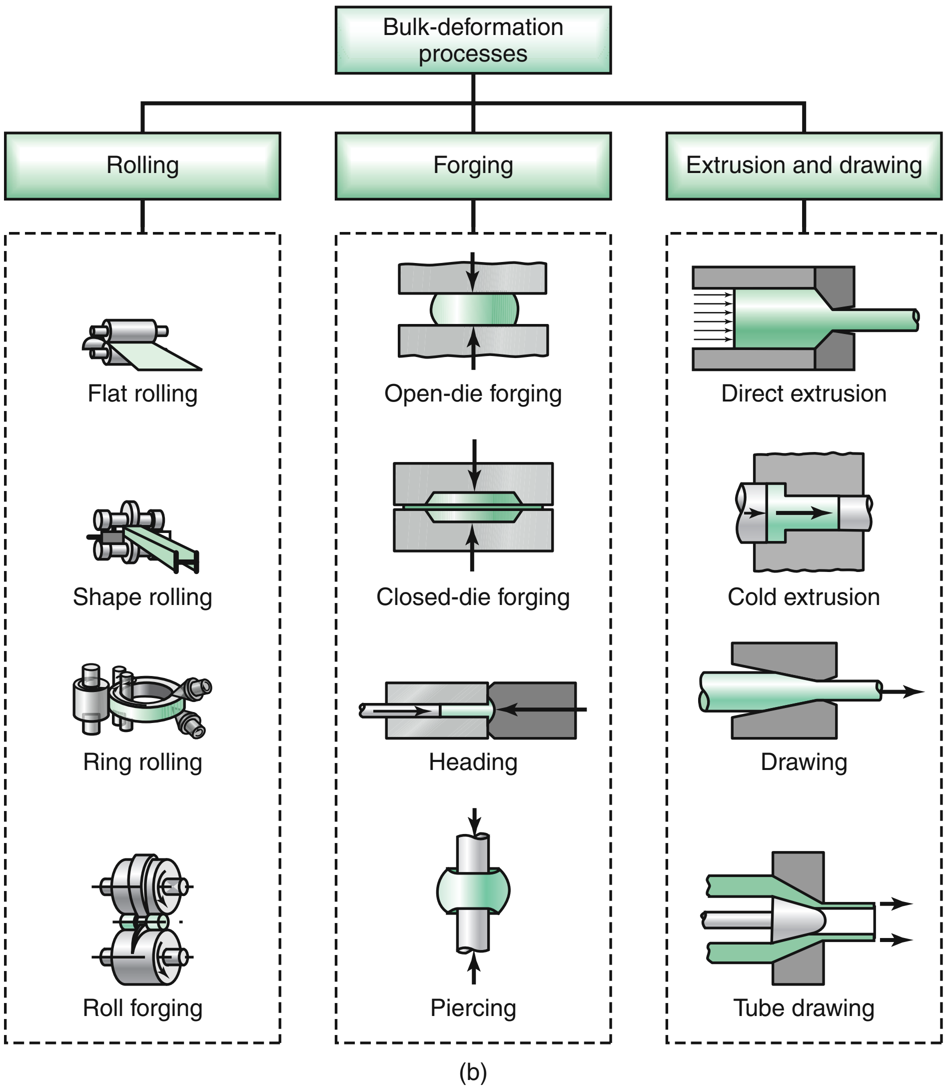


FIGURE I.6b Schematic illustrations of various bulk-deformation processes.

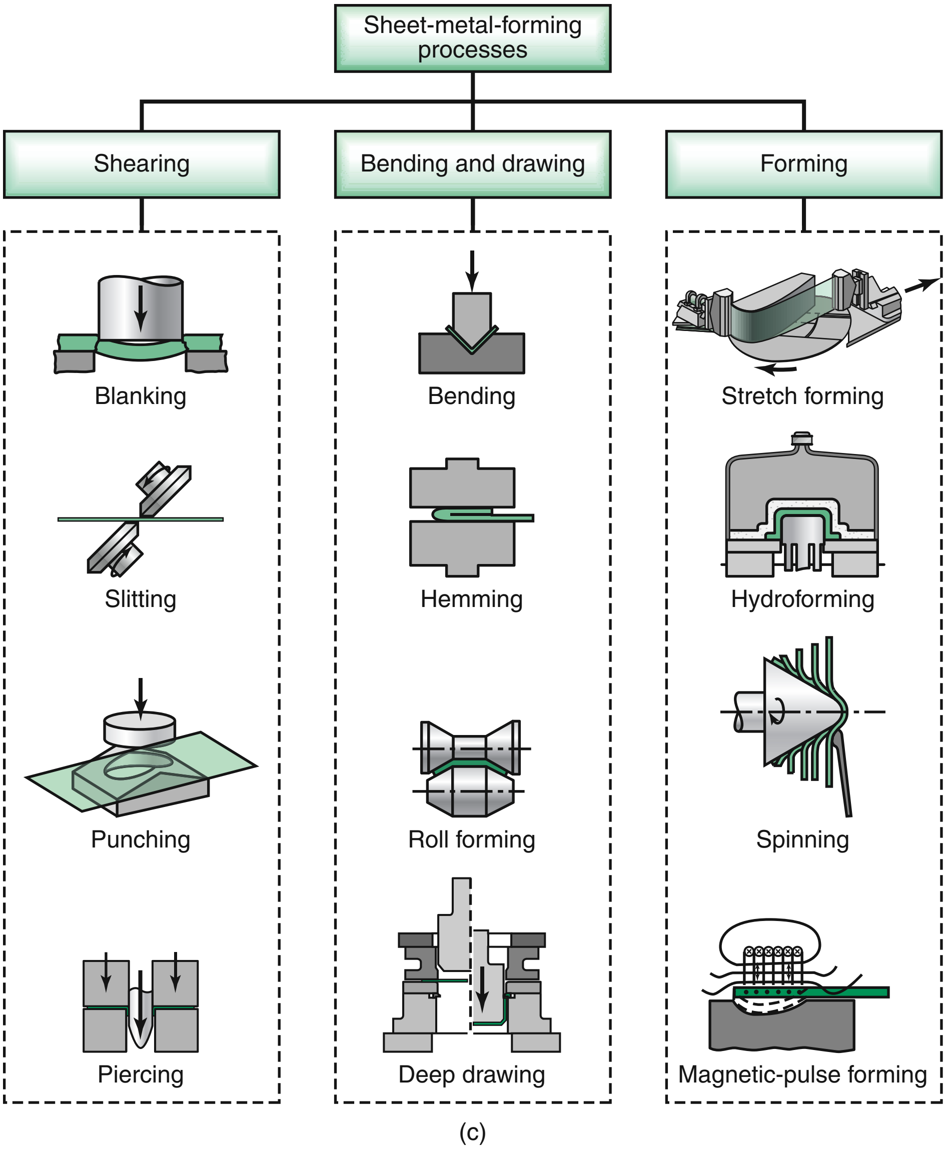


FIGURE I.6c Schematic illustrations of various sheet-metal-forming processes.

systems (MEMS) and nanoelectromechanical systems (NEMS), typically involving processes such as lithography, surface and bulk micromachining, etching, LIGA, and various specialized processes (Chapters 28 and 29).

Process Selection. The selection of a particular manufacturing process or, more often, sequence of processes, depends on the geometric features of the parts to be produced, including the dimensional tolerances and surface texture required, and on numerous factors pertaining to the particular workpiece material and its manufacturing properties. To emphasize the challenges involved, consider the following two cases:

a. Brittle and hard materials cannot be shaped or formed without the risk of fracture, unless they are performed at elevated temperatures, whereas these materials can easily be cast, machined, or ground.

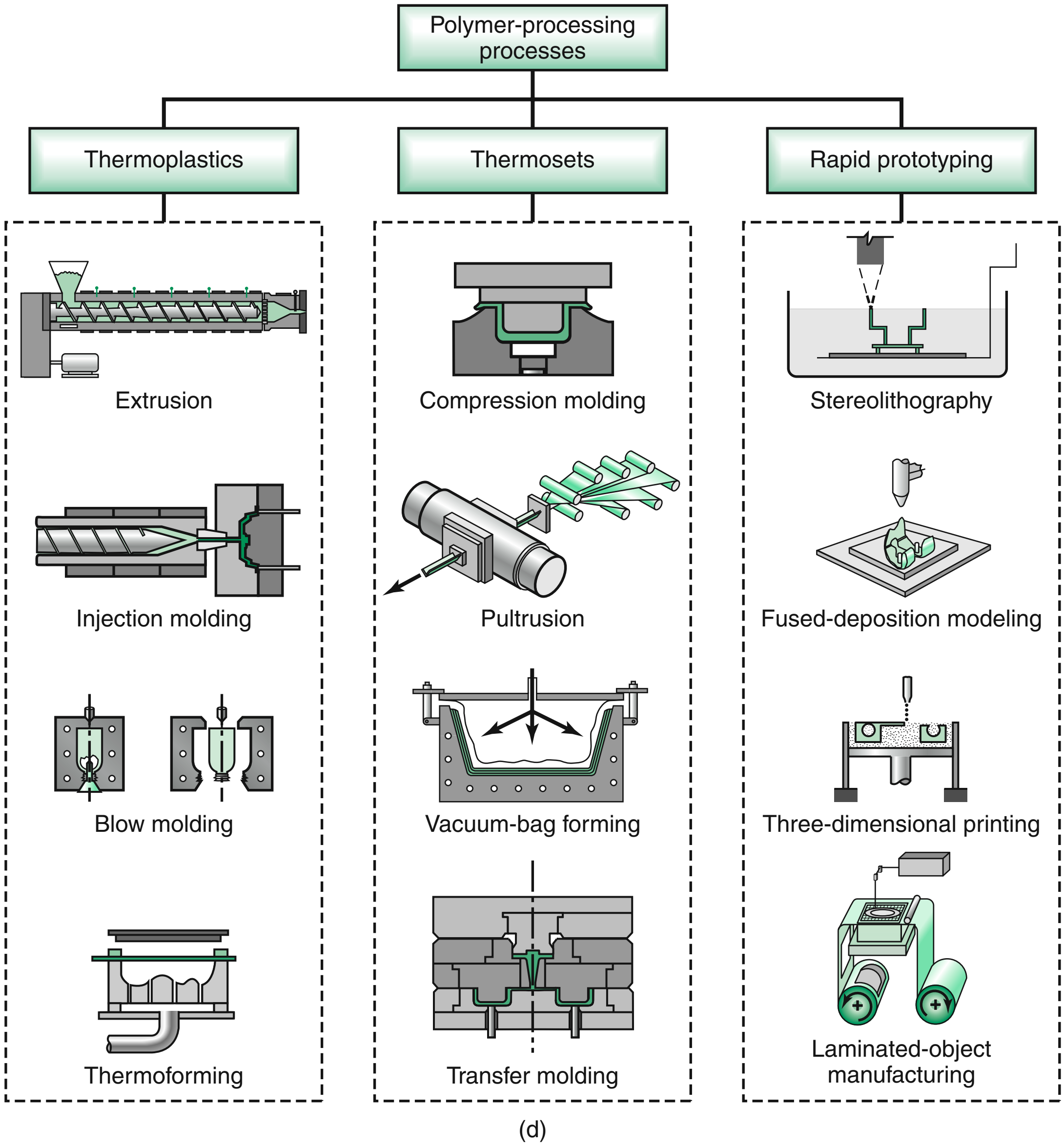


FIGURE I.6d Schematic illustrations of various polymer-processing methods.

b. Metals that have been preshaped at room temperature become less formable during subsequent processing, which, in practice, is often required to complete the part; this is because the metals have become stronger, harder, and less ductile than they were prior to processing them further.

There is a constant demand for new approaches to production problems and, especially, for manufacturing cost reduction. For example, sheet-metal parts traditionally have been cut and fabricated using common mechanical tools such as punches and dies. Although still widely used, some of these operations are now being replaced by laser cutting, as shown in Fig. I.7 on p. 24, thus eliminating the need for hard tools, which have only fixed shapes and can be expensive and time consuming to make.

The laser path in this cutting operation is computer controlled, thereby increasing the operation's flexibility and its capability of producing an infinite variety of

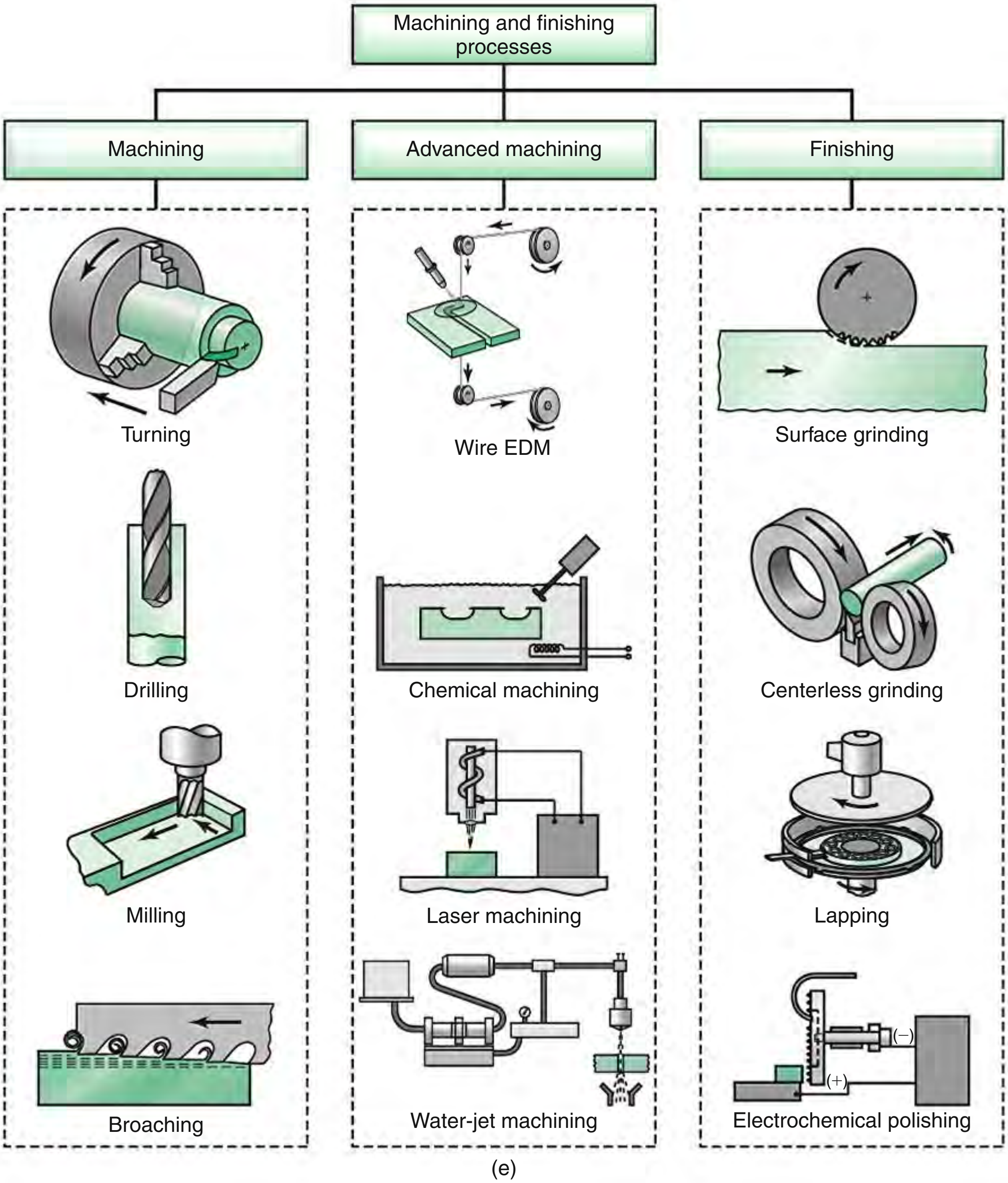


FIGURE I.6e Schematic illustrations of various machining and finishing processes.

shapes accurately, repeatedly, and economically. However, because of the high heat involved in using lasers, the surfaces produced after cutting have very different characteristics (such as discoloration and a different surface texture) than those produced by traditional methods. This difference can have significant effects not only on the appearance of the material, but especially on its subsequent processing and in the

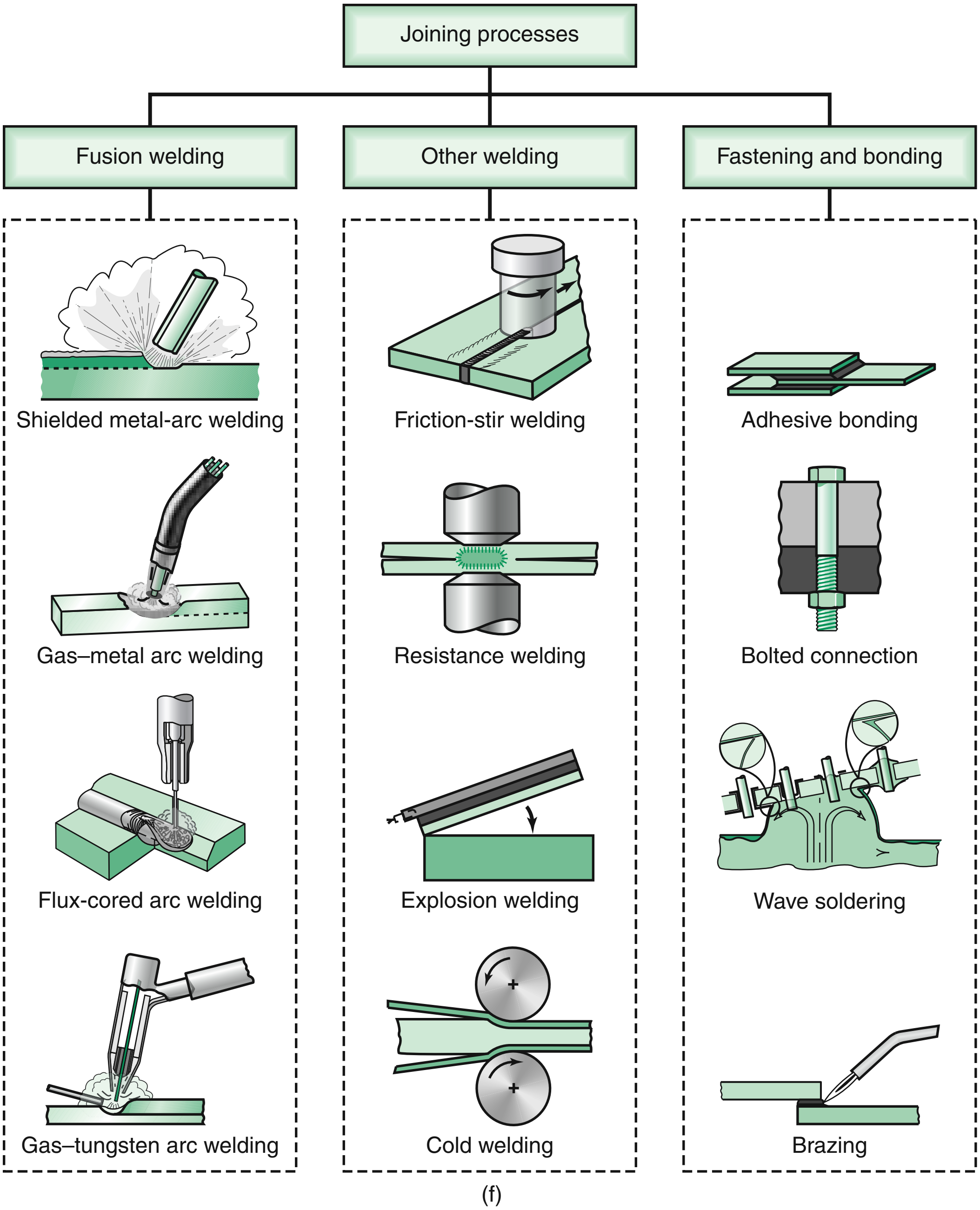


FIGURE I.6f Schematic illustrations of various joining processes.

service life of the product. Moreover, the inherent flexibility of laser cutting is countered by the fact that it is a much slower operation than traditional punching.

In process selection, several factors can have a major role, such as the part size, shape complexity, and dimensional accuracy and surface finish required. For example,

- Flat parts and thin cross sections can be difficult to cast
- Complex parts generally cannot be shaped easily and economically by such metalworking techniques as forging, whereas, depending on the part size and the

level of complexity, the parts may be precision cast, fabricated from individual pieces, or produced by powder-metallurgy techniques

- Dimensional tolerances and surface finish in hot-working operations are not as fine as those obtained in operations performed at room temperature (called *cold working*), because of the dimensional changes, distortion, warping, and surface oxidation that occur at the elevated temperatures involved.

FIGURE I.7 Cutting sheet metal with a laser beam. *Source*: Courtesy of Rofin-Sinar, Inc., and Society of Manufacturing Engineers.

The size of manufactured products, and the machinery and equipment involved in processing them, vary widely, ranging from microscopic gears and machanisms of micrometer size, as illustrated in Fig. I.8, to (a) the main landing gear for the Boeing 777 aircraft, which is 4.3 m (14 ft) high and includes three axles and six wheels; (b) the runner for the turbine for a hydroelectric power plant, which is 4.6 m (180 in.) in diameter and weighs 50,000 kg (110,000 lb); and (c) a large steam turbine rotor weighing 300,000kg (700,000 lb).

Process Substitution. It is common practice in industry that, for a variety of reasons and after a review of all appropriate and applicable processes, a particular production method (that may have been employed in the past) may well have to be substituted with another. Consider, for example, the following products that can be produced by any of the sets of processes indicated: (a) cast vs. forged crankshaft, (b) stamped sheet-metal vs. forged or cast automobile wheels, (c) cast vs. stamped sheet-metal frying pan, (d) injection molded vs. extruded or cast polymer bracket, and (e) welded vs. riveted sheet-metal safety hood for a machine.

Many varieties of such products are widely available in the marketplace. However, a customer's preference will depend on his or her particular needs, which include factors such as the product's appeal to the customer, its cost, whether maintenance is required,

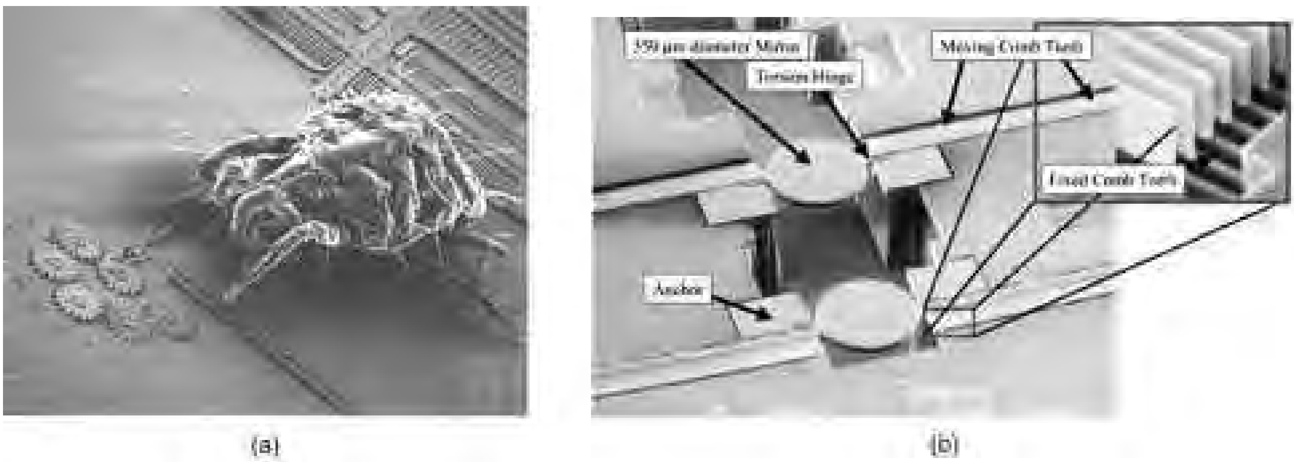


FIGURE I.8 (a) Microscopic gears with dust mite. *Source*: Courtesy Sandia National Laboratory; (b) A movable micromirror component of a light sensor. Note the 100-μm scale at the bottom of the figure. *Source*: Courtesy of R. Mueller, University of California at Berkeley.

whether the product is for industrial or consumer use, the parameters to which the product will be subjected (such as temperatures and chemicals), and any environmental concerns that have to be addressed.

Net-shape and Near-net-shape Manufacturing. *Net-shape* and *near-net-shape manufacturing* together constitute an important methodology by which a part is made in only one operation at or close to the final desired dimensions, tolerances, and surface finish. The difference between net shape and near net shape is a matter of degree of how close the product is to its final dimensional characteristics.

The necessity for, and benefits of, net-shape manufacturing can be appreciated from the fact that, in the majority of cases, more than one additional operation is often necessary to produce the part. For example, a cast or forged gear or crankshaft generally will not have the necessary dimensional characteristics, thus requiring additional processing, such as machining or grinding. These additional operations can contribute significantly to the cost of a product.

Typical examples of net-shape manufacturing include precision casting (Chapter 11), forging (Chapter 14), forming sheet metal (Chapter 16), powder metallurgy and injection molding of metal powders (Chapter 17), and injection molding of plastics (Chapter 19).

Ultraprecision Manufacturing. Dimensional accuracies for some modern equipment and instrumentation are now reaching the magnitude of the atomic lattice. Various techniques, including the use of highly sophisticated technologies (see micromechanical and microelectromechanical device fabrication in Chapter 29), are rapidly being developed to attain such extreme accuracy. Also, mirrorlike surfaces on metals can now be produced by machining with a very sharp diamond with a nose radius of 250 micrometers as the cutting tool. The machine is highly specialized, with very high stiffness (to minimize deflections, as well as vibration and chatter, during machining) and is operated in a room where the ambient temperature is controlled to within 1°C in order to avoid thermal distortions of the machine.

Types of Production. The number of parts to be produced (e.g., the annual quantity) and the rate (number of pieces made per unit time) are important economic considerations in determining the appropriate processes and the types of machinery required. Note, for example, that light bulbs, beverage cans, fuel-injection nozzles, and hubcaps are produced in numbers and at rates that are much higher than those for jet engines and tractors.

Following is a brief outline of the general types of production, in increasing order of annual quantities produced:

a. **Job shops**: Small lot sizes, typically less than 100, using general-purpose machines such as lathes, milling machines, drill presses, and grinders, many now equipped with computer controls.
b. **Small-batch production**: Quantities from about 10 to 100, using machines similar to those in job shops.
c. **Batch production**: Lot sizes typically between 100 and 5000, using more advanced machinery with computer control.
d. **Mass production**: Lot sizes generally over 100,000, using special-purpose machinery, known as *dedicated machines*, and various automated equipment for transferring materials and parts in progress.

EXAMPLE I.4 Saltshaker and Pepper Mill

The saltshaker and pepper mill set shown in Fig. I.9 consists of metallic as well as nonmetallic components. The main parts (the body) of the set are made by injection molding of a thermoplastic (Chapter 19), such as an acrylic, which has both transparency and other desirable characteristics for this application and is easy to mold. The round metal top of the saltshaker is made of sheet metal, has punched holes (Chapter 16), and is electroplated for improved appearance (Section 34.9).

The knob on the top of the pepper mill is made by machining (Chapter 23) and is threaded on the inside to allow it to be screwed and unscrewed. The square rod connecting the top portion of the pepper mill to the two pieces shown at the bottom of the figure is made by a rolling operation (Chapter 13). The two grinder components, shown at the bottom of the figure, are made of stainless steel. A design for manufacturing analysis indicated that casting or machining the two components would be too costly; consequently, it was determined that an appropriate and economical method would be the powder-metallurgy technique (Chapter 17).

FIGURE I.9 A saltshaker and pepper mill set. The two metal pieces (at the bottom) for the pepper mill are made by powder-metallurgy techniques. *Source*: Reproduced with permission from *Success Stories on P/M Parts*, Metal Powder Industries Federation, Princeton, NJ, 1998.

I.7 Computer-integrated Manufacturing

Computer-integrated manufacturing (CIM), as the name suggests, integrates the software and hardware needed for computer graphics, computer-aided modeling, and computer-aided design and manufacturing activities, from initial product concept through its production and distribution in the marketplace. This comprehensive and integrated approach began in the 1970s and has been particularly effective because of its capability of making possible the following tasks:

- Responsiveness to rapid changes in product design modifications and to varying market demands
- Better use of materials, machinery, and personnel
- Reduction in inventory
- Better control of production and management of the total manufacturing operation.

The following is a brief outline of the various elements in CIM, all described in detail in Chapters 38 and 39:

1. **Computer numerical control** (CNC). First implemented in the early 1950s, this is a method of controlling the movements of machine components by the direct insertion of coded instructions in the form of numerical data.
2. **Adaptive control** (AC). The processing parameters in an operation are automatically adjusted to optimize the production rate and product quality

FIGURE I.10 Automated spot welding of automobile bodies in a mass-production line. *Source*: Courtesy of Ford Motor Company.

and to minimize manufacturing cost. For example, machining forces, temperature, surface finish, and the dimensions of the part can be constantly monitored; if they move outside the specified range, the system adjusts the appropriate variables until the parameters are within the specified range.

3. **Industrial robots.** Introduced in the early 1960s, industrial robots (Fig. I.10) have rapidly been replacing humans, especially in operations that are repetitive, dangerous, and boring. As a result, variability in product quality is decreased and productivity improved. Robots are particularly effective in assembly operations, and some (*intelligent robots*) have been developed with sensory-perception capabilities and movements that simulate those of humans.
4. **Automated materials handling.** Computers have made possible highly efficient handling of materials and components in various stages of completion (*work in progress*), as in moving a part from one machine to another, and then to points of inspection, to inventory, and finally, to shipment.
5. **Automated assembly systems.** These systems continue to be developed to replace assembly by human operators, although humans still have to perform some operations. Assembly costs can be high, depending on the type of product; consequently, products are now being designed so that they can be assembled more easily, and faster by automated machinery, thus reducing the total manufacturing cost.
6. **Computer-aided process planning** (CAPP). By optimizing process planning, this system is capable of improving productivity, product quality, and consistency and hence reducing costs. Functions such as cost estimating and monitoring work standards (time required to perform a certain operation) are also incorporated into the system.
7. **Group technology** (GT). The concept behind group technology is that parts can be grouped and produced by classifying them into families according to similarities in design and the manufacturing processes employed to produce them. In this way, part designs and process plans can be standardized and new

parts (based on similar parts made previously) can be produced efficiently and economically.

8. **Just-in-time production** (JIT). The principle behind JIT is that (1) supplies of raw materials and parts are delivered to the manufacturer just in time to be used, (2) parts and components are produced just in time to be made into subassemblies, and (3) products are assembled and finished just in time to be delivered to the customer. As a result, inventory carrying costs are low, defects in components are detected right away, productivity is increased, and high-quality products are made at low cost.
9. **Cellular manufacturing** (CM). This system utilizes workstations that consist of a number of *manufacturing cells*, each containing various production machines controlled by a central robot, with each machine performing a different operation on the part, including inspection.
10. **Flexible manufacturing systems** (FMS). These systems integrate manufacturing cells into a large production facility, with all of the cells interfaced with a central computer. Although very costly, flexible manufacturing systems are capable of producing parts efficiently, but in relatively small quantities, and of quickly changing manufacturing sequences required for different parts. Flexibility enables these systems to meet rapid changes in market demand for all types of products.
11. **Expert systems** (ES). Consisting basically of complex computer programs, these systems have the capability of performing various tasks and solving difficult real-life problems, much as human experts would, including expediting the traditional iterative process in design optimization.
12. **Artificial intelligence** (AI). Computer-controlled systems are now capable of learning from experience and of making decisions that optimize operations and minimize costs, ultimately replacing human intelligence.
13. **Artificial neural networks** (ANN). These networks are designed to simulate the thought processes of the human brain, with such capabilities as modeling and simulating production facilities, monitoring and controlling manufacturing processes, diagnosing problems in machine performance, and conducting financial planning and managing a company's manufacturing strategy.

EXAMPLE I.5 Mold for Making Sunglasses Frames

The metal mold used for injection molding of plastic sunglasses is made on a computer numerical-control milling machine, by using a cutter (called a ball-nosed end mill), as illustrated in Fig. I.11. First, a model of the sunglasses is made using a computer-aided design software package, from which a model of the mold is automatically generated. The geometric information is sent to the milling machine, and the machining steps are planned.

Next, an offset is added to each surface to account for the nose radius of the end mill during machining, thus determining the cutter path (i.e., the path followed by the center of rotation of the machine spindle). The numerical-control programming software executes this machining program on the milling machine, producing the die cavity with appropriate dimensions and tolerances. Electrical-discharge machining (Section 27.5) can also be used to make this mold; however, it was determined that the procedure was about twice as expensive as machining the mold by computer numerical control, and it produced molds with lower dimensional accuracy.

Source: Courtesy of Mold Threads, Inc.

(a) (b)

FIGURE I.11 Machining a mold cavity for making sunglasses. (a) Computer model of the sunglasses as designed and viewed on the monitor. (b) Machining of the die cavity, using a computer numerical-control milling machine. *Source*: Courtesy of Mastercam/CNC Software, Inc.

I.8 Quality Assurance and Total Quality Management

Product quality is one of the most critical aspects of manufacturing, because it directly influences customer satisfaction, thus playing a crucial role in determining a product's success in the global marketplace (Chapter 36). The traditional approach of inspecting products after they are made has largely been replaced by the recognition that *quality must be built into the product* from its initial design through all subsequent stages of manufacture and assembly.

Because products are typically made through several manufacturing steps and operations, each step can involve its own significant variations in performance, which can occur even within a relatively short time. A production machine, for example, may perform differently when it is first turned on than when it warms up during its use or when the ambient temperature in the plant fluctuates. Consequently, *continuous control of processes* (known as *online monitoring*) is a critical factor in maintaining product quality, and the objective must be to *control processes*, *not products*.

Quality assurance and *total quality management* (TQM) are widely recognized as being the responsibility of everyone involved in the design and manufacture of products and their components. *Product integrity* is a term generally used to define the degree to which a product

- Functions reliably during its life expectancy, as shown in Table I.4,
- Is suitable for its intended purposes, and
- Can be maintained with relative ease.

TABLE I.4

Average Life Expectancy of Various Products

Type of product	Life expectancy (years)
U.S. dollar bill	1.5
Personal computer	2
Car battery	4
Hair dryer	5
Automobile	8
Dishwasher	10
Kitchen disposal unit	10
Vacuum cleaner	10
Water heater (gas)	12
Clothes dryer (gas)	13
Clothes washer	13
Air-conditioning unit (central)	15
Manufacturing cell	15
Refrigerator	17
Furnace (gas)	18
Machinery	30
Nuclear reactor	40

Note: Significant variations can be observed, depending on the quality of the product and how well it has been maintained.

TABLE I.5

Relative Cost of Repair at Various Stages of Product Development and Sale

Stage	Relative cost of repair
When part is being made	1
Subassembly of the product	10
Assembly of the product	100
Product at the dealership	1000
Product at the customer	10,000

As Table I.5 indicates, producing defective products can be very costly to the manufacturer, with costs varying by orders of magnitude.

Pioneers in quality control, particularly W.E. Deming (1900–1993), J.M. Juran (1904–2008), and G. Taguchi (1924–), all emphasized the importance of management's commitment to (a) product quality, (b) pride of workmanship at all levels of production, and (c) the necessity of using **statistical process control** (SPC) and **control charts** (Chapter 36). They also pointed out the importance of online monitoring and rapidly identifying the *sources of quality problems* in production, before even another defective part is produced. The major goal of control is to *prevent* defective parts from ever being made, rather than to inspect, detect, and reject defective parts after they have been made.

As an indication of strict quality control, computer chips are now made with such high quality that only a few out of a million chips may be defective. The level of defects is identified in terms of *standard deviation*, denoted by the symbol *sigma*. Three sigma in manufacturing would result in 2700 defective parts per million, which is much too high in modern manufacturing. In fact, it has been estimated that at this level, no modern computer would function reliably. At **six sigma**, defective parts are reduced to only 3.4 per million parts made. This level has been reached through major improvements in manufacturing *process capabilities* in order to *reduce variability* in product quality.

Important developments in quality assurance include the implementation of **experimental design**, a technique in which the factors involved in a manufacturing process and their interactions are studied simultaneously. For example, the variables affecting dimensional accuracy or surface finish in a machining operation can be identified readily, thus making it possible for appropriate preventive on-time actions to be taken.

Quality Standards. Global manufacturing and competitiveness have led to an obvious need for international conformity and consensus in establishing quality control methods. This need resulted in the establishment of the ISO 9000 standards series on quality management and quality assurance standards, as well as of the QS 9000 standards (Section 36.6). A company's registration for these standards, which is a *quality process certification* and not a product certification, means that the company conforms to consistent practices as specified by its own quality system. ISO 9000 and QS 9000 have permanently influenced the manner in which companies conduct business in world trade, and they are now the world standard for quality.

Human-factors Engineering. This topic deals with human–machine interactions and thus is an important aspect of manufacturing operations in a plant, as well as of products in their normal use. The human-factors approach results in the design and manufacture of safe products; it emphasizes **ergonomics**, which is defined as the study of how a workplace and the machinery and equipment in it can best be designed for comfort, safety, efficiency, and productivity.

Some examples of the need for proper ergonomic considerations are represented by (a) a mechanism that is difficult to operate manually, causing injury to the worker, (b) a poorly designed keyboard that causes pain to the user's hands and arms during its normal use (known as *repetitive stress syndrome*), and (c) a control panel on a machine that is difficult to reach or use safely and comfortably.

Product Liability. Designing and manufacturing safe products is among the essential aspects of a manufacturer's responsibilities. All those involved with product design, manufacture, and marketing must fully recognize the consequences of a product's failure, including failure due to forseeable misuse of the product.

As is widely known, a product's malfunction or failure can cause bodily injury or even death, as well as financial loss to an individual, to bystanders, or to an organization. This important topic is referred to as *product liability*, and the laws governing it generally vary from state to state and from country to country. Among the numerous examples of products that could involve liability are the following:

- A grinding wheel shatters and blinds a worker
- A cable supporting a platform snaps, allowing the platform to drop and cause bodily harm or death
- Automotive brakes suddenly become inoperative because of the failure of a particular component of the brake system
- Production machinery lacks appropriate safety guards
- Electric and pneumatic tools lack appropriate warnings and instructions for their safe use
- Aircraft landing gears fail to descend and lock properly.

I.9 Lean Production and Agile Manufacturing

Lean production is a methodology that involves a thorough assessment of each activity of a company, with the basic purpose of minimizing waste at all levels and calling for the elimination of unnecessary operations that do not provide any added value to the product being made. This approach, also called *lean manufacturing*, identifies all of a manufacturer's activities from the viewpoint of the customer and optimizes the processes used in order to *maximize added value*. Lean production focuses on (a) the efficiency and effectiveness of each and every manufacturing operation, (b) the efficiency of the machinery and equipment used, and (c) the activities of the personnel involved in each operation. This methodology also includes a comprehensive analysis of the costs incurred in each activity and those for productive and for nonproductive labor.

The lean production strategy requires a fundamental change in corporate culture, as well as an understanding of the importance of *cooperation and teamwork* among the company's workforce and management. Lean production does not necessarily require cutting back on a company's physical or human resources; rather, it aims at *continually* improving efficiency and profitability by removing all waste in the company's operations and dealing with any problems as soon as they arise.

Agile Manufacturing. The principle behind *agile manufacturing* is ensuring *agility*—and hence *flexibility*—in the manufacturing enterprise, so that it can respond rapidly and effectively to changes in product demand and the needs of the customer. Flexibility can be achieved through people, equipment, computer hardware and software, and advanced communications systems. As an example of this approach, it has been predicted that the automotive industry could configure and build a car in three days and that, eventually, the traditional assembly line will be replaced by a system in which a nearly custom made car will be produced by combining several individual modules.

The methodologies of both lean and agile production require that a manufacturer **benchmark** its operations. Benchmarking involves assessing the competitive position of other manufacturers with respect to one's own position (including product quality, production time, and manufacturing cost) and setting realistic goals for the future. Benchmarking thus becomes a *reference point* from which various measurements can be made and to which they can be compared.

I.10 Manufacturing Costs and Global Competition

Always critically important, the economics of manufacturing has become even more so with (a) ever-increasing global competition and (b) the demand for high-quality products, generally referred to as *world-class manufacturing*, at low prices. Typically, the *manufacturing cost* of a product represents about 40% of its *selling price*, which often is the overriding consideration in a product's marketability and general customer satisfaction. An approximate, but typical, breakdown of costs in modern manufacturing is given in Table I.6. The percentages indicated can, however, vary significantly depending on product type.

The *total cost* of manufacturing a product generally consists of the following components:

1. **Materials**. Raw-material costs depend on the material itself, as well as on supply and demand. Low cost may not be the deciding factor if the cost of processing a

TABLE I.6

Typical Cost Breakdown in Manufacturing	
Design	5%
Materials	50%
Manufacturing	
Direct labor	15%
Indirect labor	30%

particular material is higher than that for a more expensive material. For example, a low-cost piece of material may require more time to machine or form than one of higher cost, thus increasing production costs.

2. **Tooling**. Tooling costs include those for cutting tools, dies, molds, workholding devices, and fixtures. Some cutting tools cost as little as \$2 and as much as about \$100 for materials such as cubic boron nitride and diamond. Depending on their size and the materials involved in making them, molds and dies can cost from only a few hundred dollars to over \$2 million for a set of dies for stamping sheet metal to make automobile fenders.
3. **Fixed**. Fixed costs include costs for energy, rent for facilities, insurance, and real-estate taxes.
4. **Capital**. Production machinery, equipment, buildings, and land are typical capital costs. Machinery costs can range from a few thousand to over a million dollars. Although the cost of computer-controlled machinery can be very high, such an expenditure may well be warranted in view of its long-range benefit of reducing labor costs.
5. **Labor**. Labor costs consist of direct and indirect costs. *Direct labor*, also called *productive labor*, concerns the labor that is directly involved in manufacturing products. *Indirect labor* pertains to servicing of the total manufacturing operation; it is also called *nonproductive labor* or *overhead*. Direct-labor costs may be only 10 to 15% of the total cost (Table I.6), but it can be as much as 60% for labor-intensive products. Reductions in the direct-labor share of manufacturing costs can be achieved by such means as extensive automation, computer control of all aspects of manufacturing, the implementation of modern technologies, and increased efficiency of operations.

As shown in Table I.7, there is a worldwide disparity in labor costs, by an order of magnitude. It is not surprising that today numerous consumer products are manufactured mostly in Pacific Rim countries, especially China, or they are assembled in Mexico. Likewise, software and information technologies are often much less costly to develop in countries such as India and China than in the United States or Europe. As living standards continue to rise, however, labor costs, too, are beginning to rise significantly in such countries.

Outsourcing. A more recent trend has been *outsourcing*, defined as the purchase by a company of parts or labor from an outside source, from either another company or another country, in order to reduce design and manufacturing costs. There is increasing evidence, however, that, depending on the type of product, manufacturing abroad can have significant challenges, including the rising cost of shipping. Another problem is the social impact and political implications of any ensuing lowered employment, especially in the European Union countries and the United States.

TABLE I.7

Approximate Relative Hourly Compensation for Workers in Manufacturing in 2006 (United States = 100)

Norway	154	Italy	96
Germany	137	Japan	81
Denmark	127	Spain	73
Austria	122	Korea (South)	56
Belgium	121	New Zealand	54
Switzerland	119	Israel	48
Netherlands	118	Singapore	45
Finland	117	Portugal	32
Sweden	114	Czech Republic	27
France, United Kingdom	112	Argentina, Slovakia	22
Ireland	103	Poland	21
United States, Australia	**100**	Mexico	12
Canada	97	China, Philippines	5

Note: Compensation can vary significantly with benefits. *Source*: U.S. Department of Labor.

I.11 General Trends in Manufacturing

Following are some general trends that have been observed regarding various aspects of manufacturing today:

Global manufacturing trends

1. Product variety and complexity continue to increase.
2. Product life cycles are becoming shorter.
3. Markets have become multinational and global competition has been increasing rapidly.
4. Market conditions fluctuate widely.
5. Customers are consistently demanding high-quality, low-cost products and on-time delivery.

Materials

6. Material composition, purity, and defects (impurities, inclusions, and flaws) are coming under more control in order to further enhance overall properties, manufacturing characteristics, reliability, and service life.
7. Developments have occurred in the selection of materials for improved recyclability.
8. Developments continue in nanomaterials, nanopowders, composites, superconductors, semiconductors, amorphous alloys, shape-memory alloys (smart materials), tool and die materials, and coatings.
9. Testing methods and equipment, including the use of advanced computers and software, particularly for ceramics, carbides, and composite materials, are continually being improved.
10. Increasing control over the thermal treatment of materials is resulting in more predictable and reliable properties.

11. Weight savings are being achieved with the use of materials with higher strength-to-weight and stiffness-to-weight ratios, particularly in the automotive and aerospace industries.

Manufacturing operations

12. Improvements are being made in predictive models of the effects of material-processing parameters on product integrity, applied during a product's design stage.
13. Developments continue in ultraprecision manufacturing, micromanufacturing, and nanomanufacturing, approaching the level of atomic dimensions.
14. Computer simulation, modeling, and control strategies are being applied to all areas of manufacturing.
15. Rapid-prototyping technologies are increasingly being applied to the production of tooling and direct digital manufacturing.
16. Optimization of manufacturing processes and production systems are making them more agile.

Manufacturing systems

17. Advances in computer software and hardware are being applied to all aspects of production.
18. Developments have occurred in control systems, industrial robots, automated inspection, handling and assembly, and sensor technology.
19. Lean production and information technology are being implemented as tools to help meet major global challenges.

Goals in manufacturing

20. View manufacturing activities not as individual, separate tasks, but as making up a *large system*, with all its parts interrelated.
21. Meet all *design requirements, product specifications*, and relevant *national and international standards* for products.
22. Build *quality* into the product at each stage of its production.
23. Implement the most *economical and environmentally friendly (green)* manufacturing methods.
24. Continually evaluate advances in *materials, production methods*, and *computer integration*, with a view toward realizing their appropriate, timely, and economical implementation.
25. Adopt production methods that are sufficiently *flexible* in order to rapidly respond to changing global market demands and provide on-time delivery to the customer.
26. Continue efforts aimed at achieving *higher levels of productivity* and eliminating or minimizing waste with optimum use of an organization's resources.
27. Cooperate with customers for timely feedback for *continuous improvement* of a company's products.

Metal-Casting Processes and Equipment

PART II

As described throughout the rest of this book, several different methods are available to shape metals into useful products. One of the oldest processes is **casting**, which basically involves pouring molten metal into a mold cavity. Upon solidification, the metal takes the shape of the cavity. Examples of cast parts are shown in Figure II.1. Casting first was used around 4000 B.C. to make ornaments, arrowheads, and various other objects. A wide variety of products can be cast, and the process is capable of producing intricate shapes in one piece, including those with internal cavities, such as engine blocks. Figure II.2 shows cast components in a typical automobile, a product that was used in the introduction to Part I to illustrate the selection and use of a variety of materials. The casting processes developed over the years are shown in Fig. II.3.

(a) (b)

FIGURE II.1 Examples of cast parts. (a) A die-cast aluminum transmission housing. (b) A tree of rings produced through investment casting. *Source*: (a) Courtesy of North American Die Casting Association, (b) Courtesy of Romanoff, Inc.

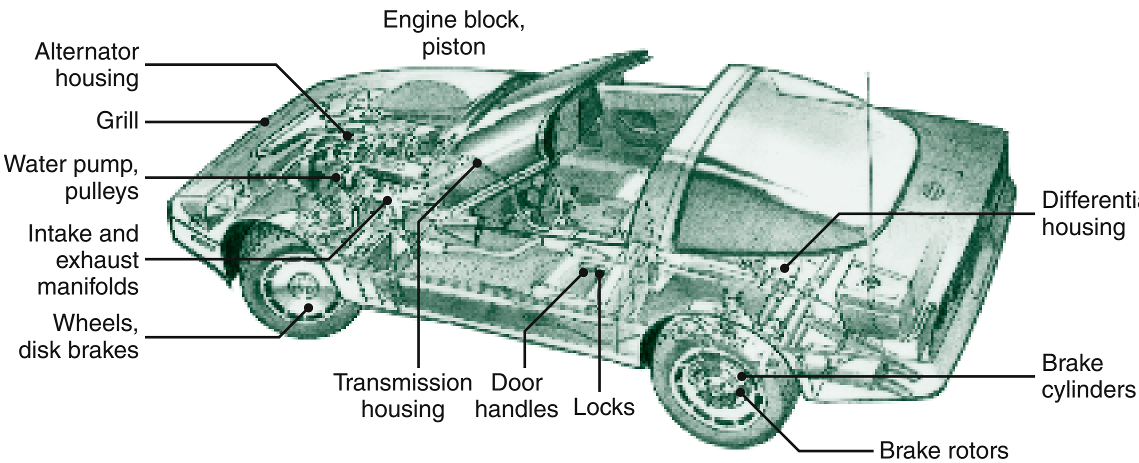


FIGURE II.2 Cast parts in a typical automobile.

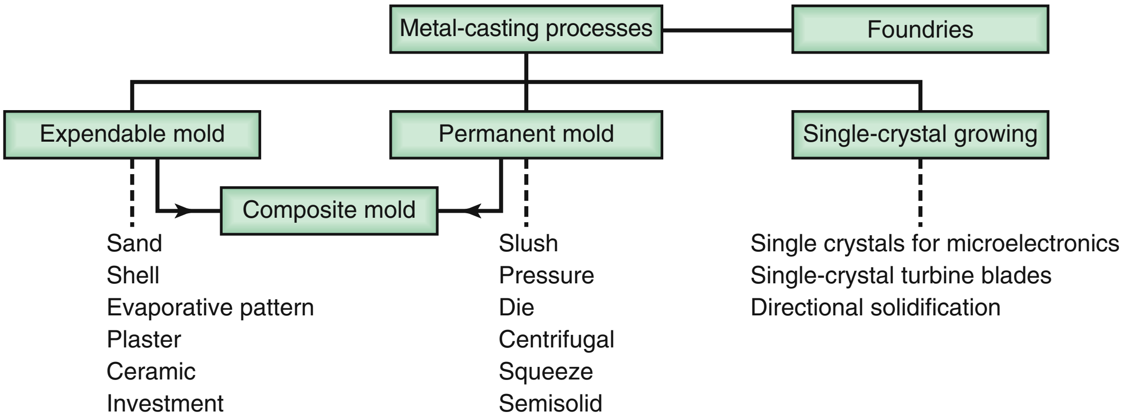


FIGURE II.3 Outline of metal-casting processes described in Part II.

As in all manufacturing operations, each casting process has its own characteristics, applications, advantages, limitations, and costs. Casting processes are most often selected over other manufacturing methods for the following reasons:

- Casting can produce complex shapes and can incorporate internal cavities or hollow sections.
- Very large parts can be produced in one piece.
- Casting can utilize materials that are difficult or uneconomical to process by other means.
- The casting process can be economically competitive with other manufacturing processes.

Almost all metals can be cast in (or nearly in) the final shape desired, often requiring only minor finishing operations. This capability places casting among the most important *net-shape manufacturing* technologies, along with net-shape forging (Chapter 14), stamping of sheet metal (Chapter 16), and powder metallurgy and metal-injection molding (Chapter 17). With modern processing techniques and the control of chemical composition, mechanical properties of castings can equal those made by other manufacturing processes.

Fundamentals of Metal Casting

CHAPTER 10

- First used about 6 thousand years ago, casting continues to be an important manufacturing process for producing very small, as well as very large and complex, parts.
- The first topic discussed is solidification of molten metals, including the differences between solidification of pure metals and alloys, as well as concepts such as grain nucleation and freezing range.
- Fluid flow in casting is then described, with Bernoulli's and the continuity equations being applied to establish a framework for analyzing molten metal flow through a mold.
- The concept and importance of turbulence versus laminar flow is introduced.
- Heat transfer and shrinkage of castings are also discussed, including Chvorinov's rule for solidification time.
- The chapter ends with a description of the causes of porosity in castings and common methods of reducing them to improve cast-metal properties.

EXAMPLES:

10.1 Introduction

The **casting** process basically involves (a) pouring molten metal into a mold patterned after the part to be manufactured, (b) allowing it to solidify, and (c) removing the part from the mold. As with all other manufacturing processes, an understanding of the underlying science is essential for the production of good-quality, economical castings and for establishing proper techniques for mold design and casting practice.

Important considerations in casting operations are as follows:

- Flow of the molten metal into the mold cavity
- Solidification and cooling of the metal in the mold
- Influence of the type of mold material.

This chapter describes relationships among the many factors involved in casting. The flow of molten metal into the mold cavity first is discussed in terms of mold design and fluid-flow characteristics. Solidification and cooling of metals in the mold are affected by several factors, including the metallurgical and thermal properties of the metal. The type of mold also has an important influence, because it affects the rate of cooling. The chapter finishes with a description of the factors influencing defect formation.

Industrial metal-casting processes, design considerations, and casting materials are described in Chapters 11 and 12. The casting of ceramics and of plastics, which involves methods and procedures somewhat similar to those for metal, are described in Chapters 18 and 19, respectively.

10.2 Solidification of Metals

After molten metal is poured into a **mold**, a series of events takes place during the solidification of the metal and its cooling to ambient temperature. These events greatly influence the size, shape, uniformity, and chemical composition of the grains formed throughout the casting, which in turn influence the overall properties of the metal. The significant factors affecting these events are the type of metal, the thermal properties of both the metal and the mold, the geometric relationship between volume and surface area of the casting, and the shape of the mold.

10.2.1 Pure Metals

Because a pure metal has a clearly defined melting (or freezing) point, it solidifies at a constant temperature, as shown in Fig. 10.1. Pure aluminum, for example, solidifies at 660°C (1220°F), iron at 1537°C (2798°F), and tungsten at 3410°C (6170°F). (See also Table 3.1 and Fig. 4.4.) After the temperature of the molten metal drops to its freezing point, its temperature remains constant while the *latent heat of fusion* is given off. The *solidification front* (solid–liquid interface) moves through the molten metal from the mold walls in toward the center. The solidified metal, called the casting, is taken out of the mold and allowed to cool to ambient temperature.

As shown in Fig. 10.1b and described in greater detail in Section 10.5.2, metals shrink while cooling and generally also shrink when they solidify (see Table 10.1).

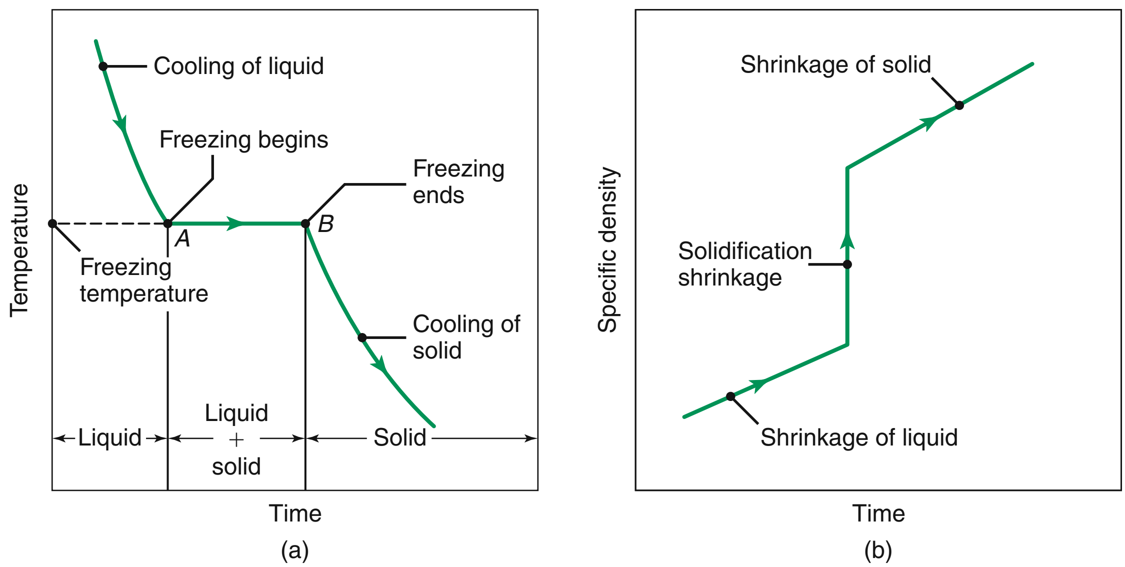


FIGURE 10.1 (a) Temperature as a function of time for the solidification of pure metals. Note that freezing takes place at a constant temperature. (b) Density as a function of time.

This is an important consideration, because shrinkage can lead to microcracking and associated porosity, which can in turn compromise the mechanical properties of the casting.

As an example of the grain structure that develops in a casting, Fig. 10.2a shows a cross section of a box-shaped mold. At the mold walls, which are at ambient temperature or typically are much cooler than the molten metal, the metal cools rapidly and produces a solidified **skin**, or *shell*, of fine equiaxed grains. The grains generally grow in a direction opposite to that of the heat transfer out through the mold. Those grains that have favorable orientation grow preferentially and are called **columnar grains** (Fig. 10.3). Those grains that have substantially different orientations are blocked from further growth. As the driving force of the heat transfer is reduced away from the mold walls, the grains become equiaxed and coarse. This process of grain development is known as **homogenous nucleation**, meaning that the grains (crystals) grow upon themselves, starting at the mold wall.

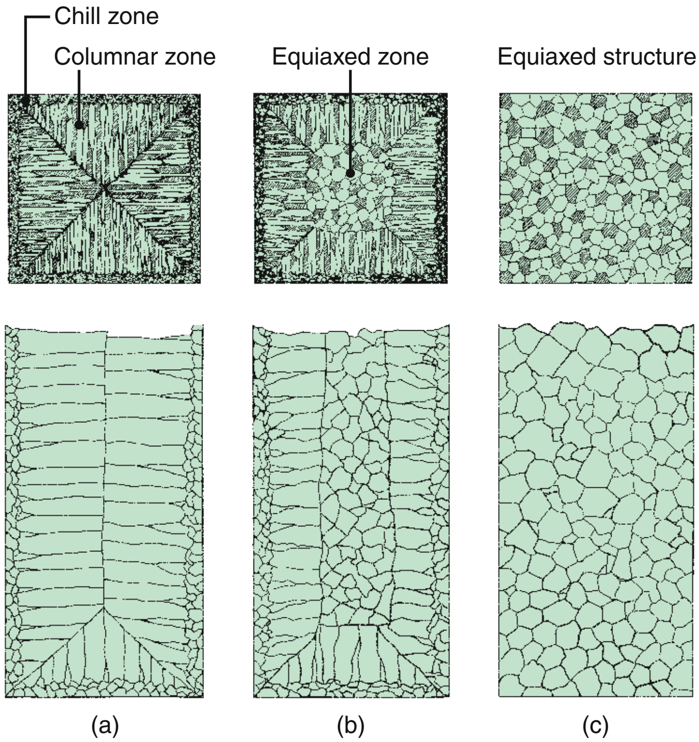


FIGURE 10.2 Schematic illustration of three cast structures of metals solidified in a square mold: (a) pure metals; (b) solid–solution alloys; and (c) structure obtained by using nucleating agents. *Source*: After G.W. Form, J.F. Wallace, J.L. Walker, and A. Cibula.

10.2.2 Alloys

Solidification in alloys begins when the temperature drops below the liquidus, T_L, and is complete when it reaches the solidus, T_S (Fig. 10.4). Within this temperature range, the alloy is in a *mushy* or *pasty* state consisting of **columnar dendrites** (from the Greek *dendron*, meaning "akin to," and *drys*, meaning "tree"). Note the presence of liquid metal between the dendrite arms. Dendrites have three-dimensional arms and branches (secondary arms), which eventually interlock, as can be seen in Fig. 10.5. The study of dendritic structures (although complex) is important, because such structures contribute to detrimental factors, such as compositional variations, segregation, and microporosity within a cast part.

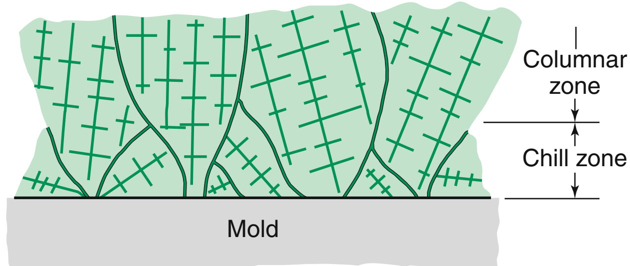


FIGURE 10.3 Development of a preferred texture at a cool mold wall. Note that only favorably oriented grains grow away from the surface of the mold.

The width of the **mushy zone** (where both liquid and solid phases are present) is an important factor during solidification. This zone is described in terms of a temperature difference, known as the **freezing range**:

$$\text{Freezing range} = T_L - T_S. \tag{10.1}$$

It can be seen in Fig. 10.4 that pure metals have a freezing range that approaches zero and that the solidification front moves as a plane without forming a mushy zone. *Eutectics* (Section 4.3) solidify in a similar manner, with an essentially plane front. The type of structure developed after solidification depends on the composition of the eutectic. In alloys with a nearly symmetrical phase diagram, the structure is generally lamellar, with two or more solid phases present, depending on

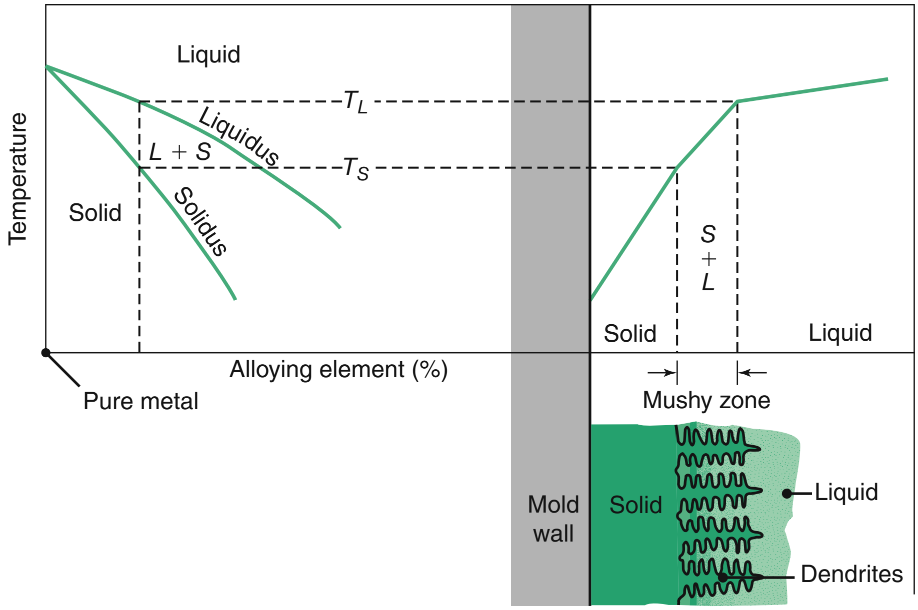


FIGURE 10.4 Schematic illustration of alloy solidification and temperature distribution in the solidifying metal. Note the formation of dendrites in the mushy zone.

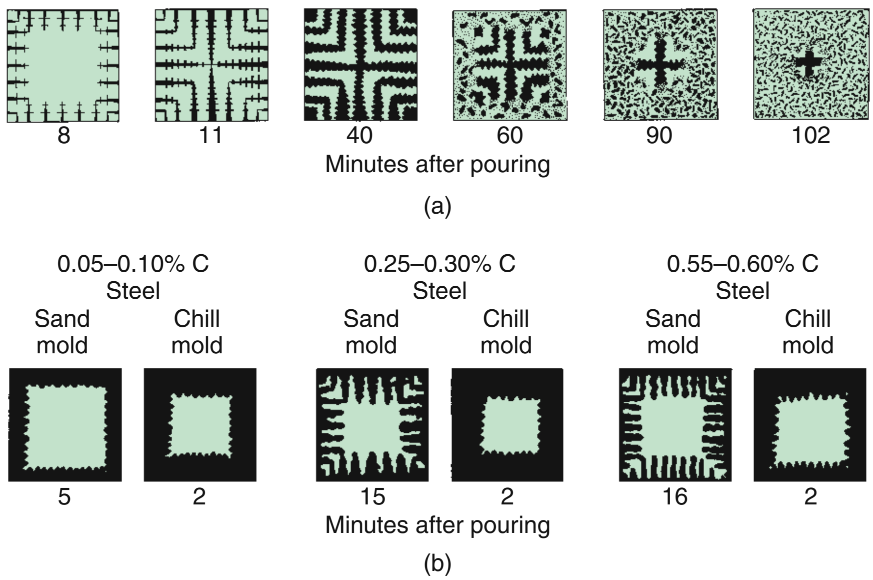


FIGURE 10.5 (a) Solidification patterns for gray cast iron in a 180-mm (7-in.) square casting. Note that after 11 minutes of cooling, dendrites reach each other, but the casting is still mushy throughout. It takes about 2 hours for this casting to solidify completely. (b) Solidification of carbon steels in sand and chill (metal) molds. Note the difference in solidification patterns as the carbon content increases. *Source*: After H.F. Bishop and W.S. Pellini.

the alloy system. When the volume fraction of the minor phase of the alloy is less than about 25%, the structure generally becomes fibrous. These conditions are particularly important for cast irons.

For alloys, a *short freezing range* generally involves a temperature difference of less than 50°C (90°F), and a *long freezing range* greater than 110°C (200°F). Ferrous castings generally have narrow mushy zones, whereas aluminum and magnesium alloys have wide mushy zones. Consequently, these alloys are in a mushy state throughout most of the solidification process.

Effects of Cooling Rates. Slow cooling rates (on the order of 10^2 K/s) or long local solidification times result in *coarse* dendritic structures with large spacing between dendrite arms. For higher cooling rates (on the order of 10^4 K/s) or short local solidification times, the structure becomes *finer* with smaller dendrite arm spacing. For still higher cooling rates (on the order of from 10^6 to 10^8 K/s) the structures developed are *amorphous*, as described in Section 6.14.

The structures developed and the resulting grain size influence the properties of the casting. As grain size decreases, the strength and the ductility of the cast alloy increase, microporosity (interdendritic shrinkage voids) in the casting decreases, and the tendency for the casting to crack (*hot tearing*, see Fig. 10.12) during solidification decreases. Lack of uniformity in grain size and grain distribution results in castings with *anisotropic properties*.

A criterion describing the kinetics of the liquid–solid interface is the ratio G/R, where G is the *thermal gradient* and R is the *rate* at which the interface moves. Typical values for G range from 10^2 to 10^3 K/m and for R range from 10^{-3} to 10^{-4} m/s. Dendritic-type structures (Fig. 10.6a and b) typically have a G/R ratio in the range from 10^5 to 10^7, whereas ratios of 10^{10} to 10^{12} produce a plane-front, nondendritic liquid–solid interface (Fig. 10.7).

10.2.3 Structure–property Relationships

Because all castings are expected to possess certain properties to meet design and service requirements, the relationships between properties and the structures developed during solidification are important aspects of casting. This section describes these relationships in terms of dendrite morphology and the concentration of alloying elements in various regions within the metal.

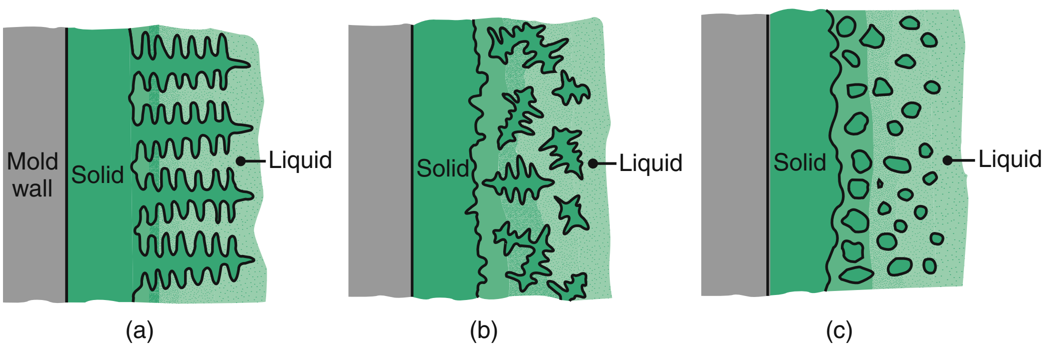


FIGURE 10.6 Schematic illustration of three basic types of cast structures: (a) columnar dendritic; (b) equiaxed dendritic; and (c) equiaxed nondendritic. *Source*: Courtesy of D. Apelian.

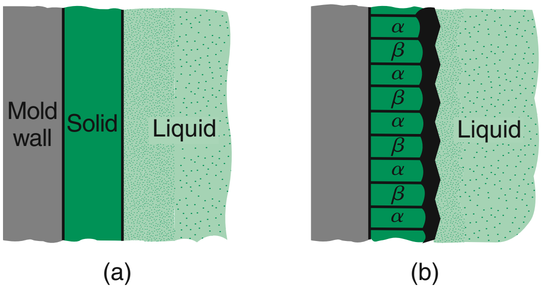


FIGURE 10.7 Schematic illustration of cast structures in (a) plane front, single phase, and (b) plane front, two phase. *Source*: Courtesy of D. Apelian.

The compositions of dendrites and the liquid metal are given by the *phase diagram* of the particular alloy. When the alloy is cooled very slowly, each dendrite develops a uniform composition. However, under the normally faster cooling rates encountered in practice, **cored dendrites** are formed. Cored dendrites have a surface composition different from that at their centers, a difference referred to as a *concentration gradient*. The surface of the dendrite has a higher concentration of alloying elements than does its core, due to solute rejection from the core toward the surface during solidification of the dendrite (**microsegregation**). The darker shading in the interdendritic liquid near the dendrite roots shown in Fig. 10.6 indicates that these regions have a higher solute concentration; microsegregation in these regions is much more pronounced than in others.

There are several types of **segregation**. In contrast to microsegregation, **macrosegregation** involves differences in composition throughout the casting itself. In situations where the solidification front moves away from the surface of a casting as a plane (Fig. 10.7), lower melting-point constituents in the solidifying alloy are driven toward the center (**normal segregation**). Consequently, such a casting has a higher concentration of alloying elements at its center than at its surfaces. In dendritic structures such as those found in solid–solution alloys (Fig. 10.2b), the opposite occurs; that is, the center of the casting has a lower concentration of alloying elements (**inverse segregation**) than does its surface. The reason is that liquid metal (having a higher concentration of alloying elements) enters the cavities developed from solidification shrinkage in the dendrite arms, which have solidified sooner.

Another form of segregation is due to gravity. **Gravity segregation** describes the process whereby higher density inclusions or compounds sink and lighter elements (such as antimony in an antimony–lead alloy) float to the surface.

A typical cast structure of a solid–solution alloy with an inner zone of equiaxed grains is shown in Fig. 10.2b. This inner zone can be extended throughout the casting, as shown in Fig. 10.2c, by adding an **inoculant** (*nucleating agent*) to the alloy. The inoculant induces nucleation of the grains throughout the liquid metal (**heterogeneous nucleation**).

Because of the presence of *thermal gradients* in a solidifying mass of liquid metal, and due to gravity and the resultant density differences, *convection* has a strong influence on the structures developed. Convection promotes the formation of an outer chill zone, refines grain size, and accelerates the transition from columnar to equiaxed grains. The structure shown in Fig. 10.6b also can be obtained by increasing convection within the liquid metal, whereby dendrite arms separate (**dendrite multiplication**). Conversely, reducing or eliminating convection results in coarser and longer columnar dendritic grains.

The dendrite arms are not particularly strong and can be broken up by agitation or mechanical vibration in the early stages of solidification (as in **semisolid metal forming** and **rheocasting**, described in Section 11.4.7). This process results in finer grain size, with equiaxed nondendritic grains distributed more uniformly throughout the casting (Fig. 10.6c). A side benefit is the **thixotropic** behavior of alloys (that is, the viscosity decreases when the liquid metal is agitated), leading to improved castability. Another form of semisolid metal forming is *thixotropic casting*, where a solid billet is heated to the semisolid state and then injected into a die-casting mold (Section 11.4.5). The heating is usually by convection in a furnace, but can be enhanced by the use of mechanical or electromagnetic methods.

10.3 Fluid Flow

To emphasize the importance of fluid flow in casting, let's briefly describe a basic gravity-casting system, as shown in Fig. 10.8. The molten metal is poured through a **pouring basin** or **cup**; it then flows through the **gating system** (consisting of sprue, runners, and gates) into the mold cavity. As also illustrated in Fig. 11.3, the **sprue** is a tapered vertical channel through which the molten metal flows downward in the mold. **Runners** are the channels that carry the molten metal from the sprue into the mold cavity or connect the sprue to the **gate** (that portion of the runner through which the molten metal enters the mold cavity). **Risers** (also called **feeders**) serve as reservoirs of molten metal to supply any molten metal necessary to prevent porosity due to shrinkage during solidification.

Although such a gating system appears to be relatively simple, successful casting requires proper design and control of the solidification process to ensure adequate fluid flow in the system. For example, an important function of the gating system in sand casting is to *trap contaminants* (such as oxides and other inclusions) and remove them from the molten metal by having the contaminants adhere to the walls of the gating system, thereby preventing them from reaching the mold cavity. Furthermore, a properly designed gating system helps avoid or minimize problems such as premature cooling, turbulence, and gas entrapment. Even before it reaches the mold cavity, the molten metal must be handled carefully to avoid the formation of oxides on molten-metal surfaces from exposure to the environment or the introduction of impurities into the molten metal.

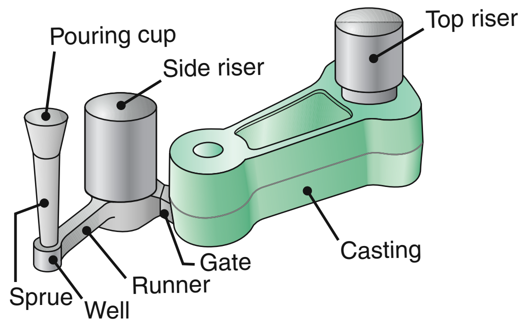


FIGURE 10.8 Schematic illustration of a typical riser-gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification.

Two basic principles of fluid flow are relevant to gating design: Bernoulli's theorem and the law of mass continuity.

Bernoulli's Theorem. This theorem is based on the principle of the conservation of energy and relates pressure, velocity, the elevation of the fluid at any location in the system, and the frictional losses in a system that is full of liquid. The Bernoulli equation is

$$h + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{constant}, \tag{10.2}$$

where h is the elevation above a certain reference level, p is the pressure at that elevation, v is the velocity of the liquid at that elevation, ρ is the density of the fluid (assuming that it is incompressible), and g is the gravitational constant. Conservation of energy requires that, at a particular location in the system, the following relationship be satisfied:

$$h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} = h_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + f, \tag{10.3}$$

where the subscripts 1 and 2 represent two different locations in the system and f represents the frictional loss in the liquid as it travels through the system. The frictional loss includes such factors as energy loss at the liquid-mold wall interfaces and turbulence in the liquid.

Mass Continuity. The law of mass continuity states that, for incompressible liquids and in a system with impermeable walls the rate of flow is constant. Thus,

$$Q = A_1 v_1 = A_2 v_2, \tag{10.4}$$

where Q is the volume rate of flow (such as m^3/s), A is the cross sectional area of the liquid stream, and v is the average velocity of the liquid in that cross section. The subscripts 1 and 2 refer to two different locations in the system. According to this law, the flow rate must be maintained everywhere in the system. The wall permeability is important, because otherwise some liquid will escape through the walls (as occurs in sand molds). Thus, the flow rate will decrease as the liquid moves through the system. Coatings often are used to inhibit such behavior in sand molds.

Sprue Design. An application of the two principles just stated is the traditional tapered design of sprues (shown in Fig. 10.8). Note that in a free-falling liquid (such as water from a faucet), the cross sectional area of the stream decreases as the liquid gains velocity downward. Thus, if we design a sprue with a constant cross sectional area and pour the molten metal into it, regions can develop where the liquid loses contact with the sprue walls. As a result, **aspiration** (a process whereby air is sucked in or entrapped in the liquid) may take place. One of two basic alternatives is used to prevent aspiration: A tapered sprue is used to prevent molten metal separation from the sprue wall, or straight-sided sprues are supplied with a **choking** mechanism at the bottom, consisting of either a choke core or a runner choke, as shown in Fig. 11.3. The choke slows the flow sufficiently to prevent aspiration in the sprue.

The specific shape of a tapered sprue that prevents aspiration can be determined from Eqs. (10.3) and (10.4). Assuming that the pressure at the top of the sprue is equal to the pressure at the bottom, and that there are no frictional losses, the relationship between height and cross sectional area at any point in the sprue is given by the parabolic relationship

$$\frac{A_1}{A_2} = \sqrt{\frac{h_2}{h_1}}, \tag{10.5}$$

where, for example, the subscript 1 denotes the top of the sprue and 2 denotes the bottom. Moving downward from the top, the cross sectional area of the sprue must therefore decrease. Depending on the assumptions made, expressions other than Eq. (10.5) can also be obtained. For example, we may assume a certain molten-metal velocity, V_1, at the top of the sprue. Then, using Eqs. (10.3) and (10.4), an expression can be obtained for the ratio A_1/A_2 as a function of h_1, h_2, and V_1.

Modeling. Another application of the foregoing equations is in the *modeling of mold filling*. For example, consider the situation shown in Fig. 10.7 where molten metal is poured into a pouring basin; it flows through a sprue to a runner and a gate and fills the mold cavity. If the pouring basin has a much larger cross sectional area than the sprue bottom, then the velocity of the molten metal at the top of the pouring basin is very low and can be taken to be zero. If frictional losses are due to a viscous dissipation of energy, then f in Eq. (10.3) can be taken to be a function of the vertical distance and is often approximated as a linear function. Therefore, the velocity of the molten metal leaving the gate is obtained from Eq. (10.3) as

$$v = c\sqrt{2gh},$$

where h is the distance from the sprue base to the liquid metal height and c is a friction factor. For frictionless flow, c equals unity and for flows with friction, c is always between 0 and 1. The magnitude of c varies with mold material, runner layout, and channel size and can include energy losses due to turbulence, as well as viscous effects.

If the liquid level has reached a height of x at the gate, then the gate velocity is

$$v = c\sqrt{2g}\sqrt{h - x}.$$

The flow rate through the gate will be the product of this velocity and the gate area according to Eq. (10.4). The shape of the casting will determine the height as a function of time. Integrating Eq. (10.4) gives the mean fill time and flow rate, and dividing the casting volume by this mean flow rate gives the mold fill time.

Simulation of mold filling assists designers in the specification of the runner diameter, as well as the size and number of sprues and pouring basins. To ensure that the runners stay open, the fill time must be a small fraction of the solidification time, but the velocity should not be so high as to erode the mold material (referred to as *mold wash*) or to result in too high of a Reynolds number (see the following). Otherwise, turbulence and associated air entrainment results. Many computational tools are now available to evaluate gating designs and assist in the sizing of components such as Magmasoft, ProCast, Quikcast, and Powercast.

Flow Characteristics. An important consideration of the fluid flow in gating systems is the presence of **turbulence**, as opposed to the *laminar flow* of fluids. Turbulence is flow that is highly chaotic; in casting systems such flow can lead to aspiration. The *Reynolds number*, Re, is used to quantify this aspect of fluid flow. It represents the ratio of the *inertia* to the *viscous* forces in fluid flow and is defined as

$$\text{Re} = \frac{vD\rho}{\eta}, \tag{10.6}$$

where v is the velocity of the liquid, D is the diameter of the channel, and ρ and η are the density and viscosity of the liquid, respectively. The higher the Reynolds number, the greater the tendency for turbulent flow to occur.

In gating systems, Re typically ranges from 2000 to 20,000, where a value of up to 2000 represents laminar flow. Between 2000 and 20,000, it represents a mixture of laminar and turbulent flow. Such a mixture generally is regarded as harmless in gating systems. However, Re values in excess of 20,000 represent severe turbulence, resulting in significant air entrainment and the formation of *dross* (the scum that forms on the surface of molten metal) from the reaction of the liquid metal with air and other gases. Techniques for minimizing turbulence generally involve avoidance of sudden changes in flow direction and in the geometry of channel cross sections in gating system design.

Dross or slag can be eliminated only by *vacuum casting* (Section 11.4.2). Conventional atmospheric casting mitigates dross or slag by (a) skimming, (b) using properly designed pouring basins and runner systems, or (c) using filters, which also can eliminate turbulent flow in the runner system. Filters usually are made of ceramics, mica, or fiberglass; their proper location and placement are important for effective filtering of dross and slag.

10.4 Fluidity of Molten Metal

The capability of molten metal to fill mold cavities is called *fluidity*, which consists of two basic factors: (1) characteristics of the molten metal and (2) casting parameters. The following characteristics of molten metal influence fluidity:

Viscosity. As viscosity and its sensitivity to temperature (*viscosity index*) increase, fluidity decreases.

Surface Tension. A high surface tension of the liquid metal reduces fluidity. Because of this, oxide films on the surface of the molten metal have a significant adverse effect on fluidity. For example, an oxide film on the surface of pure molten aluminum triples the surface tension.

Inclusions. Because they are insoluble, inclusions can have a significant adverse effect on fluidity. This effect can be verified by observing the viscosity of a liquid (such as oil) with and without sand particles in it; the liquid with sand in it has a higher viscosity and, hence, lower fluidity.

Solidification Pattern of the Alloy. The manner in which solidification takes place (Section 10.2) can influence fluidity. Moreover, fluidity is inversely proportional to the freezing range: The shorter the range (as in pure metals and eutectics), the higher the fluidity. Conversely, alloys with long freezing ranges (such as solid–solution alloys) have lower fluidity.

The following casting parameters influence fluidity and also influence the fluid flow and thermal characteristics of the system:

Mold Design. The design and dimensions of the sprue, runners, and risers all influence fluidity.

Mold Material and its Surface Characteristics. The higher the thermal conductivity of the mold and the rougher its surfaces, the lower the fluidity of the molten metal. Although heating the mold improves fluidity, it slows down solidification of the metal. Thus, the casting develops coarse grains and hence has lower strength.

Degree of Superheat. *Superheat* (defined as the increment of temperature of an alloy above its melting point) improves fluidity by delaying solidification. The **pouring temperature** often is specified instead of the degree of superheat, because it is specified more easily.

Rate of Pouring. The slower the rate of pouring molten metal into the mold, the lower the fluidity because of the higher rate of cooling when poured slowly.

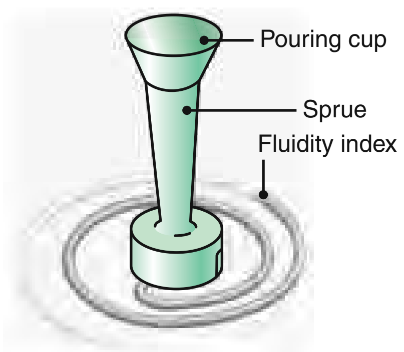


FIGURE 10.9 A test method for fluidity using a spiral mold. The *fluidity index* is the length of the solidified metal in the spiral passage. The greater the length of the solidified metal, the greater is the metal's fluidity.

Heat Transfer. This factor directly affects the viscosity of the liquid metal (see below).

Although complex, the term **castability** generally is used to describe the ease with which a metal can be cast to produce a part with good quality. Castability includes not only fluidity, but the nature of casting practices as well.

10.4.1 Tests for Fluidity

Several tests have been developed to quantify fluidity, although none is accepted universally. In one such common test, the molten metal is made to flow along a channel that is at room temperature (Fig. 10.9); the distance the metal flows before it solidifies and stops flowing is a measure of its fluidity. Obviously, this length is a function of the thermal properties of the metal and the mold, as well as of the design of the channel. Still, such fluidity tests are useful and simulate casting situations to a reasonable degree.

10.5 Heat Transfer

The heat transfer during the complete cycle (from pouring, to solidification, and to cooling to room temperature) is another important consideration in metal casting. Heat flow at different locations in the system is a complex phenomenon and depends on several factors relating to the material cast and the mold and process parameters. For instance, in casting thin sections, the metal flow rates must be high enough to avoid premature chilling and solidification. On the other hand, the flow rate must not be so high as to cause excessive turbulence—with its detrimental effects on the casting process.

A typical temperature distribution at the mold liquid–metal interface is shown in Fig. 10.10. Heat from the liquid metal is given off through the mold wall and to the surrounding air. The temperature drop at the air–mold and mold–metal interfaces is caused by the presence of boundary layers and imperfect contact at these interfaces. The shape of the curve depends on the thermal properties of the molten metal and the mold.

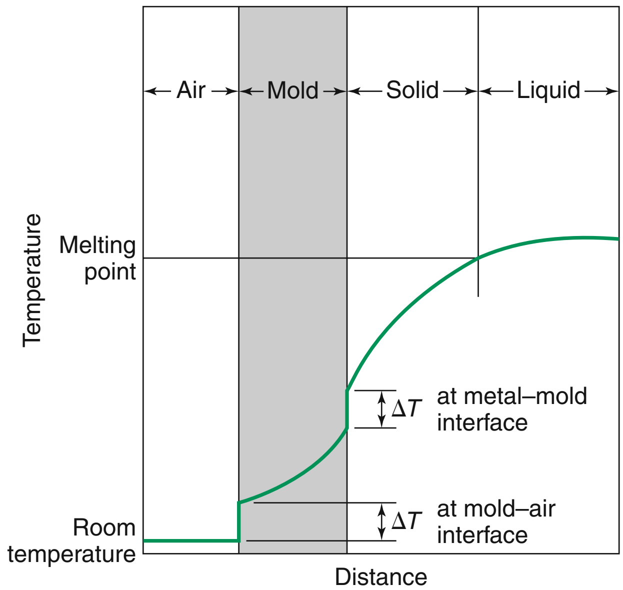


FIGURE 10.10 Temperature distribution at the interface of the mold wall and the liquid metal during the solidification of metals in casting.

10.5.1 Solidification Time

During the early stages of solidification, a thin skin begins to form at the relatively cool mold walls, and as time passes, the thickness of the skin increases (Fig. 10.11). With flat mold walls, this thickness is proportional to the square root of time. Thus, doubling the time will make the skin $\sqrt{2} = 1.41$ times or 41% thicker.

The **solidification time** is a function of the volume of a casting and its surface area (*Chvorinov's rule*):

$$\text{Solidification time} = C\left(\frac{\text{Volume}}{\text{Surface area}}\right)^n, \qquad (10.7)$$

where C is a constant that reflects (a) the mold material, (b) the metal properties (including latent heat), and (c) the temperature. The parameter n has a value between 1.5 and 2, but usually is taken as 2. Thus, a large solid sphere will solidify and cool to ambient temperature at a much slower rate than will a smaller solid sphere. The reason for this is that the volume of a sphere is proportional to the cube of its diameter, and the surface area is proportional to the square of its diameter. Similarly, it can be shown that molten metal in a cube-shaped mold will solidify faster than in a spherical mold of the same volume (see Example 10. 1).

The effects of mold geometry and elapsed time on skin thickness and shape are shown in Fig. 10.11. As illustrated, the unsolidified molten metal has been poured from the mold at different time intervals ranging from 5 seconds to 6 minutes. Note that (as expected) the skin thickness increases with elapsed time, and the skin is thinner at internal angles (location A in the figure) than at external angles (location B). The latter condition is caused by slower cooling at internal angles than at external angles.

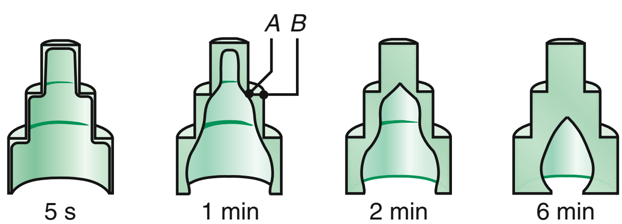


FIGURE 10.11 Solidified skin on a steel casting. The remaining molten metal is poured out at the times indicated in the figure. Hollow ornamental and decorative objects are made by a process called slush casting, which is based on this principle. *Source*: After H.F. Taylor, J. Wulff, and M.C. Flemings.

EXAMPLE 10.1 Solidification Times for Various Shapes

Three metal pieces being cast have the same volume, but different shapes: One is a sphere, one a cube, and the other a cylinder with its height equal to its diameter. Which piece will solidify the fastest, and which one the slowest? Assume that $n = 2$.

Solution The volume of the piece is taken as unity. Thus from Eq. (10.7),

$$\text{Solidification time} \propto \frac{1}{(\text{Surface area})^2}.$$

The respective surface areas are as follows:

Sphere:

$$V = \left(\frac{4}{3}\right)\pi r^3, \; r = \left(\frac{3}{4\pi}\right)^{1/3}.$$

$$A = 4\pi r^2 = 4\pi\left(\frac{3}{4\pi}\right)^{2/3} = 4.84.$$

Cube:

$$V = a^3, \; a = 1, \text{ and } A = 6a^2 = 6.$$

Cylinder:

$$V = \pi r^2 h = 2\pi r^3, \; r = \left(\frac{1}{2\pi}\right)^{1/3},$$

$$A = 2\pi r^2 + 2\pi r h = 6\pi r^2 = 6\pi\left(\frac{1}{2\pi}\right)^{2/3} = 5.54.$$

The respective solidification times are therefore

$$t_{\text{sphere}} = 0.043C, \; t_{\text{cube}} = 0.028C, \; t_{\text{cylinder}} = 0.033C.$$

Hence, the cube-shaped piece will solidify the fastest, and the spherical piece will solidify the slowest.

10.5.2 Shrinkage

Because of their thermal expansion characteristics, metals usually shrink (contract) during solidification and while cooling to room temperature. *Shrinkage*, which causes dimensional changes and sometimes warping and cracking, is the result of the following three sequential events:

1. Contraction of the molten metal as it cools prior to its solidification.
2. Contraction of the metal during phase change from liquid to solid (latent heat of fusion).
3. Contraction of the solidified metal (the casting) as its temperature drops to ambient temperature.

The largest potential amount of shrinkage occurs during the cooling of the casting to ambient temperature. The amount of contraction during the solidification of various metals is shown in Table 10.1. Note that some metals (such as gray cast

TABLE 10.1

Volumetric Solidification Contraction or Expansion for Various Cast Metals

Contraction (%)		Expansion (%)	
Aluminum	7.1	Bismuth	3.3
Zinc	6.5	Silicon	2.9
Al–4.5% Cu	6.3	Gray iron	2.5
Gold	5.5		
White iron	4–5.5		
Copper	4.9		
Brass (70–30)	4.5		
Magnesium	4.2		
90% Cu–10% Al	4		
Carbon steels	2.5–4		
Al–12% Si	3.8		
Lead	3.2		

iron) expand. (The reason is that graphite has a relatively high specific volume, and when it precipitates as graphite flakes during solidification of the gray cast iron, it causes a net expansion of the metal.) Shrinkage is further discussed in Section 12.2.1 in connection with design considerations in casting.

10.6 Defects

As will be seen in this section (as well as in other sections throughout Parts II through VI), various defects can develop during manufacturing that depend on factors such as materials, part design, and processing techniques. While some defects affect only the appearance of the parts made, others can have major adverse effects on the structural integrity of the parts.

Several defects can develop in castings (Figs. 10.12 and 10.13). Because different names have been used in the past to describe the same defect, the International Committee of Foundry Technical Associations has developed a standardized nomenclature consisting of seven basic categories of casting defects, identified with boldface capital letters:

A—Metallic projections, consisting of fins, flash, or projections such as swells and rough surfaces.

B—Cavities, consisting of rounded or rough internal or exposed cavities including blowholes, pinholes, and shrinkage cavities (see *porosity*, Section 10.6.1).

C—Discontinuities, such as cracks, cold or hot tearing, and cold shuts. If the solidifying metal is constrained from shrinking freely, cracking and tearing may occur. Although several factors are involved in tearing, coarse grain size and the presence of low-melting-point segregates along the grain boundaries (*intergranular*) increase the tendency for hot tearing. *Cold shut* is an interface in a casting that lacks complete fusion because of the meeting of two streams of liquid metal from different gates.

D—Defective surface, such as surface folds, laps, scars, adhering sand layers, and oxide scale.

E—Incomplete casting, such as misruns (due to premature solidification), insufficient volume of the metal poured, and runout (due to loss of metal

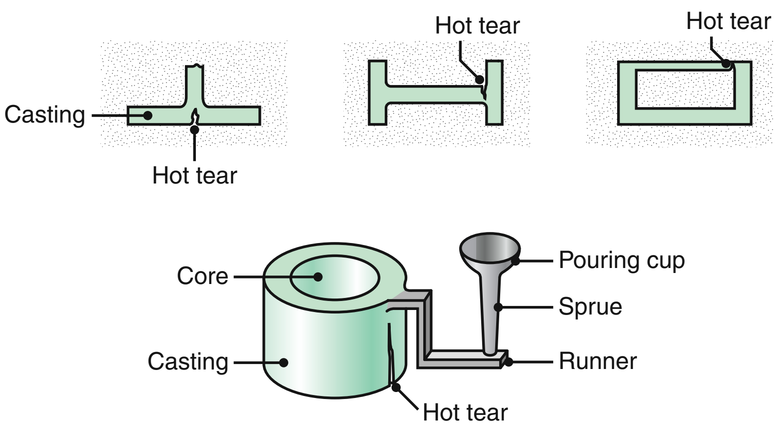


FIGURE 10.12 Examples of hot tears in castings. These defects occur because the casting cannot shrink freely during cooling, owing to constraints in various portions of the molds and cores. Exothermic (heat-producing) compounds may be used (as exothermic padding) to control cooling at critical sections to avoid hot tearing.

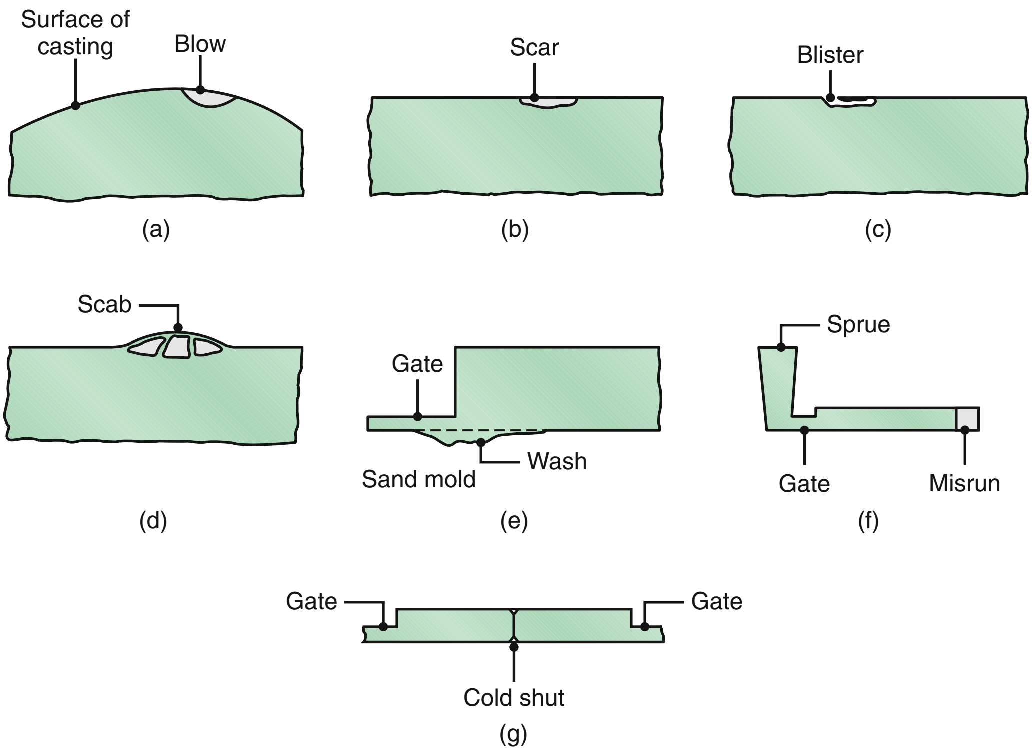


FIGURE 10.13 Examples of common defects in castings. These defects can be minimized or eliminated by proper design and preparation of molds and control of pouring procedures. *Source*: After J. Datsko.

from the mold after pouring). Incomplete castings also can result from the molten metal being at too low a temperature or from pouring the metal too slowly.

F—Incorrect dimensions or shape, due to factors such as improper shrinkage allowance, pattern-mounting error, irregular contraction, deformed pattern, or warped casting.

G—Inclusions, which form during melting, solidification, and molding; these are generally nonmetallic. They are regarded as harmful because they act as stress raisers and thus reduce the strength of the casting. Inclusions may form during melting when the molten metal reacts with the environment (usually oxygen) or with the crucible or mold material. Chemical reactions among components in the molten metal itself may produce inclusions; slags and other foreign material entrapped in the molten metal also become inclusions, although filtering can remove particles as small as 30 μm. Finally, spalling of the mold and core surfaces can produce inclusions, thus indicating the importance of the quality of molds and of their maintenance.

10.6.1 Porosity

Porosity in a casting may be caused by *shrinkage*, entrained or dissolved *gases*, or both. Porous regions can develop in castings because of **shrinkage** of the solidified metal. Thin sections in a casting solidify sooner than thicker regions; as a result, molten metal flows into the thicker regions that have not yet solidified. Porous regions may develop at their centers because of contraction as the surfaces of the thicker region begin to solidify first. *Microporosity* also can develop when the liquid metal solidifies and shrinks between dendrites and between dendrite branches.

Porosity is detrimental to the ductility of a casting and its surface finish, making the casting permeable and thus affecting the pressure tightness of a cast pressure vessel. Porosity caused by shrinkage can be reduced or eliminated by various means, including the following:

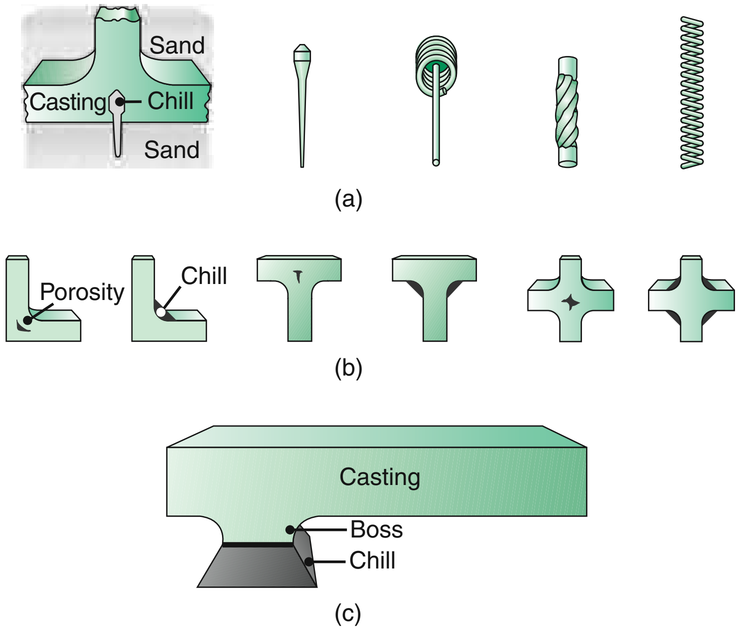


FIGURE 10.14 Various types of (a) internal and (b) external chills (dark areas at corners) used in castings to eliminate porosity caused by shrinkage. Chills are placed in regions where there is a larger volume of metal, as shown in (c).

- Adequate liquid metal should be provided to avoid cavities caused by shrinkage.
- Internal or external **chills**, as those used in sand casting (Fig. 10.14), also are an effective means of reducing shrinkage porosity. The function of chills is to increase the rate of solidification in critical regions. Internal chills usually are made of the same material as the casting and are left in the casting. However, problems may arise that involve proper fusion of the internal chills with the casting; thus, foundries generally avoid the use of internal chills for this reason. External chills may be made of the same material as the casting or may be iron, copper, or graphite.
- With alloys, porosity can be reduced or eliminated by making the temperature gradient steep. For example, mold materials that have higher thermal conductivity may be used.
- Subjecting the casting to *hot isostatic pressing* is another method of reducing porosity (see Section 17.3.2).

Because **gases** are more soluble in liquid metals than solid metals (Fig. 10.15), when a metal begins to solidify, the dissolved gases are expelled from the solution. Gases also may result from reactions of the molten metal with the mold materials. Gases either accumulate in regions of existing porosity (such as in interdendritic regions) or cause microporosity in the casting, particularly in cast iron, aluminum, and copper. Dissolved gases may be removed from the molten metal by *flushing* or *purging* with an inert gas or by melting and pouring the metal in a vacuum. If the dissolved gas is oxygen, the molten metal can be *deoxidized*. Steel usually is deoxidized with aluminum, silicon, copper-based alloys with phosphorus, copper, titanium, or zirconium-bearing materials.

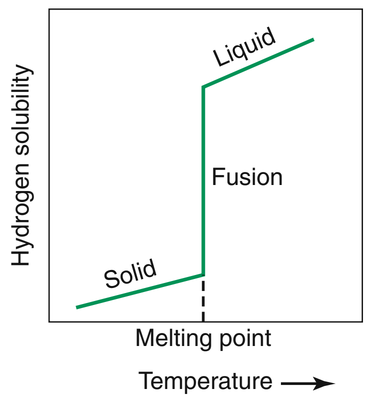


FIGURE 10.15 Solubility of hydrogen in aluminum. Note the sharp decrease in solubility as the molten metal begins to solidify.

Whether microporosity is a result of shrinkage or is caused by gases may be difficult to determine. If the porosity is spherical and has smooth walls (similar to the shiny holes in Swiss cheese), it is generally from gases. If the walls are rough and angular, porosity is likely from shrinkage between dendrites. Gross porosity is from shrinkage and usually is called a **shrinkage cavity**.

EXAMPLE 10.2 Casting of Aluminum Automotive Pistons

Figure 10.16 shows an aluminum piston used in automotive internal combustion engines. These products must be manufactured at very high rates with very tight dimensional tolerances and strict material requirements in order to achieve proper operation. Economic concerns are obviously paramount, and it is essential that pistons be produced with a minimum of expensive finishing operations and with few rejected parts.

Aluminum pistons are manufactured through casting because of the capability to produce near-net shaped parts at the required production rates. However, with poorly designed molds, underfills or excess porosity can cause parts to be rejected, adding to the cost. These defects were traditionally controlled through the use of large machining allowances coupled with the intuitive design of molds based on experience.

The pistons are produced from high-silicon alloys, such as 413.0 aluminum alloy. This alloy has high fluidity and can create high-definition surfaces through permanent mold casting (see Section 11.4); it also has high resistance to corrosion, good weldability, and low specific gravity. The universal acceptance of aluminum pistons for internal combustion engine applications is due mainly to their light weight and high thermal conductivity. Their low inertia allows for higher engine speeds and reduced counterweighting in the crankshaft, and the higher thermal conductivity allows for more efficient heat transfer from the engine.

The H13 tool-steel mold is preheated 200° to 450°C, depending on the cast alloy and part size. Initially, preheat is achieved with a hand-held torch, but after a few castings, the mold reaches a steady-state temperature profile. The molten aluminum is heated to between 100° and 200°C above its liquidus temperature, and then a shot is placed into the infeed section of the mold. Once the molten metal shot is in place, a piston drives the metal into the mold. Because of the high thermal conductivity of the mold material, heat extraction from the molten metal is rapid, and the metal can solidify in small channels before filling the mold completely. Solidification usually starts at one end of the casting, before the mold is fully filled.

As with most alloys, it is desired to begin solidification at one extreme end of the casting and have the solidification front proceed across the volume of the casting. This results in a directionally solidified microstructure and the elimination of gross porosity that arises when two solidification fronts meet inside a casting. Regardless, casting defects such as undercuts, hot spots, porosity, cracking, and entrapped air zone defects (such as blowholes and scabs) can occur.

FIGURE 10.16 Aluminum piston for an internal combustion engine: (a) as cast and (b) after machining. The part on the left is as cast, including risers, sprue, and well, as well as a machining allowance; the part on the right is the piston after machining. *Source*: After S. Paolucci.

In order to improve the reliability of, and reduce the costs associated with, permanent mold casting, computer-based modeling of mold filling can suggest potential causes of defects. The computer models use the Bernoulli and continuity equations, coupled with heat transfer and solidification, to model the casting process and identify potential shortcomings. For example, Fig. 10.17 shows a result from a simulation of mold filling in which a volume of entrapped air remains in the mold. This defect is corrected by placing a vent in the area of concern, to allow air to escape during casting. Computer simulation allows designers to evaluate mold features and geometries before purchasing expensive tooling and has become an indispensible process in reducing costs and eliminating defects in casting.

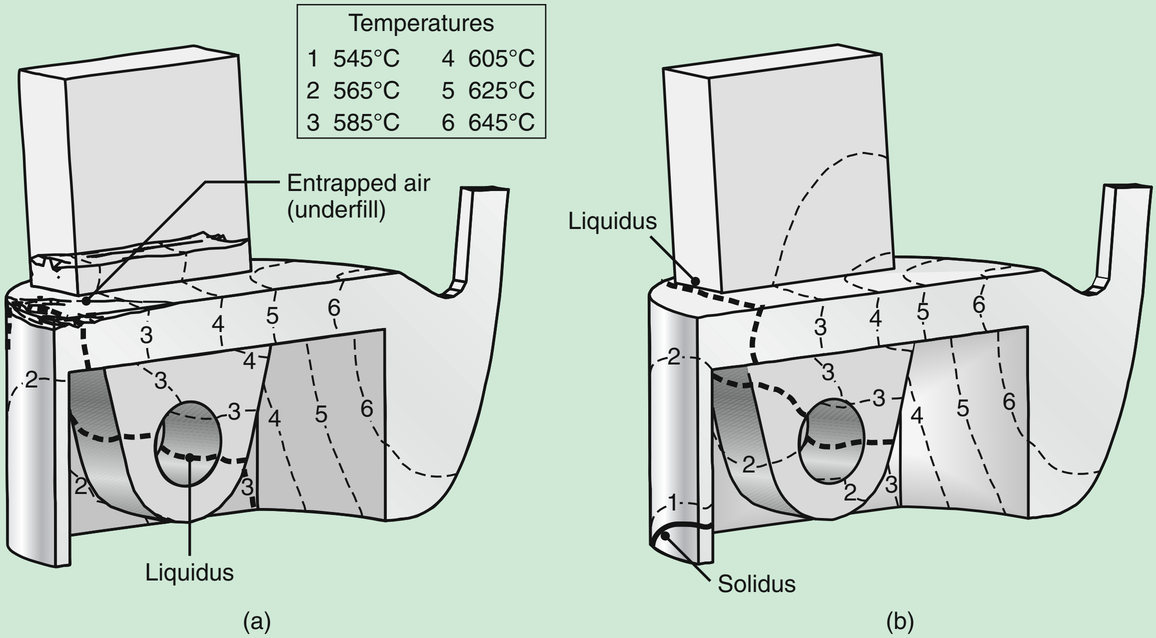


FIGURE 10.17 Simulation of mold filling and solidification. (a) 3.7 seconds after start of pour. Note that the mushy zone has been established before the mold is completely filled. (b) Using a vent in the mold for removal of entrapped air, 5 seconds after pouring. *Source*: After S. Paolucci.

SUMMARY

- Casting is a solidification process in which molten metal is poured into a mold and allowed to cool. The metal may flow through a variety of passages (pouring basins, sprues, runners, risers, and gating systems) before reaching the final mold cavity. Bernoulli's theorem, the continuity law, and the Reynolds number are the analytical tools used in designing castings, with the goals of achieving an appropriate flow rate and eliminating defects associated with fluid flow.
- Solidification of pure metals takes place at a constant temperature, whereas solidification of alloys occurs over a range of temperatures. Phase diagrams are important tools for identifying the solidification point or points for technologically important metals.
- The composition and cooling rates of the molten metal affect the size and shape of the grains and the dendrites in the solidifying alloy. In turn, the size and structure

of grains and dendrites influence properties of the solidified casting. Solidification time is a function of the volume and surface area of a casting (Chvorinov's rule).

- The grain structure of castings can be controlled by various means to obtain desired properties. Because metals contract during solidification and cooling, cavities can form in the casting. Porosity caused by gases evolved during solidification can be a significant problem, particularly because of its adverse effect on the mechanical properties of castings. Various defects also can develop in castings from lack of control of material and process variables.
- Although most metals shrink during solidification, gray cast iron and some aluminum alloys actually expand. Dimensional changes and cracking (hot tearing) are difficulties that can arise during solidification and cooling. Seven basic categories of casting defects have been identified.
- Melting practices have a direct effect on the quality of castings, as do foundry operations, such as pattern and mold making, pouring of the melt, removal of cast parts from molds, cleaning, heat treatment, and inspection.

KEY TERMS

Aspiration
Bernoulli's theorem
Casting
Chills
Columnar dendrite
Columnar grain
Cored dendrite
Dendrite
Fluidity
Freezing range
Gate
Gating system
Heterogeneous nucleation
Homogeneous nucleation
Inoculant
Macrosegregation
Microsegregation
Mold
Mushy zone
Normal segregation
Porosity
Pouring basin
Reynolds number
Rheocasting
Riser
Runner
Segregation
Shrinkage
Skin
Solidification
Sprue
Turbulence

BIBLIOGRAPHY

Alexiades, V., **Mathematical Modeling of Melting and Freezing Processes**, Hemisphere, 1993.

Ammen, C.W., **Metalcasting**, McGraw-Hill, 1999.

Analysis of Casting Defects, American Foundrymen's Society, 1974.

ASM Handbook, Vol. 15: **Casting**, ASM International, 2008.

Campbell, J., **Castings**, Butterworth-Heinemann, 2nd ed., 2003.

Campbell, J., **Castings Practice: The Ten Rules of Casting**, Butterworth-Heinemann, 2004.

Cantor, B., O'Reilly, K., **Solidification and Casting**, Taylor & Francis, 2002.

"Casting," in *Tool and Manufacturing Engineers Handbook*, Volume II: *Forming*, Society of Manufacturing Engineers, 1984.

Kurz, W., and Fisher, D.J., **Fundamentals of Solidification**, Trans Tech Pub., 1994.

Liebermann, H.H. (ed.), **Rapidly Solidified Alloys**, Marcel Dekker, 1993.

Reikher, A., and Barkhudarov, M., **Casting: An Analytical Approach**, Springer, 2008.

Steel Castings Handbook, 6th ed., Steel Founders' Society of America, 1995.

Stefanescu, D.M., **Science and Engineering of Casting Solidification**, Springer, 2002.

Yu, K.-O. (ed.), **Modeling for Casting & Solidification Processing**, CRC Press, 2001.

REVIEW QUESTIONS

10.1. Explain why casting is an important manufacturing process.

10.2. What are the differences between the solidification of pure metals and metal alloys?

10.3. What are dendrites? Why are they called so?

10.4. Describe the difference between short and long freezing ranges.

10.5. What is superheat? Is it important?

design mold features that will remove small amounts of slag before the metal reaches the mold cavity.

10.60. Figure II.2 shows a variety of components in a typical automobile that are produced by casting. Think of other products, such as power tools and small appliances, and prepare an illustration similar to the figure.

10.61. Design an experiment to measure the constants C and n in Chvorinov's rule, Eq. (10.7). Describe the features of your design, and comment on any difficulties that might be encountered in running such an experiment.

CHAPTER

11 Metal-Casting Processes and Equipment

- Building upon the fundamentals of solidification, fluid flow, and heat transfer discussed in Chapter 10, this chapter presents the principles of casting processes.
- Casting processes are generally categorized as permanent-mold and expendable-mold processes; expendable-mold processes are further categorized as permanent-mold and expendable-pattern processes.
- The characteristics of each process are described, together with typical applications, advantages, and limitation.
- Special casting processes that produce single-crystal components as well as amorphous alloys are then described.
- The chapter ends with a discussion of inspection techniques for castings.

Typical products made by casting: engine blocks, crankshafts, hubcaps, power tool housings, turbine blades, plumbing parts, zipper teeth, dies and molds, gears, railroad wheels, propellers, office equipment, and statues.

Alternative processes: forging, powder metallurgy, machining, and fabrication.

11.1 Introduction

The first metal castings were made during the period from 4000 to 3000 B.C., using stone and metal molds for casting copper. Various casting processes have been developed over time, each with its own characteristics and applications (see also Fig. I.6a), to meet specific design requirements (Table 11.1). A large variety of parts and components are made by casting, such as engine blocks, crankshafts, automotive components and powertrains (Fig. 11.1), agricultural and railroad equipment, pipes and plumbing fixtures, power-tool housings, gun barrels, frying pans, jewelry, orthopedic implants, and very large components for hydraulic turbines.

Two trends have had a major impact on the casting industry. The first is the mechanization and automation of the casting process, which has led to significant changes in the use of equipment and labor. Advanced machinery and automated process-control systems have replaced traditional methods of casting. The second major trend has been the increasing demand for high-quality castings with close dimensional tolerances.

This chapter is organized around the major classifications of casting practices (see Fig. II.3 in the Introduction to Part II). These classifications are related to mold

TABLE 11.1

Summary of Casting Processes

Process	Advantages	Limitations
Sand	Almost any metal can be cast; no limit to part size, shape, or weight; low tooling cost	Some finishing required; relatively coarse surface finish; wide tolerances
Shell mold	Good dimensional accuracy and surface finish; high production rate	Part size limited; expensive patterns and equipment
Evaporative pattern	Most metals can be cast, with no limit to size; complex part shapes	Patterns have low strength and can be costly for low quantities
Plaster mold	Intricate part shapes; good dimensional accuracy and surface finish; low porosity	Limited to nonferrous metals; limited part size and volume of production; mold-making time relatively long
Ceramic mold	Intricate part shapes; close-tolerance parts; good surface finish	Limited part size
Investment	Intricate part shapes; excellent surface finish and accuracy; almost any metal can be cast	Part size limited; expensive patterns, molds, and labor
Permanent mold	Good surface finish and dimensional accuracy; low porosity; high production rate	High mold cost; limited part shape and complexity; not suitable for high-melting-point metals
Die	Excellent dimensional accuracy and surface finish; high production rate	High die cost; limited part size; generally limited to nonferrous metals; long lead time
Centrifugal	Large cylindrical or tubular parts with good quality; high production rate	Expensive equipment; limited part shape

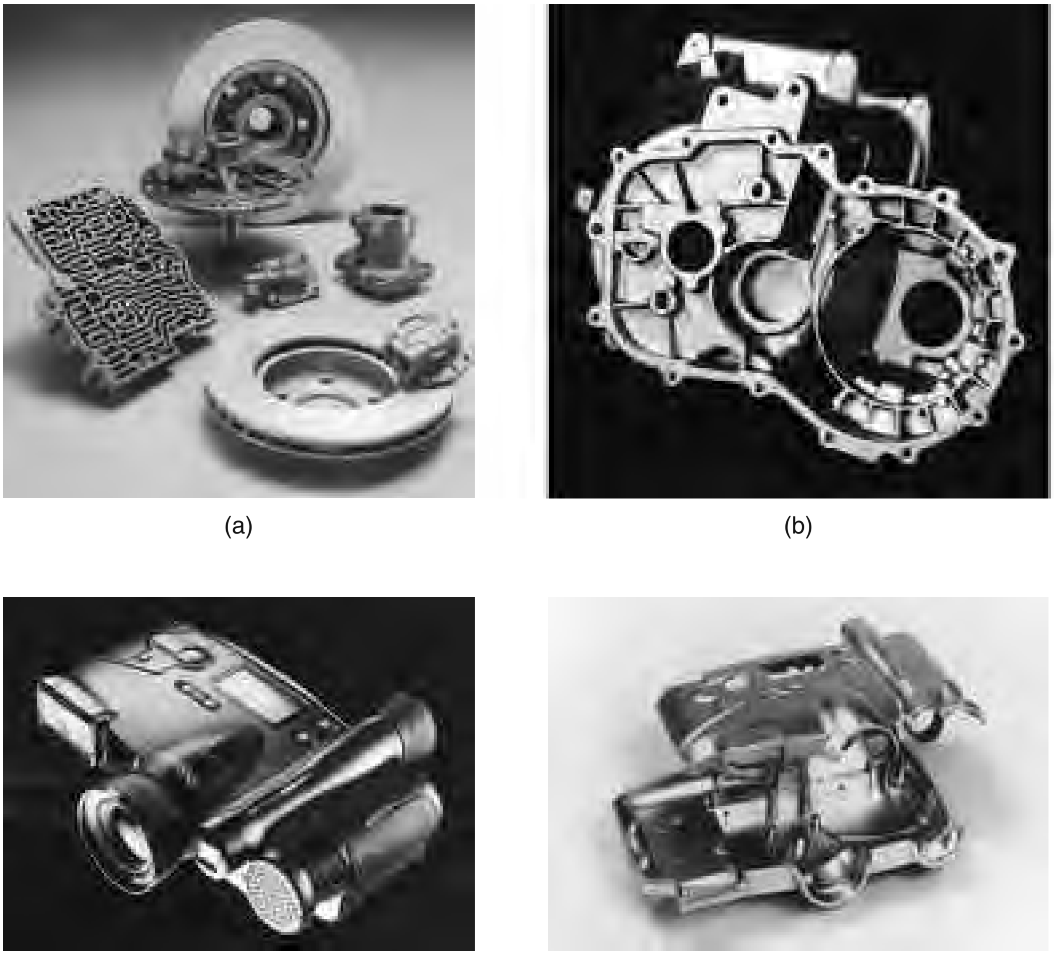
materials, pattern production, molding processes, and methods of feeding the mold with molten metal. The major categories are as follows:

1. **Expendable molds**, which typically are made of sand, plaster, ceramics, and similar materials and generally are mixed with various binders (*bonding agents*) for improved properties. A typical sand mold consists of 90% sand, 7% clay, and 3% water. As described in Chapter 8, these materials are *refractories* (that is, they are capable of withstanding the high temperatures of molten metals). After the casting has solidified, the mold is broken up to remove the casting.

   The mold is produced from a pattern; in some processes, such as sand and shell casting, the mold is expendable, but the pattern is reused to produce several molds. Such processes are referred to as *expendable-mold, permanent-pattern casting processes*. On the other hand, investment casting consumes a pattern for each mold produced; it is an example of an *expendable-mold, expendable-pattern process*.

2. **Permanent molds**, which are made of metals that maintain their strength at high temperatures. As the name implies, they are used repeatedly and are designed in such a way that the casting can be removed easily and the mold used for the next casting. Metal molds are better heat conductors than expendable nonmetallic molds (see Table 3.1); hence, the solidifying casting is subjected to a higher rate of cooling, which in turn affects the microstructure and grain size within the casting.

3. **Composite molds**, which are made of two or more different materials (such as sand, graphite, and metal) combining the advantages of each material. These molds have a permanent and an expendable portion and are used in various casting processes to improve mold strength, control the cooling rates, and optimize the overall economics of the casting process.



(a) (b) (c) (d)

FIGURE 11.1 (a) Typical gray-iron castings used in automobiles, including the transmission valve body (left) and the hub rotor with disk-brake cylinder (front). *Source*: Courtesy of Central Foundry Division of General Motors Corporation. (b) A cast transmission housing. (c) The Polaroid PDC-2000 digital camera with an AZ191D die-cast, high-purity magnesium case. (d) A two-piece Polaroid camera case made by the hot-chamber die-casting process. *Source*: (c) and (d) Courtesy of Polaroid Corporation and Chicago White Metal Casting, Inc.

The general characteristics of sand casting and other casting processes are summarized in Table 11.2. Almost all commercial metals can be cast. The surface finish obtained is largely a function of the mold material and can be very good, although, as expected, sand castings generally have rough, grainy surfaces. Dimensional tolerances generally are not as good as those in machining and other net-shape processes. However, intricate shapes, such as cast-iron engine blocks and very large propellers for ocean liners, can be made by casting.

Because of their unique characteristics and applications, particularly in manufacturing microelectronic devices (Part V), basic crystal-growing techniques also are described in this chapter, which concludes with a brief overview of modern foundries.

TABLE 11.2

General Characteristics of Casting Processes

	Sand	Shell	Evaporative pattern	Plaster	Investment	Permanent mold	Die	Centrifugal
Typical materials cast	All	All	All	Nonferrous Al, Mg, Zn, Cu)	All	All	Nonferrous (Al, Mg, Zn, Cu)	All
Weight (kg):								
Minimum	0.01	0.01	0.01	0.01	0.001	0.1	<0.01	0.01
Maximum	No limit	100+	100+	50+	100+	300	50	5000+
Typical surface finish (R_a in μm)	5–25	1–3	5–25	1–2	0.3–2	2–6	1–2	2–10
Porosity[1]	3–5	4–5	3–5	4–5	5	2–3	1–3	1–2
Shape complexity[1]	1–2	2–3	1–2	1–2	1	2–3	3–4	3–4
Dimensional accuracy[1]	3	2	3	2	1	1	1	3
Section thickness (mm):								
Minimum	3	2	2	1	1	2	0.5	2
Maximum	No limit	—	—	—	75	50	12	100
Typical dimensional tolerance (mm)	1.6–4 mm (0.25 mm for small parts)	±0.003		+0.005 − 0.010	+0.005	±0.015	±0.001 − 0.005	0.015
Equipment	3–5	3	2–3	3–5	3–5	2	1	1
Pattern/die	3–5	2–3	2–3	3–5	2–3	2	1	1
Labor	1–3	3	3	1–2	1–2	3	5	5
Typical lead time[2]	Days	Weeks	Weeks	Days	Weeks	Weeks	Weeks to months	Months
Typical production rate[2] (parts/mold-hour)	1–20	5–50	1–20	1–10	1–1000	5–50	2–200	1–1000
Minimum quantity[2]	1	100	500	10	10	1000	10,000	10–10,000

Notes: 1. Relative rating, from 1 (best) to 5 (worst). For example, die casting has relatively low porosity, mid to low shape complexity, high dimensional accuracy, high equipment and die costs, and low labor costs. These ratings are only general; significant variations can occur, depending on the manufacturing methods used.
2. Approximate values without the use of rapid prototyping technologies. Minimum quantity is 1 when applying rapid prototyping.
Source: Data taken from J.A. Schey, *Introduction to Manufacturing Processes*, 3d ed., McGraw-Hill, 2000.

11.2 Expendable-mold, Permanent-pattern Casting Processes

The major categories of expendable-mold, permanent-pattern casting processes are sand, shell mold, plaster mold, ceramic mold, and vacuum casting.

11.2.1 Sand Casting

The traditional method of casting metals is in sand molds and has been used for millennia. Sand casting is still the most prevalent form of casting; in the United States alone, about 15 million tons of metal are cast by this method each year. Typical applications of sand casting include machine bases, large turbine impellers, propellers, plumbing fixtures, and a wide variety of other products and components. The capabilities of sand casting are given in Table 11.2.

Basically, *sand casting* consists of (a) placing a pattern (having the shape of the desired casting) in sand to make an imprint, (b) incorporating a gating system, (c) removing the pattern and filling the mold cavity with molten metal, (d) allowing the metal to cool until it solidifies, (e) breaking away the sand mold, and (f) removing the casting (Fig. 11.2).

Sands. Most sand-casting operations use silica sand (SiO_2) as the mold material. Sand is inexpensive and is suitable as a mold material because of its high-temperature characteristics and high melting point. There are two general types of sand: **naturally bonded** (*bank sand*) and **synthetic** (*lake sand*). Because its composition can be controlled more accurately, synthetic sand is preferred by most foundries. For proper functioning, mold sand must be clean and preferably new.

Several factors are important in the selection of sand for molds, and certain tradeoffs with respect to properties are involved. Sand having fine, round grains can be packed closely and, thus, forms a smooth mold surface. Although fine-grained sand enhances mold strength, the fine grains also lower mold *permeability* (where fluids and gases penetrate through pores). Good permeability of molds and

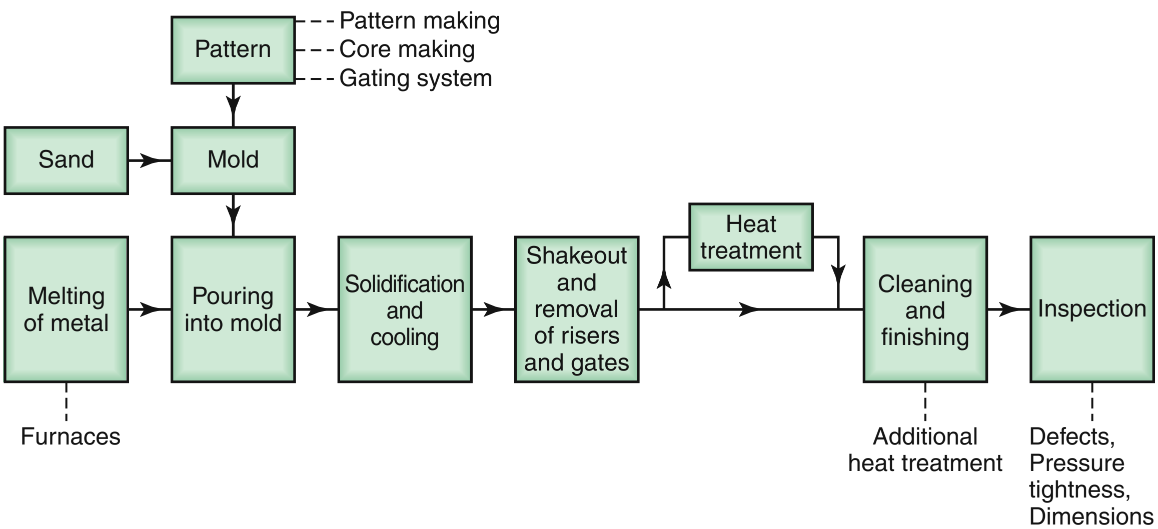


FIGURE 11.2 Outline of production steps in a typical sand-casting operation.

cores allows gases and steam evolved during the casting to escape easily. The mold also should have good *collapsibility* to allow the casting to shrink while cooling and, thus, to avoid defects in the casting, such as hot tearing and cracking (see Fig. 10.12).

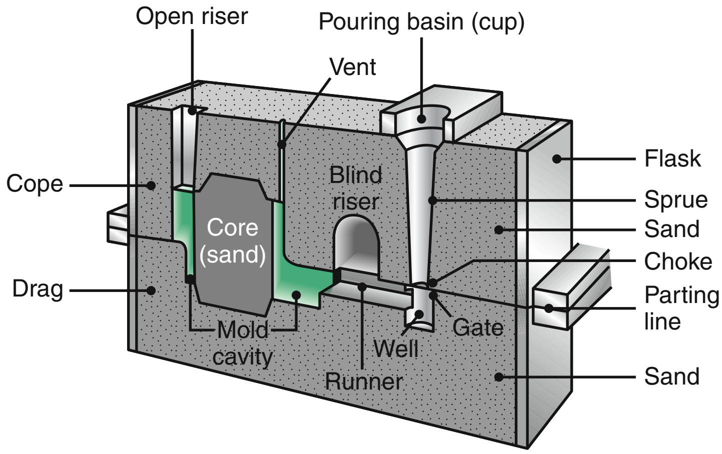


FIGURE 11.3 Schematic illustration of a sand mold, showing various features.

Types of Sand Molds. Sand molds (Fig. 11.3) are characterized by the types of sand that comprise them and by the methods used to produce them. There are three basic types of sand molds: green-sand, cold-box, and no-bake molds. The most common mold material is **green molding sand**, which is a mixture of sand, clay, and water. The term "green" refers to the fact that the sand in the mold is moist or damp while the metal is being poured into it. Green-sand molding is the least expensive method of making molds, and the sand is recycled easily for subsequent reuse. In the **skin-dried** method, the mold surfaces are dried, either by storing the mold in air or by drying it with torches. Because of their higher strength, these molds generally are used for large castings.

In the **cold-box mold** process, various organic and inorganic *binders* are blended into the sand to bond the grains chemically for greater strength. These molds are more dimensionally accurate than green-sand molds, but are more expensive. In the **no-bake mold** process, a synthetic liquid resin is mixed with the sand and the mixture hardens at room temperature. Because the bonding of the mold in this and in the cold-box process takes place without heat, they are called **cold-setting processes**.

Sand molds can be oven dried (*baked*) prior to pouring the molten metal; they are then stronger than green-sand molds and impart better dimensional accuracy and surface finish to the casting. However, this method has the drawbacks that (a) distortion of the mold is greater, (b) the castings are more susceptible to hot tearing because of the lower collapsibility of the mold, and (c) the production rate is lower because of the considerable drying time required.

The major features of molds in sand casting are as follows:

1. The **flask**, which supports the mold itself. Two-piece molds consist of a **cope** on top and a **drag** on the bottom; the seam between them is the *parting line*. When more than two pieces are used in a sand mold, the additional parts are called *cheeks*.
2. A **pouring basin** or **pouring cup**, into which the molten metal is poured.
3. A **sprue**, through which the molten metal flows downward.
4. The **runner system**, which has channels that carry the molten metal from the sprue to the mold cavity. **Gates** are the inlets into the mold cavity.
5. **Risers**, which supply additional molten metal to the casting as it shrinks during solidification. Two types of risers—a *blind riser* and an *open riser*—are shown in Fig. 11.3.
6. **Cores**, which are inserts made from sand. They are placed in the mold to form hollow regions or otherwise define the interior surface of the casting. Cores also are used on the outside of the casting to form features such as lettering on the surface or deep external pockets.

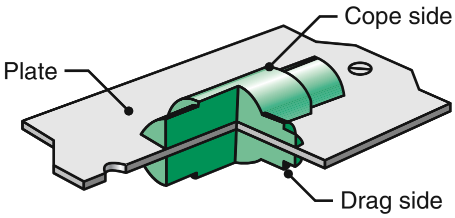


FIGURE 11.4 A typical metal match-plate pattern used in sand casting.

7. **Vents**, which are placed in molds to carry off gases produced when the molten metal comes into contact with the sand in the mold and the core. Vents also exhaust air from the mold cavity as the molten metal flows into the mold.

Patterns. *Patterns* are used to mold the sand mixture into the shape of the casting and may be made of wood, plastic, or metal. The selection of a pattern material depends on the size and shape of the casting, the dimensional accuracy and the quantity of castings required, and the molding process. Because patterns are used repeatedly to make molds, the strength and durability of the material selected for a pattern must reflect the number of castings that the mold will produce. Patterns may be made of a combination of materials to reduce wear in critical regions, and they usually are coated with a **parting agent** to facilitate the removal of the casting from the molds.

Patterns can be designed with a variety of features to fit specific applications and economic requirements. **One-piece patterns**, also called *loose* or *solid patterns*, generally are used for simpler shapes and low-quantity production; they generally are made of wood and are inexpensive. **Split patterns** are two-piece patterns, made such that each part forms a portion of the cavity for the casting; in this way, castings with complicated shapes can be produced. **Match-plate patterns** are a common type of mounted pattern in which two-piece patterns are constructed by securing each half of one or more split patterns to the opposite sides of a single plate (Fig. 11.4). In such constructions, the gating system can be mounted on the drag side of the pattern. This type of pattern is used most often in conjunction with molding machines and large production runs to produce smaller castings.

An important development in molding and pattern making is the application of **rapid prototyping** (Chapter 20). In sand casting, for example, a pattern can be fabricated in a rapid-prototyping machine and fastened to a backing plate at a fraction of the time and cost of machining a pattern. There are several rapid prototyping techniques with which these tools can be produced quickly.

Pattern design is a critical aspect of the total casting operation. The design should provide for **metal shrinkage**, permit proper metal flow in the mold cavity, and allow the pattern to be easily removed from the sand mold by means of a taper or draft (Fig. 11.5) or some other geometric feature. (These topics are described in greater detail in Chapter 12.)

Cores. For castings with internal cavities or passages, such as those found in an automotive engine block or a valve body, *cores* are utilized. Cores are placed in the mold cavity to form the interior surfaces of the casting and are removed from the finished part during shakeout and further processing. Like molds, cores must possess strength, permeability, the ability to withstand heat, and collapsibility; hence, cores are made of sand aggregates. The core is anchored by **core prints**, which are recesses added to the pattern to locate and support the core and to provide vents for the escape of gases (Fig. 11.6a). A common problem with cores is that (for some casting requirements, as in the case where a recess is required) they may lack sufficient structural support in the cavity. To keep the core from shifting, metal supports (**chaplets**) may be used to anchor the core in place (Fig. 11.6b).

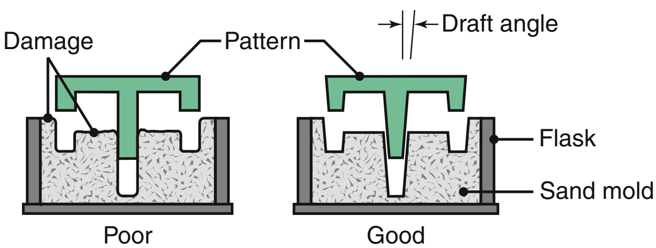


FIGURE 11.5 Taper on patterns for ease of removal from the sand mold.

Cores generally are made in a manner similar to that used in sand moldmaking; the majority are made

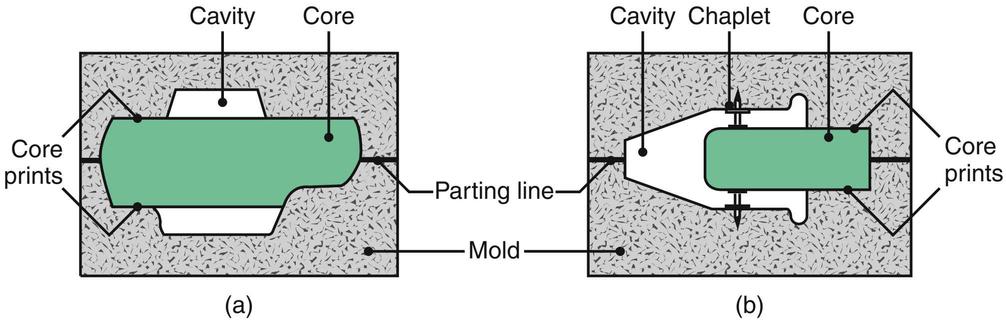


FIGURE 11.6 Examples of sand cores, showing core prints and chaplets to support the cores.

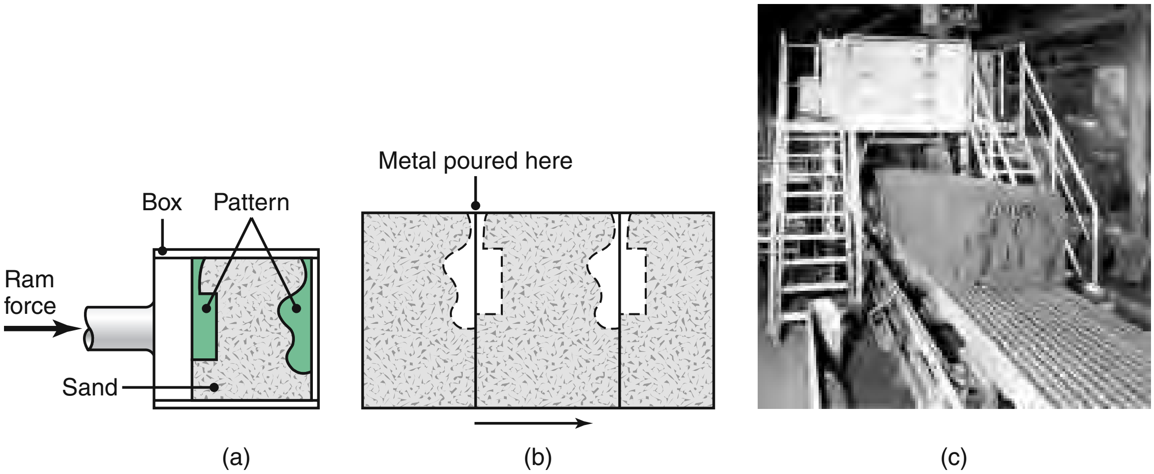


FIGURE 11.7 Vertical flaskless molding. (a) Sand is squeezed between two halves of the pattern. (b) Assembled molds pass along an assembly line for pouring. (c) A photograph of a vertical flaskless molding line. *Source*: Courtesy of American Foundry Society.

with shell (see Section 11.2.2), no-bake, or cold-box processes. Cores are shaped in *core boxes*, which are used in much the same way that patterns are used to form sand molds.

Sand-molding Machines. The oldest known method of molding, which is still used for simple castings, is to compact the sand by hand hammering (*tamping*) or ramming it around the pattern. For most operations, however, the sand mixture is compacted around the pattern by *molding machines*. These machines eliminate arduous labor, offer high-quality casting by improving the application and distribution of forces, manipulate the mold in a carefully controlled manner, and increase production rate.

In **vertical flaskless molding**, the halves of the pattern form a vertical chamber wall against which sand is blown and compacted (Fig. 11.7). Then the mold halves are packed horizontally, with the parting line oriented vertically, and moved along a pouring conveyor. This operation is simple and eliminates the need to handle flasks, allowing for very high production rates, particularly when other aspects of the operation (such as coring and pouring) are automated.

Sandslingers fill the flask uniformly with sand under a high-pressure stream; they are used to fill large flasks and are operated typically by machine. An impeller in the machine throws sand from its blades (or cups) at such high speeds that the machine not only places the sand, but also rams it appropriately.

In **impact molding**, the sand is compacted by a controlled explosion or instantaneous release of compressed gases. This method produces molds with uniform strength and good permeability.

In **vacuum molding** (also known as the *V process*), the pattern is covered tightly with a thin sheet of plastic. A flask is placed over the coated pattern and is filled with dry, binderless sand. A second sheet of plastic then is placed on top of the sand, a vacuum action compacts the sand, and the pattern can then be withdrawn. Both halves of the mold are made in this manner and subsequently assembled. During pouring, the mold remains under vacuum, but the casting cavity does not. When the metal has solidified, the vacuum is turned off and the sand falls away, releasing the casting. Vacuum molding produces castings with high-quality surface detail and dimensional accuracy; it is suited especially well for large, relatively flat (plane) castings.

The Sand-casting Operation. After the mold has been shaped and the cores have been placed in position, the two halves (cope and drag) are closed, clamped, and weighted down to prevent the separation of the mold sections under the pressure exerted when the molten metal is poured into the mold cavity. A complete sequence of operations in sand casting is shown in Fig. 11.8.

After solidification, the casting is shaken out of its mold, and the sand and oxide layers adhering to the casting are removed by vibration (using a shaker) or by sand blasting. Castings also are cleaned by blasting with steel shot or grit (*shot blasting*; Section 26.8). The risers and gates are cut off by oxyfuel-gas cutting, sawing, shearing, or abrasive wheels; or they are trimmed in dies. Gates and risers on steel castings also may be removed with air carbon-arc cutting (Section 30.8) or torches. Castings may be cleaned further by electrochemical means or by pickling with chemicals to remove surface oxides.

The casting subsequently may be *heat treated* to improve certain properties required for its intended use; heat-treatment is particularly important for steel castings. *Finishing operations* may involve machining, straightening, or forging with dies (sizing) to obtain final dimensions. *Inspection* is an important final step and is carried out to ensure that the casting meets all design and quality-control requirements.

Rammed-graphite Molding. In this process, rammed graphite (Section 8.6) is used to make molds for casting reactive metals, such as titanium and zirconium. Sand cannot be used because these metals react vigorously with silica. The molds are packed like sand molds, air dried, baked at 175°C (350°F), fired at 870°C (1600°F), and then stored under controlled humidity and temperature. The casting procedures are similar to those for sand molds.

11.2.2 Shell Molding

Shell molding was first developed in the 1940s and has grown significantly because it can produce many types of castings with close dimensional tolerances and a good surface finish at low cost. Shell-molding applications include small mechanical parts requiring high precision, such as gear housings, cylinder heads, and connecting rods. The process also is used widely in producing high-precision molding cores. The capabilities of shell-mold casting are given in Table 11.2.

In this process, a mounted pattern made of a ferrous metal or aluminum is (a) heated to a range of 175° to 370°C (350° to 700°F), (b) coated with a parting agent (such as silicone), and (c) clamped to a box or chamber. The box contains

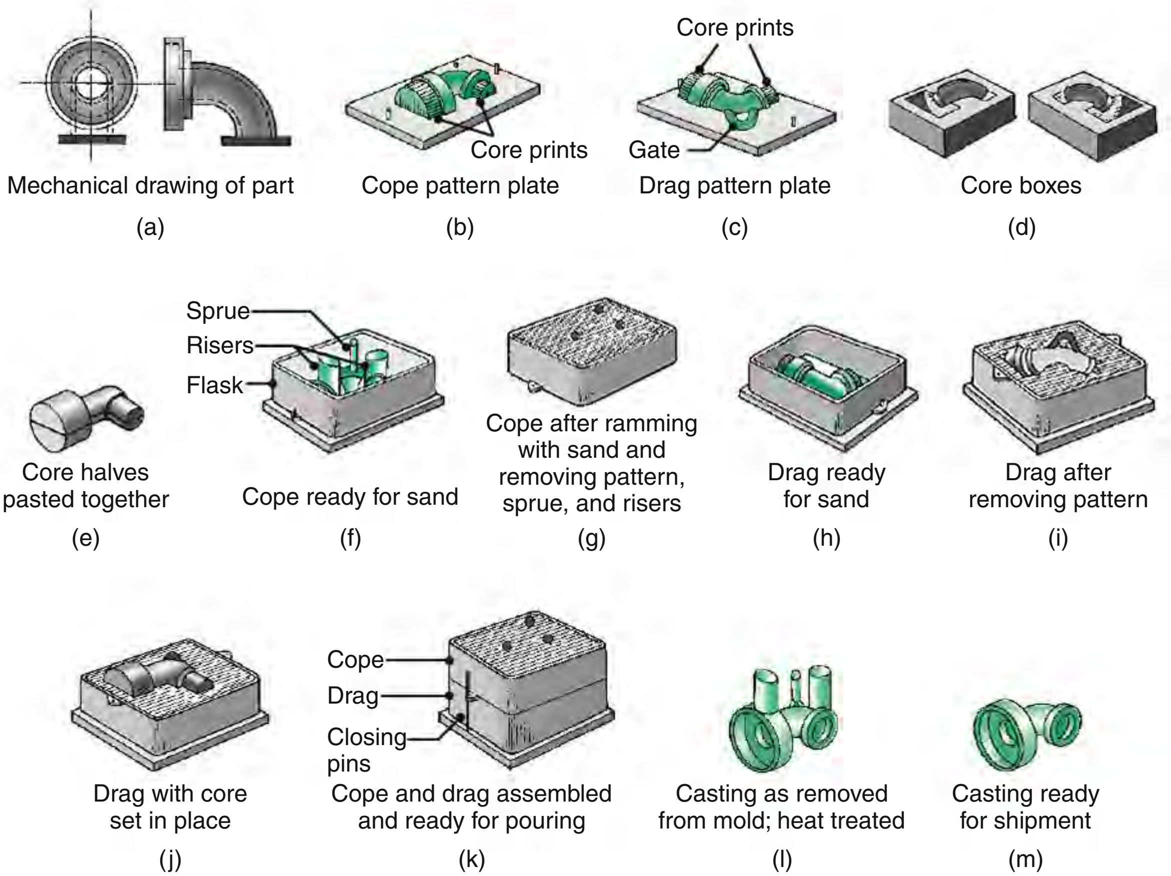


FIGURE 11.8 Schematic illustration of the sequence of operations for sand casting. (a) A mechanical drawing of the part is used to generate a design for the pattern. Considerations such as part shrinkage and draft must be built into the drawing. (b–c) Patterns have been mounted on plates equipped with pins for alignment. Note the presence of core prints designed to hold the core in place. (d–e) Core boxes produce core halves, which are pasted together. The cores will be used to produce the hollow area of the part shown in (a). (f) The cope half of the mold is assembled by securing the cope pattern plate to the flask with aligning pins and attaching inserts to form the sprue and risers. (g) The flask is rammed with sand, and the plate and inserts are removed. (h) The drag half is produced in a similar manner with the pattern inserted. A bottom board is placed below the drag and aligned with pins. (i) The pattern, flask, and bottom board are inverted, and the pattern is withdrawn, leaving the appropriate imprint. (j) The core is set in place within the drag cavity. (k) The mold is closed by placing the cope on top of the drag and securing the assembly with pins. The flasks are then subjected to pressure to counteract buoyant forces in the liquid, which might lift the cope. (l) After the metal solidifies, the casting is removed from the mold. (m) The sprue and risers are cut off and recycled, and the casting is cleaned, inspected, and heat treated (when necessary). *Source*: Courtesy of Steel Founders' Society of America.

fine sand, mixed with 2.5 to 4% of a thermosetting resin binder (such as phenol-formaldehyde) that coats the sand particles. Either the box is rotated upside down (Fig. 11.9), or the sand mixture is blown over the pattern, allowing it to form a coating.

The assembly is then placed in an oven for a short period of time to complete the curing of the resin. In most shell-molding machines, the oven consists of a metal

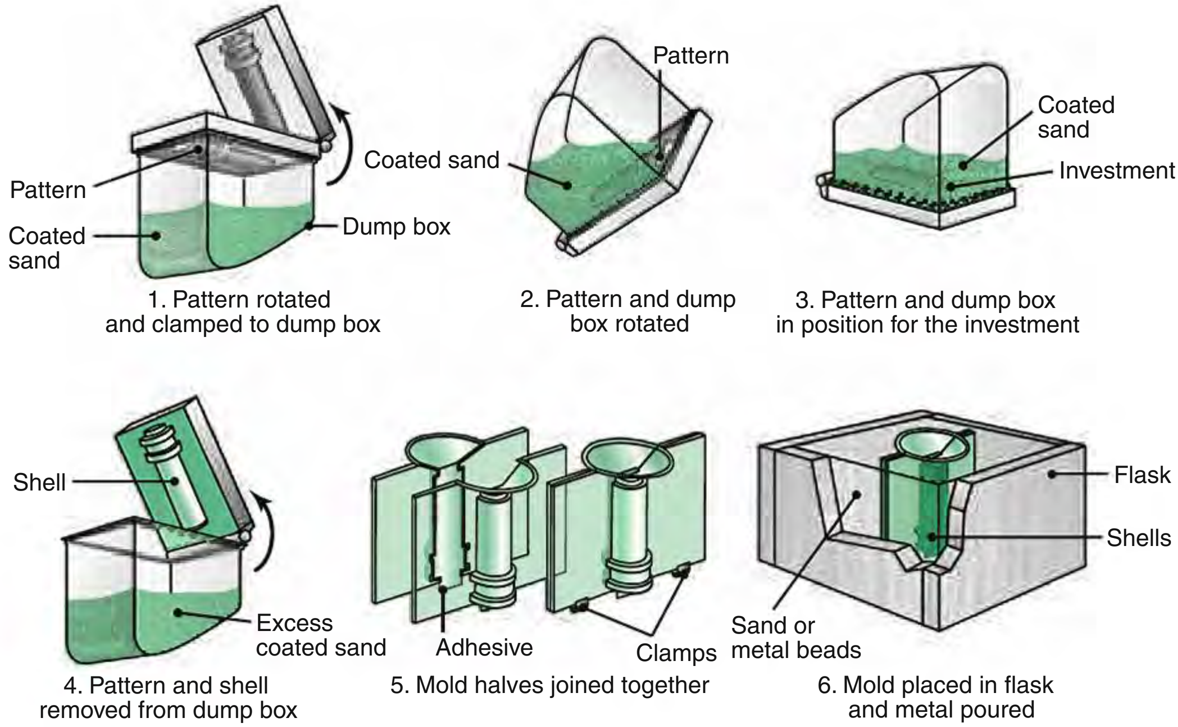


FIGURE 11.9 The shell-molding process, also called the *dump-box* technique.

box with gas-fired burners that swing over the shell mold to cure it. The shell hardens around the pattern and is removed from the pattern using built-in ejector pins. Two half-shells are made in this manner and are bonded or clamped together to form a mold.

The thickness of the shell can be determined accurately by controlling the time that the pattern is in contact with the mold. In this way, the shell can be formed with the required strength and rigidity to hold the weight of the molten liquid. The shells are light and thin—usually 5 to 10 mm (0.2 to 0.4 in.)—and consequently, their thermal characteristics are different from those for thicker molds.

Shell sand has a much lower permeability than the sand used for green-sand molding, because a sand of much smaller grain size is used for shell molding. The decomposition of the shell-sand binder also produces a high volume of gas. Consequently, unless the molds are vented properly, trapped air and gas can cause serious problems in the shell molding of ferrous castings. The high quality of the finished casting can reduce cleaning, machining, and other finishing costs significantly. Complex shapes can be produced with less labor, and the process can be automated fairly easily.

11.2.3 Plaster-mold Casting

This process, and the ceramic-mold and investment casting processes described in Sections 11.2.4 and 11.3.2, are known as **precision casting,** because of the high dimensional accuracy and good surface finish obtained. Typical parts made are lock components, gears, valves, fittings, tooling, and ornaments. The castings usually weigh less than 10 kg (22 lb) and are typically in the range of 125 to 250 g ($^1/_4$ to $^1/_2$ lb), although parts as light as 1 g (0.035 oz) have been made. The capabilities of plaster-mold casting are given in Table 11.2.

In the *plaster-molding* process, the mold is made of plaster of paris (gypsum or calcium sulfate) with the addition of talc and silica flour to improve strength and to control the time required for the plaster to set. These components are mixed with water, and the resulting slurry is poured over the pattern. After the plaster sets (usually within 15 minutes), it is removed, and the mold is dried at a temperature range of 120° to 260°C (250° to 500°F). Higher drying temperatures may be used, depending on the type of plaster. The mold halves are assembled to form the mold cavity and are preheated to about 120°C (250°F). The molten metal is then poured into the mold.

Because plaster molds have very low permeability, gases evolved during solidification of the metal cannot escape. Consequently, the molten metal is poured either in a vacuum or under pressure. Mold permeability can be increased substantially by the *Antioch process*, in which the molds are dehydrated in an *autoclave* (pressurized oven) for 6 to 12 hours and then rehydrated in air for 14 hours. Another method of increasing the permeability of the mold is to use foamed plaster containing trapped air bubbles.

Patterns for plaster molding generally are made of materials such as aluminum alloys, thermosetting plastics, brass, or zinc alloys. Wood patterns are not suitable for making a large number of molds, because they are repeatedly in contact with the water-based plaster slurry and warp or degrade quickly. Since there is a limit to the maximum temperature that the plaster mold can withstand (generally about 1200°C; 2200°F), plaster-mold casting is used only for aluminum, magnesium, zinc, and some copper-based alloys. The castings have a good surface finish with fine details. Because plaster molds have lower thermal conductivity than other mold materials, the castings cool slowly, and thus a more uniform grain structure is obtained with less warpage. The wall thickness of the cast parts can be 1 to 2.5 mm (0.04 to 0.1 in.).

11.2.4 Ceramic-mold Casting

The *ceramic-mold casting* process (also called *cope-and-drag investment casting*) is similar to the plaster-mold process, except that it uses refractory mold materials suitable for high-temperature applications. Typical parts made are impellers, cutters for machining operations, dies for metalworking, and molds for making plastic and rubber components. Parts weighing as much as 700 kg (1500 lb) have been cast by this process.

The slurry is a mixture of fine-grained zircon ($ZrSiO_4$), aluminum oxide, and fused silica, which are mixed with bonding agents and poured over the pattern (Fig. 11.10), which has been placed in a flask.

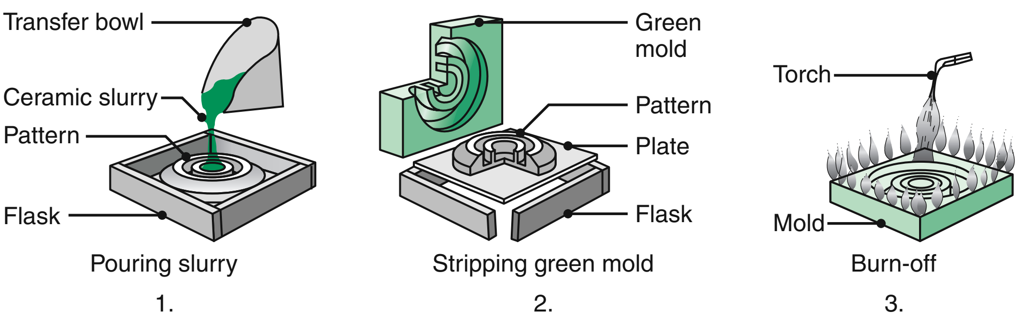


FIGURE 11.10 Sequence of operations in making a ceramic mold. *Source*: *Metals Handbook*, Vol. 5, 8th ed.

The pattern may be made of wood or metal. After setting, the molds (ceramic facings) are removed, dried, ignited to burn off volatile matter, and baked. The molds are clamped firmly and used as all-ceramic molds. In the *Shaw process*, the ceramic facings are backed by fireclay (which resists high temperatures) to give strength to the mold. The facings then are assembled into a complete mold, ready to be poured.

The high-temperature resistance of the refractory molding materials allows these molds to be used for casting ferrous and other high-temperature alloys, stainless steels, and tool steels. Although the process is somewhat expensive, the castings have good dimensional accuracy and surface finish over a wide range of sizes and intricate shapes.

11.3 Expendable-mold, Expendable-pattern Casting Processes

Evaporative-pattern and investment casting are sometimes referred to as *expendable-pattern* casting processes or *expendable mold–expendable pattern* processes. They are unique in that a mold and a pattern must be produced for each casting, whereas the patterns in the processes described in the preceding section are reusable. Typical applications are cylinder heads, engine blocks, crankshafts, brake components, manifolds, and machine bases.

11.3.1 Evaporative-pattern Casting (Lost-foam Process)

The *evaporative-pattern casting* process uses a polystyrene pattern, which evaporates upon contact with molten metal to form a cavity for the casting; this process is also known as *lost-foam casting* and falls under the trade name *full-mold* process. It has become one of the more important casting processes for ferrous and nonferrous metals, particularly for the automotive industry.

In this process, polystyrene beads containing 5 to 8% pentane (a volatile hydrocarbon) are placed in a preheated die that is usually made of aluminum. The polystyrene expands and takes the shape of the die cavity. Additional heat is applied to fuse and bond the beads together. The die is then cooled and opened, and the polystyrene pattern is removed. Complex patterns also may be made by bonding various individual pattern sections using hot-melt adhesive (Section 32.4.1).

The pattern is coated with a water-based refractory slurry, dried, and placed in a flask. The flask is then filled with loose, fine sand, which surrounds and supports the pattern (Fig 11.11) and may be dried or mixed with bonding agents to give it additional strength. The sand is compacted periodically, without removing the polystyrene pattern; then the molten metal is poured into the mold. The molten metal vaporizes the pattern and fills the mold cavity, completely replacing the space previously occupied by the polystyrene. Any degradation products from the polystyrene are vented into the surrounding sand.

The flow velocity of the molten metal in the mold depends on the rate of degradation of the polymer. Studies have shown that the flow of the metal is basically laminar, with Reynolds numbers in the range of 400 to 3000. The velocity of the molten metal at the metal–polymer pattern front (interface) is in the range of 0.1 to 1.0 m/s and can be controlled by producing patterns with cavities or hollow sections. Thus, the velocity will increase as the molten metal crosses these hollow regions, similar to pouring the metal into an empty cavity.

Because the polymer requires considerable energy to degrade, large thermal gradients are present at the metal–polymer interface. In other words, the molten metal cools faster than it would if it were poured directly into an empty cavity. Consequently, fluidity is less than in sand casting. This has important effects on the

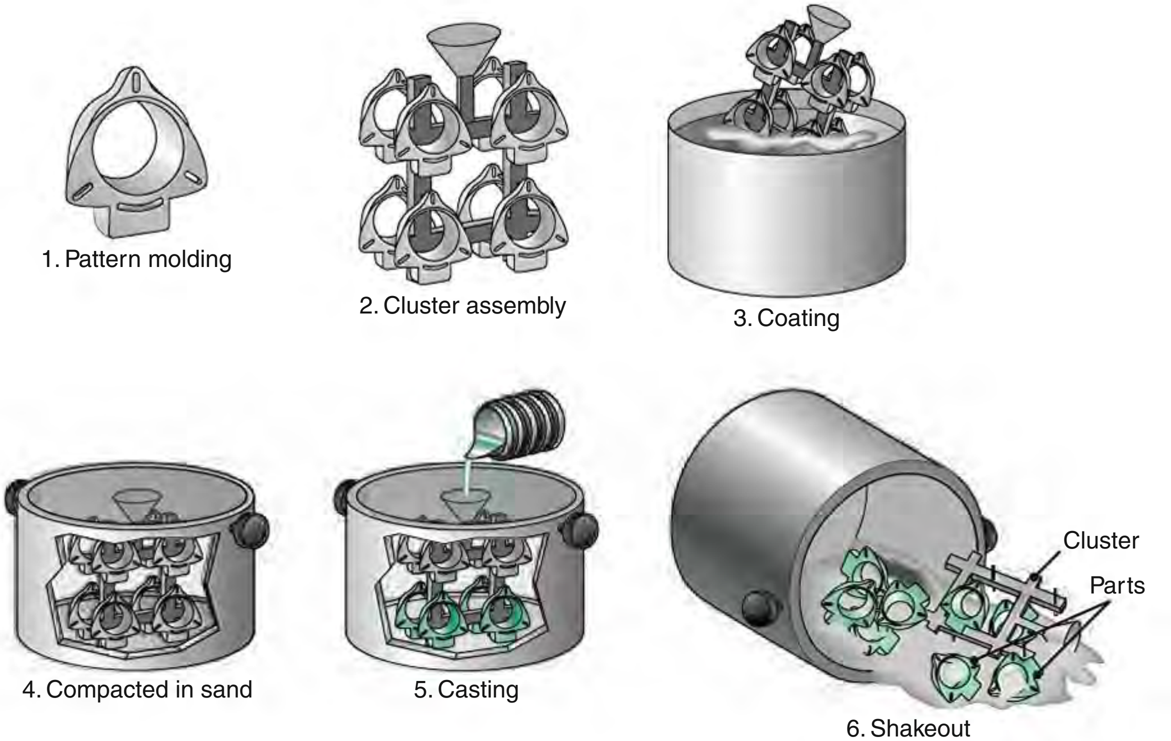


FIGURE 11.11 Schematic illustration of the expendable-pattern casting process, also known as lost-foam or evaporative-pattern casting.

microstructure throughout the casting and also leads to directional solidification of the metal. Polymethylmethacrylate (PMMA) and polyalkylene carbonate also may be used as pattern materials for ferrous castings.

The evaporative-pattern process has a number of advantages over other casting methods:

- The process is relatively simple because there are no parting lines, cores, or riser systems. Hence, it has design flexibility.
- Inexpensive flasks are satisfactory for the process.
- Polystyrene is inexpensive and can be processed easily into patterns having complex shapes, various sizes, and fine surface detail.
- The casting requires minimal finishing and cleaning operations.
- The process can be automated and is economical for long production runs. However, major factors are the cost to produce the die used for expanding the polystyrene beads to make the pattern and the need for two sets of tooling.

In a modification of the evaporative-pattern process, called the *Replicast® C-S process*, a polystyrene pattern is surrounded by a ceramic shell; then the pattern is burned out prior to pouring the molten metal into the mold. Its principal advantage over investment casting (using wax patterns, Section 11.3.2) is that carbon pickup into the metal is avoided entirely. Further developments in evaporative-pattern casting include the production of metal-matrix composites (Sections 9.5 and 19.14). During the molding of the polymer pattern, fibers or particles are embedded throughout, which then become an integral part of the casting. Additional techniques include the modification and grain refinement of the casting by using grain refiners and modifier master alloys within the pattern while it is being molded.

CASE STUDY 11.1 Lost-foam Casting of Engine Blocks

One of the most important components in an internal combustion engine is the engine block; it provides the basic structure that encloses the pistons and cylinders and thus encounters significant pressure during operation. Recent industry trends have focused upon high-quality, low-cost lightweight designs; additional economic benefits can be attained through casting more complex geometries and by incorporating multiple components into one part. Recognizing that evaporative-pattern (lost-foam) casting can simultaneously satisfy all of these requirements, Mercury Castings built a lost-foam casting line to produce aluminum engine blocks and cylinder heads.

One example of a part produced through lost-foam casting is a 45 kW (60-hp), three-cylinder engine block used for marine applications and illustrated in Fig. 11.12a. Previously manufactured as eight separate die castings, the block was converted to a single 10 kg (22-lb) casting, with a weight and cost savings of 1 kg (2 lb) and $25 on each block, respectively. Lost-foam casting also allowed consolidation of the engine's cylinder head and exhaust and cooling systems into the block, thus eliminating the associated machining operations and fasteners required in sand-cast or die-cast designs. In addition, since the pattern contained holes, and these could be cast without the use of cores, numerous drilling operations were eliminated.

Mercury Marine also was in the midst of developing a new V6 engine utilizing a new corrosion-resistant aluminum alloy with increased wear resistance. This engine design also required a cylinder block and head integration, featuring hollow sections for water jacket cooling that could not be cored out in die casting or semipermanent mold processes (used for its other V6 blocks). Based on the success the foundry had with the three-cylinder lost-foam block, engineers applied this process for casting the V6 die block (Fig. 11.12b). The new engine block involves only one casting that is lighter and cheaper than the previous designs. Produced with an integrated cylinder head and exhaust and cooling system, this component is cast hollow to create more efficient water jacket cooling of the engine during its operation.

The company also has developed a pressurized lost-foam process. First a foam pattern is made, placed in a flask, and surrounded by sand. Then the flask is inserted into a pressure vessel where a robot pours molten aluminum onto the polystyrene pattern. A lid on the pressure vessel is closed, and a pressure of 1 MPa (150 psi) is applied to the casting until it solidifies (in about 15 minutes). The result is a casting with better dimensional accuracy, lower porosity, and improved strength as compared to conventional lost-foam casting.

Source: Courtesy of Mercury Marine.

(a) (b)

FIGURE 11.12 (a) Metal is poured into a mold for lost-foam casting of a 60-hp, three-cylinder marine engine; (b) finished engine block. *Source*: Mercury Marine.

11.3.2 Investment Casting

The *investment-casting* process, also called the **lost-wax process**, was first used during the period from 4000 to 3000 B.C. Typical parts made are components for office equipment, as well as mechanical components such as gears, cams, valves, and ratchets. Parts up to 1.5 m (60 in.) in diameter and weighing as much as 1140 kg (2500 lb) have been cast successfully by this process. The capabilities of investment casting are given in Table 11.2.

The sequence involved in investment casting is shown in Fig. 11.13. The pattern is made of wax, or of a plastic such as polystyrene, by molding or rapid-prototyping techniques. The pattern is then dipped into a slurry of refractory material such as very fine silica and binders, including water, ethyl silicate, and acids. After this initial coating has dried, the pattern is coated repeatedly to increase its thickness for better strength. Note that the initial coating can use smaller particles to develop a better surface finish in the casting; subsequent layers use larger particles and are intended to build coating thickness quickly.

The term *investment* derives from the fact that the pattern is invested (surrounded) with the refractory material. Wax patterns require careful handling because they are not strong enough to withstand the forces encountered during mold making; however, unlike plastic patterns, wax can be recovered and reused.

The one-piece mold is dried in air and heated to a temperature of 90° to 175°C (200° to 375°F). It is held in an inverted position for a few hours to melt out the wax. The mold is then fired to 650° to 1050°C (1200° to 1900°F) for about four hours (depending on the metal to be cast) to drive off the water of crystallization (chemically combined water) and to burn off any residual wax. After the metal has been poured

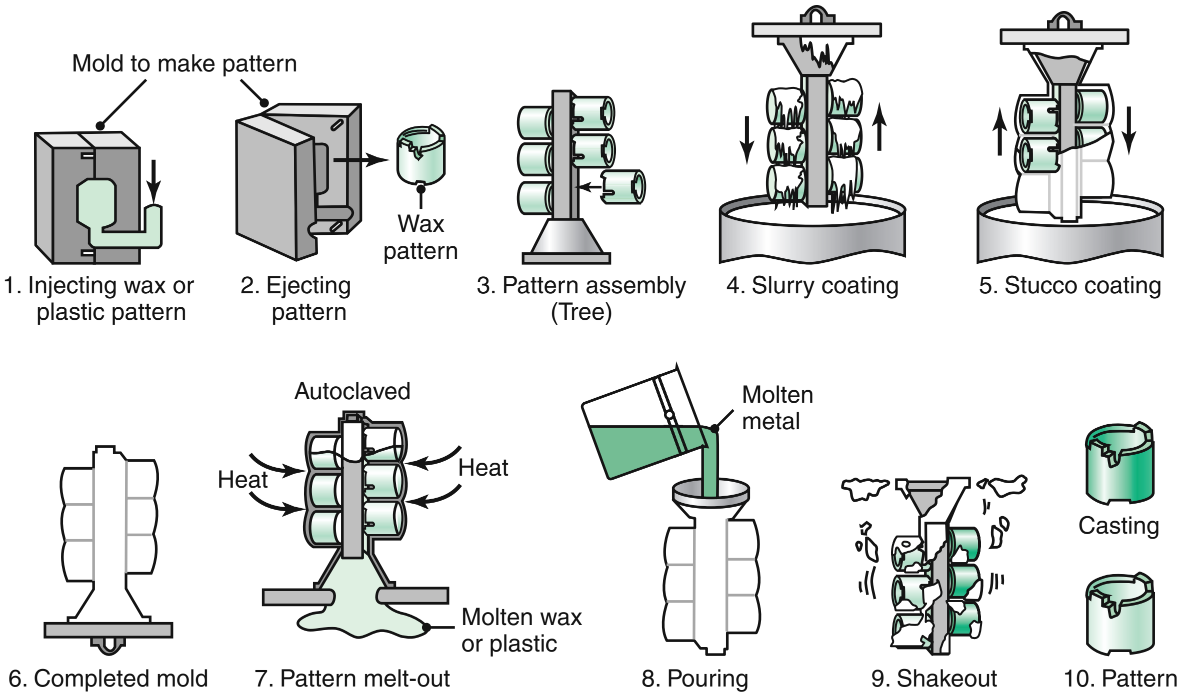


FIGURE 11.13 Schematic illustration of the investment-casting (lost-wax) process. Castings produced by this method can be made with very fine detail and from a variety of metals. *Source*: Courtesy of Steel Founders' Society of America.

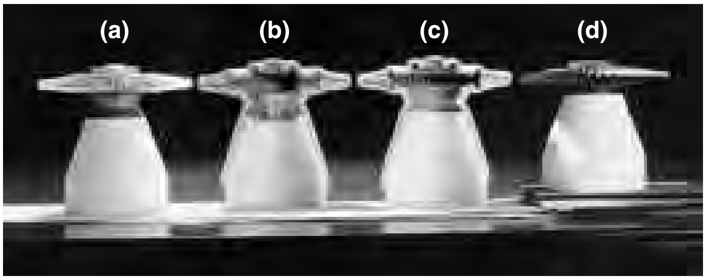


FIGURE 11.14 Investment casting of an integrally cast rotor for a gas turbine. (a) Wax pattern assembly. (b) Ceramic shell around wax pattern. (c) Wax is melted out and the mold is filled, under a vacuum, with molten superalloy. (d) The cast rotor, produced to net or near-net shape. *Source*: Courtesy of Howmet Corporation.

and has solidified, the mold is broken up and the casting is removed. A number of patterns can be joined to make one mold, called a **tree** (Fig. 11.13), significantly increasing the production rate. For small parts, the tree can be inserted into a permeable flask and filled with a liquid slurry investment. The investment then is placed into a chamber and evacuated (to remove the air bubbles in it) until the mold solidifies. The flask usually is placed in a vacuum-casting machine, so that molten metal is drawn into the permeable mold and onto the part, producing fine detail.

Although the mold materials and labor involved make the lost-wax process costly, it is suitable for casting high-melting-point alloys with good surface finish and close dimensional tolerances; few or no finishing operations, which otherwise would add significantly to the total cost of the casting, are required. The process is capable of producing intricate shapes, with parts weighing from 1 g to 35 kg (0.035 oz to 75 lb), from a wide variety of ferrous and nonferrous metals and alloys. Recent advances include the casting of titanium aircraft-engine and structural airframe components with wall thicknesses on the order of 1.5 mm (0.060 in.), thus competing with previously used sheet-metal structures.

Ceramic-shell Investment Casting. A variation of the investment-casting process is *ceramic-shell casting*. It uses the same type of wax or plastic pattern, which is dipped first in ethyl silicate gel and subsequently into a fluidized bed (see Section 4.12) of fine-grained fused silica or zircon flour. The pattern is then dipped into coarser grained silica to build up additional coatings and develop a proper thickness so that the pattern can withstand the thermal shock due to pouring. The rest of the procedure is similar to investment casting. The process is economical and is used extensively for the precision casting of steels and high-temperature alloys.

The sequence of operations involved in making a turbine disk by this method is shown in Fig. 11.14. If ceramic cores are used in the casting, they are removed by leaching with caustic solutions under high pressure and temperature. The molten metal may be poured in a vacuum to extract evolved gases and reduce oxidation, thus improving the casting quality. To further reduce microporosity, the castings made by this (as well as other processes) are subjected to hot isostatic pressing. Aluminum castings, for example, are subjected to a gas pressure up to 100 MPa (15 ksi) at 500°C (900°F).

EXAMPLE 11.1 Investment-cast Superalloy Components for Gas Turbines

Since the 1960s, investment-cast superalloys have been replacing wrought counterparts in high-performance gas turbines. The microstructure of an integrally investment-cast gas-turbine rotor is shown in the upper half of Fig. 11.15. Note the fine, uniform equiaxed grains throughout the rotor cross section. Casting procedures include the use of a nucleant addition to the molten metal, as well as close control of its superheat, pouring techniques, and the cooling rate of the casting (see Section 10.2). In contrast, note the coarse-grained structure in the lower half of Fig. 11.15 showing the same type of rotor cast conventionally. This rotor has inferior properties compared with the fine-grained rotor. Due to developments in these processes, the proportion of cast parts to other parts in aircraft engines has increased from 20% to about 45% by weight.

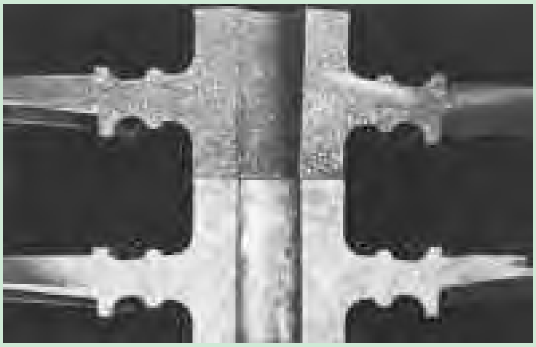


FIGURE 11.15 Cross section and microstructure of two rotors: (top) investment cast; (bottom) conventionally cast. *Source*: Courtesy of ASM International.

CASE STUDY 11.2 Investment Casting of Total Knee Replacements

With great advances in medical care in the past few decades, life expectancies have increased considerably, but so have expectations that the quality of life in later years will remain high. One of the reasons for improvements in the quality of life in the past 40 years has been the great success of orthopedic implants. Hip, knee, shoulder, spine, and other implants have resulted in increased activity and reduced pain for millions of people worldwide.

An example of an orthopedic implant that has greatly improved patient quality of life is the total knee replacement (TKR), as shown in Fig. 11.16a. TKRs are very popular and reliable for the relief of osteoarthritis, a chronic and painful degenerative condition of the knee joint that typically sets in after middle age. TKRs consist of multiple parts, including femoral, tibial, and patellar components. Typical materials used include cobalt alloys, titanium alloys, and ultrahigh-molecular-weight polyethylene (UHMWPE; Section 7.6). Each material is chosen for specific properties that are important in the application of the device.

This case study describes the investment casting of femoral components of TKRs, which are produced from cobalt–chrome alloy (Section 6.6). The manufacturing process begins with the injection molding of patterns, which are then hand assembled onto trees, as shown in Fig. 11.16b. The patterns are spaced properly on a central wax sprue and then are welded in place by dipping them into molten wax and pressing them against the sprue until the patterns are held in place. The final assembled tree is shown in Fig. 11.17a, which contains 12 knee implants arranged into four rows.

The completed trees are placed in a rack, where they form a queue and are then taken in order by an industrial robot (Section 37.6). The robot follows a set sequence in building up the mold; it first dips the pattern into a dilute slurry and then rotates it under a sifting of fine particles. Next, the robot moves the tree beneath a blower to quickly dry the ceramic coating, and then it repeats the cycle. After a few cycles of such exposure to dilute slurry and fine particles, the details of the patterns are well produced and good surface finish is ensured. The robot then dips the pattern into a thicker slurry that quickly builds up the mold thickness (Fig. 11.16c). The trees are then dried and placed into a furnace to melt out and burn the wax. The trees are then placed into another furnace to preheat them in preparation for the casting process.

A mold ready for investment casting is placed into a casting machine. The mold is placed upside down on the machine, directly over a measured volume of molten cobalt chrome. The machine then rotates so that the metal flows into the mold, as shown in Fig. 11.16d. The tree is then allowed to cool and the mold is removed. The cast parts are machined from the tree and then are further machined and

(*continued*)

polished to the required dimensional tolerance and surface finish. Figure 11.17 shows the progression of investment casting, from tree, to investment, to casting. The parts are then removed from the tree and subjected to finishing operations to obtain the final product.

Source: Courtesy of M. Hawkins, Zimmer, Inc.

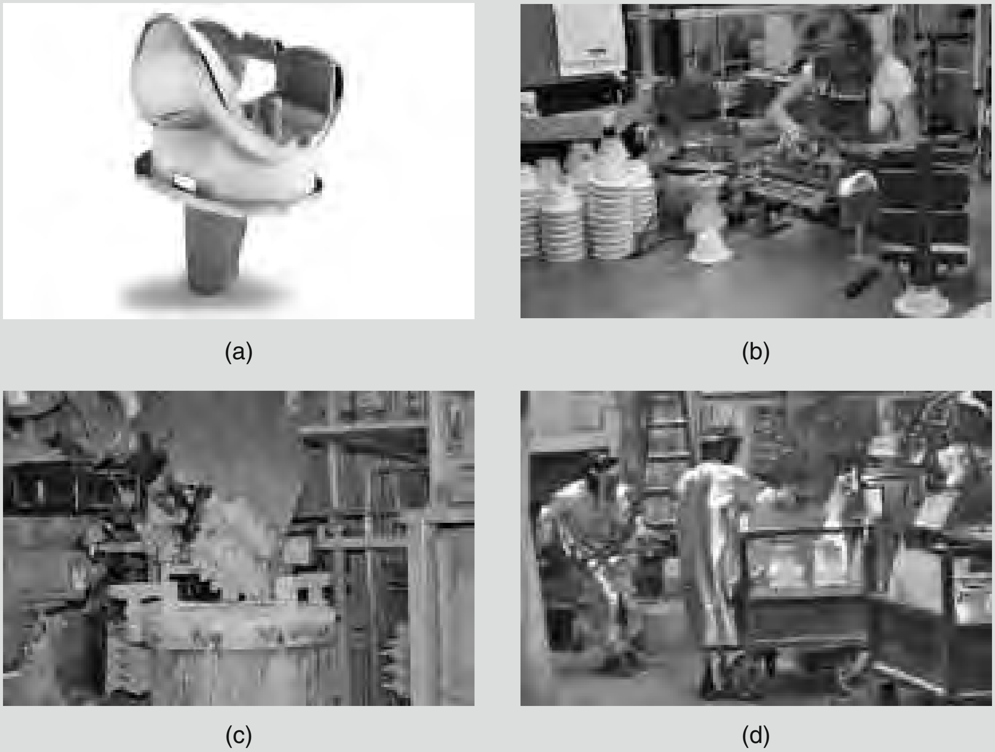


FIGURE 11.16 Manufacture of total knee replacements. (a) The Zimmer NexGen mobile-bearing knee (MBK); the femoral portion of the total knee replacement is the subject of the case study. (b) Assembly of patterns onto a central tree. (c) Dipping of the tree into slurry to develop a mold from investment. (d) Pouring of metal into a mold. *Source*: Courtesy of M. Hawkins, Zimmer, Inc.

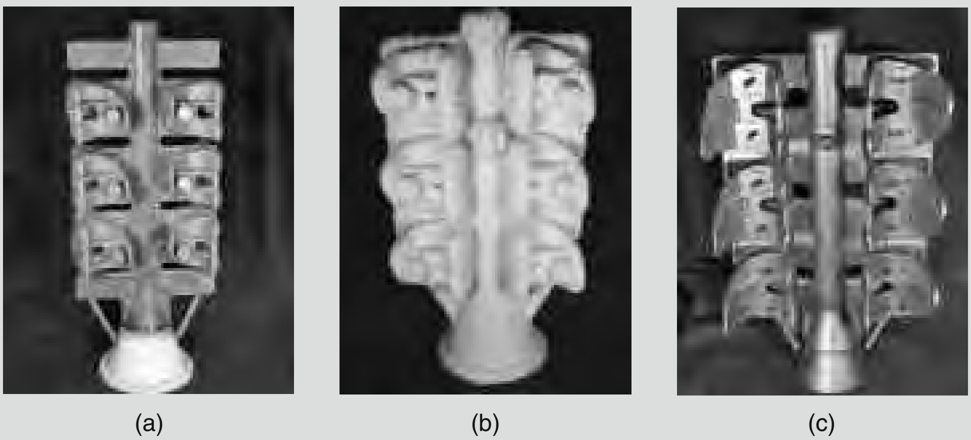


FIGURE 11.17 Progression of the tree. (a) After assembly of blanks onto the tree; (b) after coating with investment; (c) after removal from the mold. *Source*: Courtesy of M. Hawkins, Zimmer, Inc.

11.4 Permanent-mold Casting Processes

Permanent-mold casting processes have certain advantages over other casting processes.

11.4.1 Permanent-mold Casting

In *permanent-mold casting* (also called *hard-mold casting*), two halves of a mold are made from materials with high resistance to erosion and thermal fatigue, such as cast iron, steel, bronze, graphite, or refractory metal alloys. Typical parts made are automobile pistons, cylinder heads, connecting rods, gear blanks for appliances, and kitchenware. Parts that can be made economically generally weigh less than 25 kg (55 lb), although special castings weighing a few hundred kilograms have been made using this process. The capabilities of permanent-mold casting are given in Table 11.2.

The mold cavity and gating system are machined into the mold and thus become an integral part of it. To produce castings with internal cavities, cores made of metal or sand aggregate are placed in the mold prior to casting. Typical core materials are oil-bonded or resin-bonded sand, plaster, graphite, gray iron, low-carbon steel, and hot-work die steel. Gray iron is used most commonly, particularly for large molds for aluminum and magnesium casting. Inserts also are used for various parts of the mold.

In order to increase the life of permanent molds, the surfaces of the mold cavity usually are coated with a refractory slurry (such as sodium silicate and clay) or sprayed with graphite every few castings. These coatings also serve as parting agents and as thermal barriers, thus controlling the rate of cooling of the casting. Mechanical ejectors (such as pins located in various parts of the mold) may be required for the removal of complex castings; ejectors usually leave small round impressions.

The molds are clamped together by mechanical means and heated to about 150° to 200°C (300° to 400°F), to facilitate metal flow and reduce thermal damage to the dies due to high-temperature gradients. Molten metal is then poured through the gating system. After solidification, the molds are opened and the casting is removed. The mold often incorporates special cooling features, such as a means of pumping cooling water through the channels located in the mold and the use of cooling fins. Although the permanent-mold casting operation can be performed manually, it is often automated for large production runs. The process is used mostly for aluminum, magnesium, and copper alloys, as well as for gray iron, because of their generally lower melting points, although steels also can be cast using graphite or heat-resistant metal molds. Permanent-mold casting produces castings with a good surface finish, close dimensional tolerances, uniform and good mechanical properties, and at high production rates.

Although equipment costs can be high because of high die costs, labor costs are kept low through automation. The process is not economical for small production runs and is not suitable for intricate shapes, because of the difficulty in removing the casting from the mold. However, easily collapsable sand cores can be used, which are then removed from castings, leaving intricate internal cavities. This process then is called **semipermanent-mold casting**.

11.4.2 Vacuum Casting

A schematic illustration of the *vacuum-casting* process, or *countergravity low-pressure* (CL) *process* (not to be confused with the vacuum-molding process described in Section 11.2.1) is shown in Fig. 11.18. Vacuum casting is an alternative to investment, shell-mold, and green-sand casting and is suitable particularly for thin-walled (0.75 mm; 0.03 in.) complex shapes with uniform properties. Typical parts made are superalloy gas-turbine components with walls as thin as 0.5 mm (0.02 in.).

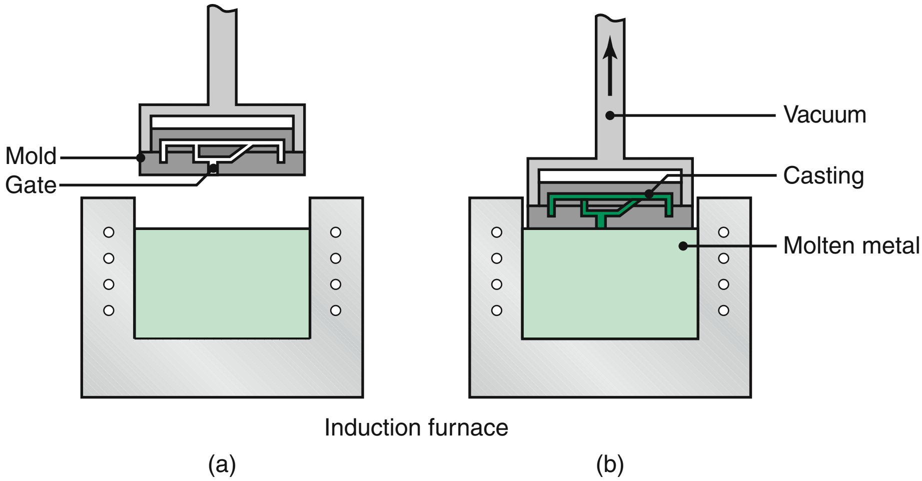


FIGURE 11.18 Schematic illustration of the vacuum-casting process. Note that the mold has a bottom gate. (a) Before and (b) after immersion of the mold into the molten metal. *Source*: After R. Blackburn.

In the vacuum-casting process, a mixture of fine sand and urethane is molded over metal dies and cured with amine vapor. The mold is then held with a robot arm and immersed partially into molten metal held in an induction furnace. The metal may be melted in air (*CLA process*) or in a vacuum (*CLV process*). The vacuum reduces the air pressure inside the mold to about two-thirds of atmospheric pressure, thus drawing the molten metal into the mold cavities through a gate in the bottom of the mold. The metal in the furnace is usually at a temperature of 55°C (100°F) above the liquidus temperature of the alloy. Consequently, it begins to solidify within a very short time. After the mold is filled, it is withdrawn from the molten metal.

The process can be automated, and production costs are similar to those for green-sand casting. Carbon, low- and high-alloy steel, and stainless steel parts weighing as much as 70 kg (155 lb) have been vacuum cast by this method. CLA parts are made easily at high volume and relatively low cost. CLV parts usually involve reactive metals, such as aluminum, titanium, zirconium, and hafnium.

11.4.3 Slush Casting

It was noted in Fig. 10.11 that a solidified skin develops in a casting and becomes thicker with time. Hollow castings with thin walls can be made by permanent-mold casting using this principle: a process called *slush casting*. This process is suitable for small production runs and generally is used for making ornamental and decorative objects (such as lamp bases and stems) and toys from low-melting-point metals such as zinc, tin, and lead alloys.

The molten metal is poured into the metal mold. After the desired thickness of solidified skin is obtained, the mold is inverted (or slung) and the remaining liquid metal is poured out. The mold halves then are opened and the casting is removed. Note that this operation is similar to making hollow chocolate shapes, eggs, and other confectionaries.

11.4.4 Pressure Casting

In the two permanent-mold processes described previously, the molten metal flows into the mold cavity by gravity. In *pressure casting* (also called *pressure pouring* or *low-pressure casting*), the molten metal is forced upward by gas pressure into a graphite or metal mold. The pressure is maintained until the metal has solidified completely in the mold. The molten metal also may be forced upward by a vacuum, which also removes dissolved gases and produces a casting with lower porosity. Pressure casting generally is used for high-quality castings, such as steel railroad-car wheels, although these wheels also may be cast in sand molds or semipermanent molds made of graphite and sand.

11.4.5 Die Casting

The *die-casting* process, developed in the early 1900s, is a further example of permanent-mold casting. The European term for this process is *pressure die casting* and should not be confused with pressure casting described in Section 11.4.4. Typical parts made by die casting are housings, business-machine and appliance components, hand-tool components, and toys. The weight of most castings ranges from less than 90 g (3 oz) to about 25 kg (55 lb). Equipment costs, particularly the cost of dies, are somewhat high, but labor costs are generally low, because the process is semi- or fully automated. Die casting is economical for large production runs. The capabilities of die casting are given in Table 11.2.

In the die-casting process, molten metal is forced into the die cavity at pressures ranging from 0.7 to 700 MPa (0.1–100 ksi). There are two basic types of die-casting machines: hot-chamber and cold-chamber machines.

The **hot-chamber process** (Fig. 11.19) involves the use of a piston, which forces a certain volume of metal into the die cavity through a gooseneck and nozzle. Pressures range up to 35 MPa (5000 psi), with an average of about 15 MPa (2000 psi). The metal is held under pressure until it solidifies in the die. To improve die life and to aid in rapid metal cooling (thereby reducing cycle time) dies usually are cooled by circulating water or oil through various passageways in the die block. Low-melting-point alloys (such as zinc, magnesium, tin, and lead) commonly are cast using this process. Cycle times usually range from 200 to 300 shots (individual injections) per hour for zinc, although very small components, such as zipper teeth, can be cast at rates of 18,000 shots per hour.

In the **cold-chamber process** (Fig. 11.20), molten metal is poured into the injection cylinder (*shot chamber*). The chamber is not heated—hence the term *cold chamber*. The metal is forced into the die cavity at pressures usually ranging from 20 to 70 MPa (3 to 10 ksi), although they may be as high as 150 MPa (20 ksi).

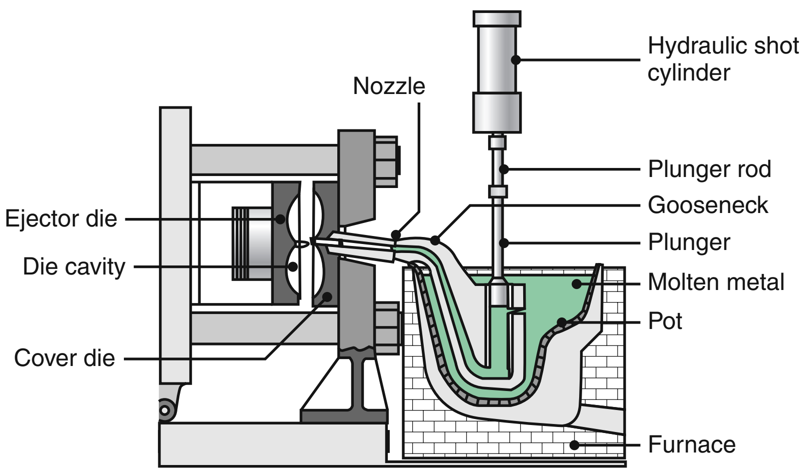


FIGURE 11.19 Schematic illustration of the hot-chamber die-casting process.

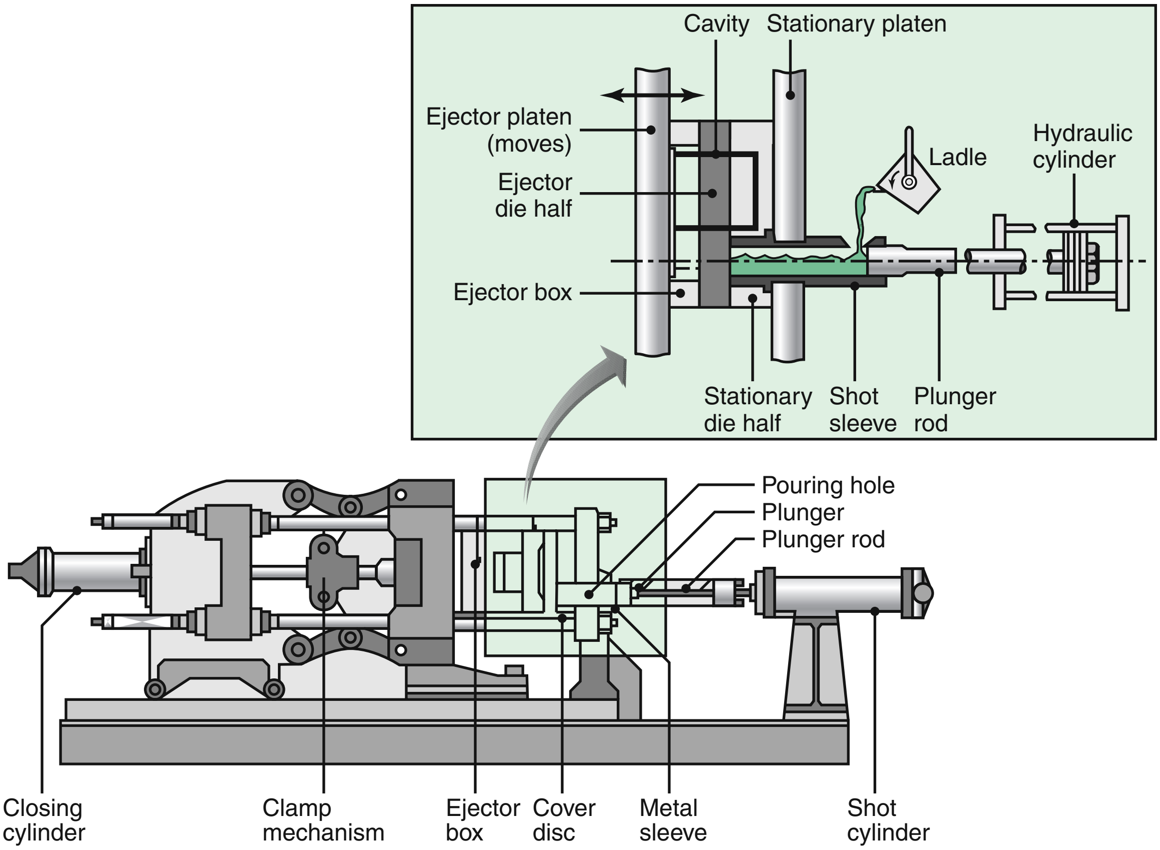


FIGURE 11.20 Schematic illustration of the cold-chamber die-casting process. These machines are large compared to the size of the casting, because high forces are required to keep the two halves of the dies closed under pressure.

The machines may be horizontal (as in the figure)—or vertical, in which case the shot chamber is vertical. High-melting-point alloys of aluminum, magnesium, and copper normally are cast using this method, although other metals (including ferrous metals) also can be cast. Molten-metal temperatures start at about 600°C (1150°F) for aluminum and some magnesium alloys, and increase considerably for copper-based and iron-based alloys.

Process Capabilities and Machine Selection. Die casting has the capability for rapid production of strong, high-quality parts with complex shapes, especially with aluminum, brass, magnesium, and zinc (Table 11.3). It also produces good dimensional accuracy and surface details, so that parts require little or no subsequent machining or finishing operations (net-shape forming). Because of the high pressures involved, walls as thin as 0.38 mm (0.015 in.) are produced, which are thinner than those obtained by other casting methods. However, ejector marks remain, as may small amounts of flash (thin material squeezed out between the dies) at the die parting line.

A typical part made by die casting is shown in Fig. 11.1d; note the intricate shape and fine surface detail. In the fabrication of certain parts, die casting can compete favorably with other manufacturing methods (such as sheet-metal stamping and forging) or other casting processes. In addition, because the molten metal chills rapidly at the die walls, the casting has a fine-grained, hard skin with high strength. Consequently, the strength-to-weight ratio of die-cast parts increases with decreasing

TABLE 11.3

Properties and Typical Applications of Some Common Die-casting Alloys

Alloy	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Applications
Aluminum 380 (3.5 Cu–8.5 Si)	320	160	2.5	Appliances, automotive components, electrical motor frames and housings
13 (12 Si)	300	150	2.5	Complex shapes with thin walls, parts requiring strength at elevated temperatures
Brass 858 (60 Cu)	380	200	15	Plumbing fixtures, lock hardware, bushings, ornamental castings
Magnesium AZ91 B (9 Al-0.7 Zn)	230	160	3	Power tools, automotive parts, sporting goods
Zinc No. 3 (4 Al)	280	—	10	Automotive parts, office equipment, household utensils, building hardware, toys
No. 5 (4 Al-1 Cu)	320	—	7	Appliances, automotive parts, building hardware, business equipment

Source: American Die Casting Institute.

wall thickness. With a good surface finish and dimensional accuracy, die casting can produce smooth surfaces for bearings that otherwise normally would be machined.

Components such as pins, shafts, and threaded fasteners can be die cast integrally. Called **insert molding**, this process is similar to placing wooden sticks in popsicles prior to freezing (see also Section 19.3). For good interfacial strength, insert surfaces may be knurled (see Fig. 23.1l on page 616), grooved, or splined. Steel, brass, and bronze inserts are used commonly in die-casting alloys. In selecting insert materials, the possibility of galvanic corrosion should be taken into account. To avoid this potential problem, the insert can be insulated, plated, or surface treated.

Because of the high pressures involved, dies for die casting have a tendency to part unless clamped together tightly. Die-casting machines are thus rated according to the clamping force that can be exerted to keep the dies closed. The capacities of commercially available machines range from about 25 to 3000 tons. Other factors involved in the selection of die-casting machines are die size, piston stroke, shot pressure, and cost.

Die-casting dies (Fig. 11.21) may be *single cavity*, *multiple cavity* (with several identical cavities), *combination cavity* (with several different cavities), or *unit dies*

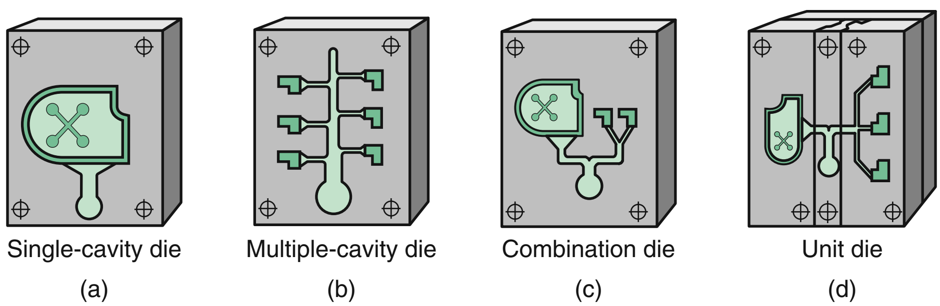


FIGURE 11.21 Various types of cavities in a die-casting die. *Source*: Courtesy of American Die Casting Institute.

(simple, small dies that can be combined in two or more units in a master holding die). Typically, the ratio of die weight to part weight is 1000 to 1; thus, the die for a casting weighing 2 kg would weigh about 2000 kg. The dies usually are made of hot-work die steels or mold steels (see Section 5.7). Die wear increases with the temperature of the molten metal. **Heat checking** of dies (surface cracking from repeated heating and cooling of the die, discussed in Section 3.6) can be a problem. When die materials are selected and maintained properly, dies may last more than a half million shots before any significant die wear takes place.

11.4.6 Centrifugal Casting

As its name implies, the *centrifugal-casting* process utilizes inertial forces (caused by rotation) to distribute the molten metal into the mold cavities—a method that was first suggested in the early 1800s. There are three types of centrifugal casting: true centrifugal casting, semicentrifugal casting, and centrifuging.

True Centrifugal Casting. In *true centrifugal casting*, hollow cylindrical parts (such as pipes, gun barrels, bushings, engine-cylinder liners, bearing rings with or without flanges, and street lampposts) are produced by the technique shown in Fig. 11.22. In this process, molten metal is poured into a rotating mold. The axis of rotation is usually horizontal, but can be vertical for short workpieces. Molds are made of steel, iron, or graphite and may be coated with a refractory lining to increase mold life. The mold surfaces can be shaped so that pipes with various external designs can be cast. The inner surface of the casting remains cylindrical, because the molten metal is distributed uniformly by the centrifugal forces. However, because of density differences, lighter elements (such as dross, impurities, and pieces of the refractory lining) tend to collect on the inner surface of the casting. Consequently, the properties of the casting can vary throughout its thickness.

Cylindrical parts ranging from 13 mm (0.5 in.) to 3 m (10 ft) in diameter and 16 m (50 ft) long can be cast centrifugally with wall thicknesses ranging from 6 to 125 mm (0.25 to 5 in.). The pressure generated by the centrifugal force is high (as much as 150 g); such high pressure is necessary for casting thick-walled parts. Castings with good quality, dimensional accuracy, and external surface detail are produced by this process. The capabilities of centrifugal casting are given in Table 11.2.

Semicentrifugal Casting. An example of *semicentrifugal casting* is shown in Fig. 11.23a. This method is used to cast parts with rotational symmetry, such as a wheel with spokes.

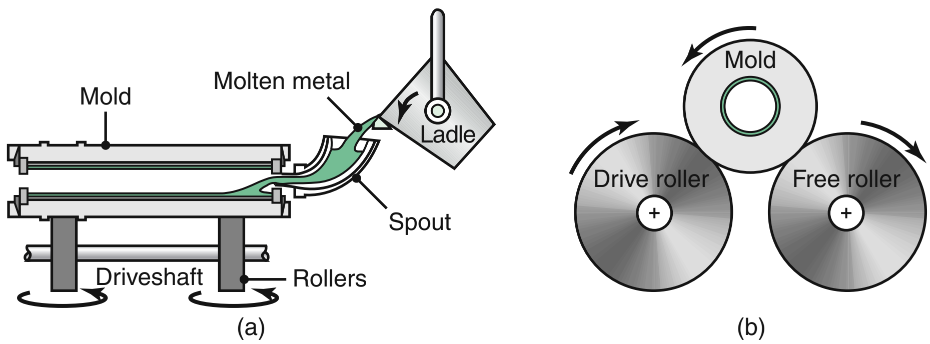


FIGURE 11.22 (a) Schematic illustration of the centrifugal-casting process. Pipes, cylinder liners, and similarly shaped parts can be cast with this process. (b) Side view of the machine.

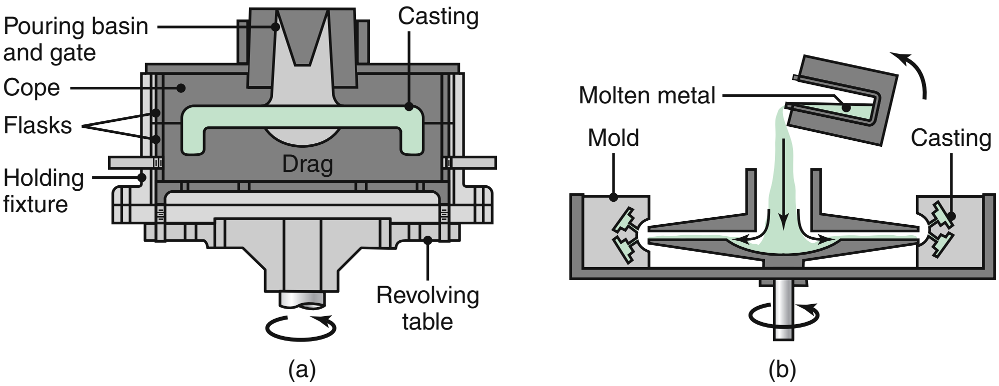


FIGURE 11.23 (a) Schematic illustration of the semicentrifugal casting process. Wheels with spokes can be cast by this process. (b) Schematic illustration of casting by centrifuging. The molds are placed at the periphery of the machine, and the molten metal is forced into the molds by centrifugal force.

Centrifuging. In *centrifuging* (also called *centrifuge casting*), mold cavities of any shape are placed at a certain distance from the axis of rotation. The molten metal is poured from the center and is forced into the mold by centrifugal forces (Fig. 11.23b). The properties of the castings can vary by distance from the axis of rotation, as in true centrifugal casting.

11.4.7 Squeeze Casting and Semisolid-metal Forming

Two casting processes that incorporate features of both casting and forging (Chapter 14) are *squeeze casting* and *semisolid-metal forming*.

Squeeze Casting. The *squeeze-casting* (or *liquid-metal forging*) process was developed in the 1960s and involves the solidification of molten metal under high pressure (Fig. 11.24). Typical products made are automotive components and mortar bodies (a short-barrelled cannon). The machinery includes a die, punch,

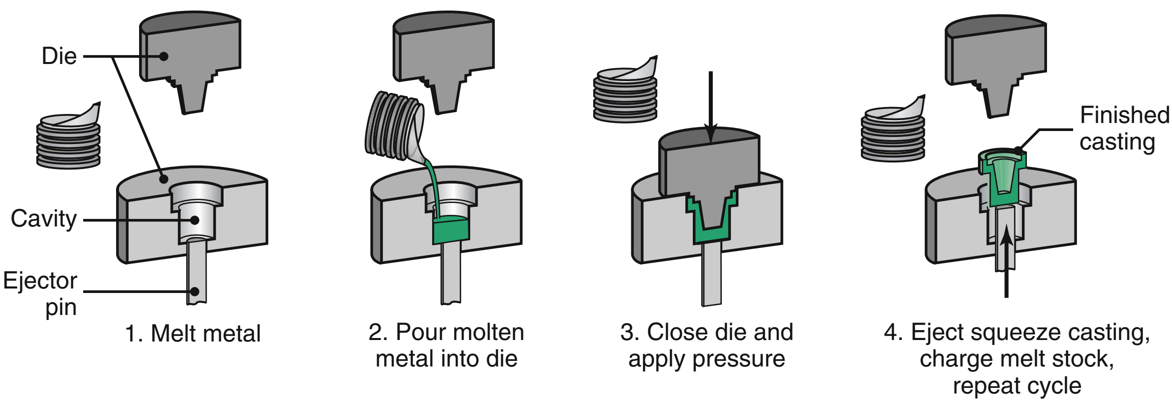


FIGURE 11.24 Sequence of operations in the squeeze-casting process. This process combines the advantages of casting and forging.

and ejector pin. The pressure applied by the punch keeps the entrapped gases in solution, and the contact under high pressure at the die–metal interface promotes rapid heat transfer, thus resulting in a fine microstructure with good mechanical properties.

The application of pressure also overcomes feeding difficulties that may arise when casting metals with a long freezing range (Section 10.2.2). The pressures required in squeeze casting are lower than those for hot or cold forging. Complex parts can be made to near-net shape with fine surface detail from both nonferrous and ferrous alloys.

Semisolid-metal Forming. *Semisolid-metal forming* (also called *mushy-state processing*; see Fig. 10.4) was developed in the 1970s and put into commercial production by 1981. When it enters the die, the metal (consiting of liquid and solid components) is stirred so that all of the dendrites are crushed into fine solids, and when cooled in the die it develops into a fine-grained structure. The alloy exhibits *thixotropic* behavior, described in Section 10.2.3; hence, the process also is called **thixoforming** or **thixomolding**, meaning its viscosity decreases when agitated. Thus, at rest and above its solidus temperature, the alloy has the consistency of butter, but when agitated vigorously, its consistency becomes more like motor oil. Processing metals in their mushy state also has led to developments in *mushy-state extrusion,* similar to injection molding (see Section 19.3), *forging*, and *rolling* (hence the term *semisolid metalworking*). These processes also are used in making parts with specially designed casting or wrought alloys and metal-matrix composites. They also have the capability for blending granukes of different alloys, called *thixoblending,* for specific applications.

Thixotropic behavior has been utilized in developing technologies that combine casting and forging of parts using cast billets that are forged when 30 to 40% liquid. Parts made include control arms, brackets, and steering components. Processing steels by thixoforming has not yet reached the same stage as with aluminum and magnesium, largely because of the high temperatures involved which adversely affect die life and the difficulty in making complex shapes. The advantages of semisolid metal forming over die casting are (a) the structures developed are homogeneous, with uniform properties, lower porosity, and high strength; (b) both thin and thick parts can be made; (c) casting as well as wrought alloys can be used; (d) parts subsequently can be heat treated, and (e) the lower superheat results in shorter cycle times. However, material and overall costs are higher than those for die casting.

Rheocasting. This technique, first investigated in the 1960s, is used for forming metals in the semisolid state. The metal is heated to just above its solidus temperature and poured into a vessel to cool it down to the semisolid state. The slurry is then mixed and delivered to the mold or die. This process is being used successfully with aluminum and magnesium alloys.

11.4.8 Composite-mold Casting Operations

Composite molds are made of two or more different materials and are used in shell molding and other casting processes. They generally are employed in casting complex shapes, such as impellers for turbines. Composite molds increase the strength of the mold, improve the dimensional accuracy and surface finish of castings, and can help reduce overall costs and processing time. Molding materials commonly used are shells (made as described previously), plaster, sand with binder, metal, and graphite. These molds also may include cores and chills to control the rate of solidification in critical areas of castings.

11.5 Casting Techniques for Single-crystal Components

The characteristics of single-crystal and polycrystalline structures in metals were described in Section 1.3. This section describes the techniques used to cast single-crystal components (such as gas turbine blades), which generally are made of nickel-based superalloys and used in the hot stages of the engine. The procedures involved also can be used for other alloys and components.

Conventional Casting of Turbine Blades. The *conventional-casting process* uses a ceramic mold. The molten metal is poured into the mold and begins to solidify at the ceramic walls. The grain structure developed is polycrystalline, similar to that shown in Fig. 10.2c. However, the presence of grain boundaries makes this structure susceptible to creep and cracking along the boundaries under the centrifugal forces and elevated temperatures commonly encountered in an operating gas turbine.

Directionally Solidified Blades. The *directional-solidification process* (Fig. 11.25a) was first developed in 1960. The ceramic mold is preheated by radiant heating, and the mold is supported by a water-cooled chill plate. After the metal is poured into the mold, the chill-plate assembly is lowered slowly. Crystals begin to grow at the chill-plate surface and on upward, like the columnar grains shown in Fig. 10.3. The blade thus is solidified directionally, with longitudinal, but no transverse, grain boundaries. Consequently, the blade is stronger in the direction of centrifugal forces developed in the gas turbine.

Single-crystal Blades. In *crystal growing*, developed in 1967, the mold has a constriction in the shape of a corkscrew or helix (Figs. 11.25b and c). The cross section is so small that it allows only one crystal to fit through. The mechanism of crystal growth is such that only the most favorably oriented crystals are able to grow (a situation similar to that shown in Fig. 10.3) through the helix, because all others are intercepted by the walls of the helical passage.

As the assembly is lowered slowly, a single crystal grows upward through the constriction and begins to grow in the mold. Strict control of the rate of movement is important. The resultant casting is a single-crystal blade. Although these blades

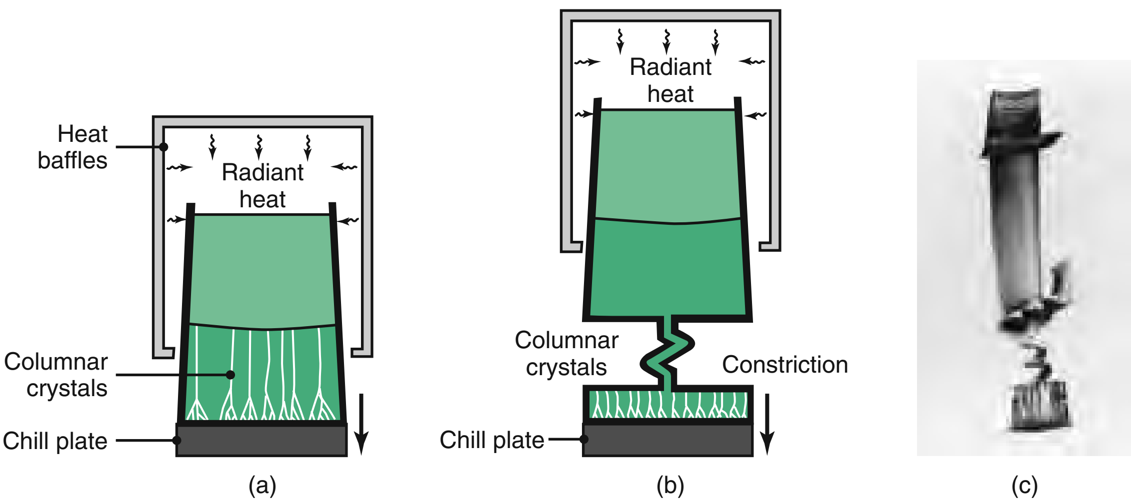


FIGURE 11.25 Methods of casting turbine blades: (a) directional solidification; (b) method to produce a single-crystal blade; and (c) a single-crystal blade with the constriction portion still attached. *Source*: (a) and (b) After B.H. Kear, (c) Courtesy of ASM International.

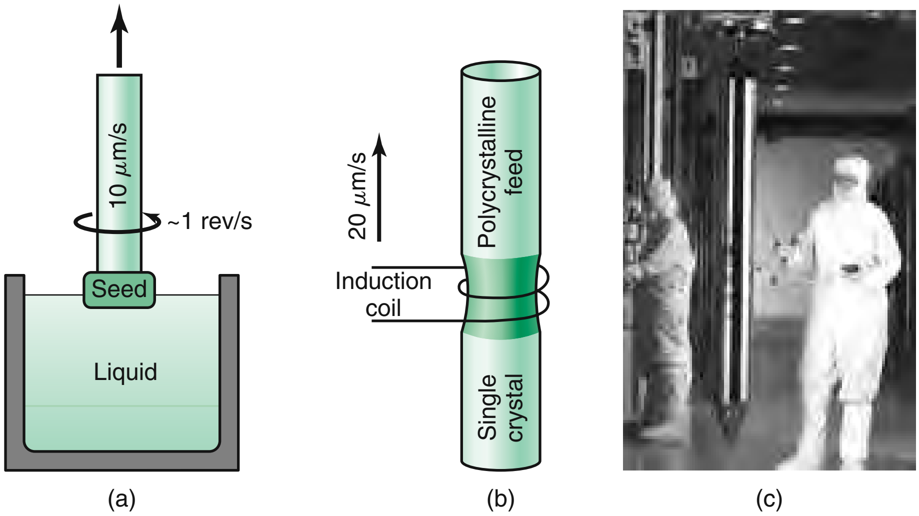


FIGURE 11.26 Two methods of crystal growing: (a) crystal pulling (Czochralski process) and (b) the floating-zone method. Crystal growing is especially important in the semiconductor industry. (c) A single-crystal ingot produced by the Czochralski process. *Source*: Courtesy of Intel Corp.

are more expensive than other types, the lack of grain boundaries makes them resistant to creep and thermal shock, so they have a longer and more reliable service life.

Single-crystal Growing. Single-crystal growing is a major activity in the semiconductor industry in the manufacture of the silicon wafers in microelectronic devices (Chapter 28). There are two basic methods of crystal growing:

- In the **crystal-pulling method**, also known as the **Czochralski** (CZ) **process** (Fig. 11.26a), a seed crystal is dipped into the molten metal and then pulled out slowly (at a rate of about 10 μm/s) while being rotated. The liquid metal begins to solidify on the seed, and the crystal structure of the seed is continued throughout. *Dopants* (alloying elements) may be added to the liquid metal to impart special electrical properties. Single crystals of silicon, germanium, and various other elements are grown with this process. Single-crystal ingots up to 400 mm (16 in.) in diameter and over 2 m (80 in.) in length have been produced by this technique, although 200- and 300-mm (8- and 12-in.) ingots are common in the production of silicon wafers for integrated circuit manufacture (Part V).
- The second technique for crystal growing is the **floating-zone method** (Fig. 11.26b). Starting with a rod of polycrystalline silicon resting on a single crystal, an induction coil heats these two pieces while the coil moves slowly upward. The single crystal grows upward while maintaining its orientation. Thin wafers are then cut from the rod, cleaned, and polished for use in microelectronic device fabrication. This process is suitable for producing diameters under 150 mm (6 in.), with very low levels of impurities.

11.6 Rapid Solidification

The properties of *amorphous alloys* (also known as *metallic glasses*) were described in Section 6.14. The technique for making these alloys (called *rapid solidification*) involves cooling the molten metal at rates as high as 10^6 K/s, so that it does not have

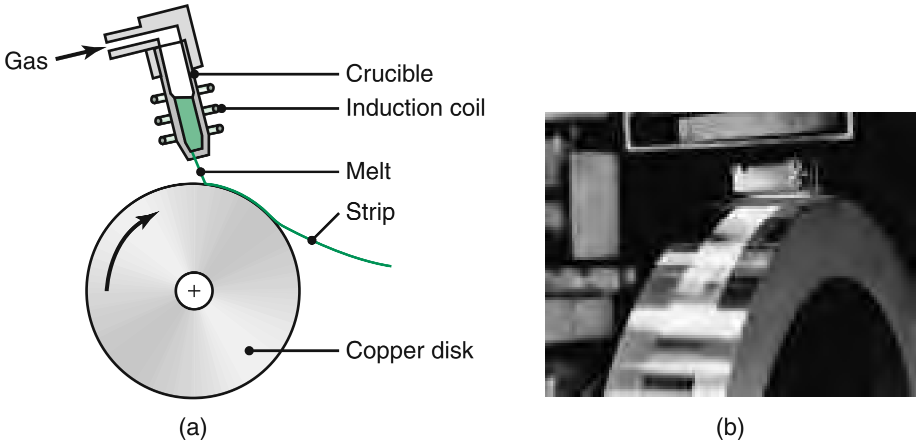


FIGURE 11.27 (a) Schematic illustration of melt spinning to produce thin strips of amorphous metal. (b) Photograph of nickel-alloy production through melt spinning. *Source*: Courtesy of Siemens AG.

sufficient time to crystallize (see also Fig. 1.10). Rapid solidification results in a significant extension of solid solubility, grain refinement, and reduced microsegregation (see Section 10.2.3), among other effects.

In a common method called **melt spinning** (Fig. 11.27), the alloy is melted by induction in a ceramic crucible. It is then propelled under high gas pressure against a rotating copper disk (chill block), which chills the alloy rapidly (**splat cooling**).

11.7 Inspection of Castings

The control of all casting stages—from mold preparation to the removal of castings from molds or dies—is essential to maintaining good quality. Several methods can be used to inspect castings to determine their quality and the presence and types of any possible defects. Castings can be inspected *visually*, or *optically*, for surface defects. Subsurface and internal defects are investigated using various *nondestructive* techniques (Section 36.10). In *destructive* testing (Section 36.11), specimens are removed from various sections of a casting and tested for strength, ductility, and other mechanical properties and to determine the presence, location, and distribution of porosity and any other defects.

Pressure tightness of cast components (valves, pumps, and pipes) usually is determined by sealing the openings in the casting and pressurizing it with water, oil, or air. (Because air is compressible, its use is very dangerous in such tests because of the possibility of a sudden explosion due to a major flaw in the casting.) For extreme leaktightness requirements in critical applications, pressurized helium or specially scented gases with detectors (sniffers) are used. The casting is then inspected for leaks while the pressure is maintained. Unacceptable or defective castings are remelted for reprocessing.

11.8 Melting Practice and Furnaces

The melting practice is an important aspect of casting operations, because it has a direct bearing on the quality of castings. Furnaces are charged with melting stock, consisting of metal, alloying elements, and various other materials (such as **flux** and slag-forming constituents). Fluxes are inorganic compounds that refine the molten metal by removing dissolved gases and various impurities. They may be added manually or can be injected automatically into the molten metal.

Melting Furnaces. The melting furnaces commonly used in foundries are electric-arc furnaces, induction furnaces, crucible furnaces, and cupolas.

- **Electric-arc** furnaces, described in Section 5.2.3 and illustrated in Fig. 5.2, are used extensively in foundries and have such advantages as a high rate of melting (and thus high-production rate), much less pollution than other types of furnaces, and the ability to hold the molten metal (keep it at a constant temperature for a period of time) for alloying purposes.
- **Induction** furnaces (Fig. 5.2c) are especially useful in smaller foundries and produce smaller composition-controlled melts. There are two basic types. The *coreless induction furnace* consists of a crucible completely surrounded with a water-cooled copper coil through which a high-frequency current passes. Because there is a strong electromagnetic stirring action during induction heating, this type of furnace has excellent mixing characteristics for alloying and adding a new charge of metal.

  The other type of induction furnace, called a *core* or *channel furnace*, uses a low-frequency current (as low as 60 Hz) and has a coil that surrounds only a small portion of the unit. These furnaces commonly are used in nonferrous foundries and are particularly suitable for (a) superheating (that is, heating above normal casting temperature to improve fluidity), (b) holding (which makes it suitable for die-casting applications), and (c) duplexing (using two furnaces—for instance, melt the metal in one furnace and transfer it to another).
- **Crucible** furnaces (Fig. 11.28a), which have been used extensively throughout history, are heated with various fuels, such as commercial gases, fuel oil, and fossil fuel, as well as electricity. Crucible furnaces may be stationary, tilting, or movable.
- **Cupolas** are basically vertical, refractory-lined steel vessels charged with alternating layers of metal, coke, and flux (Fig. 11.28b). Although they require major investments and increasingly are being replaced by induction furnaces, cupolas operate continuously, have high melting rates, and produce large amounts of molten metal.

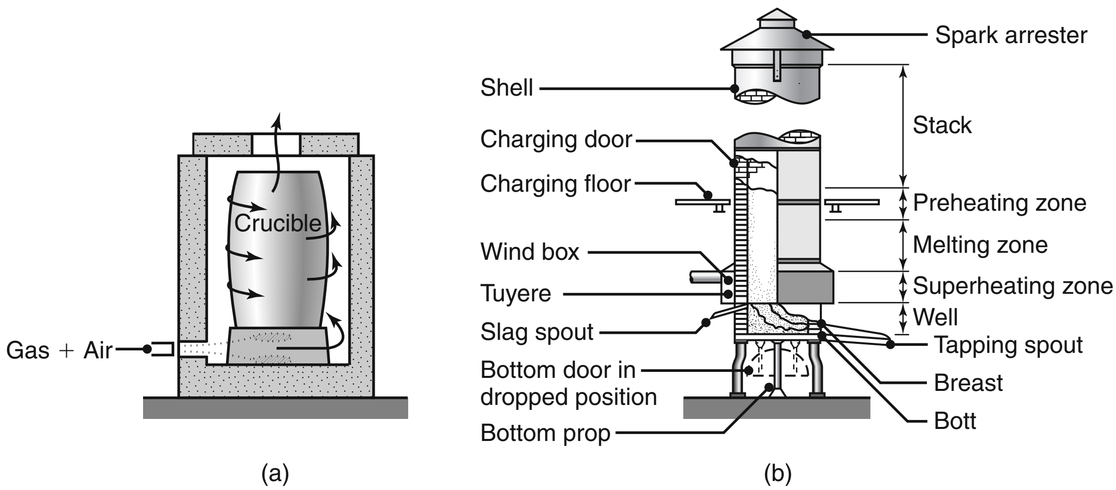


FIGURE 11.28 Two types of melting furnaces used in foundries: (a) crucible and (b) cupola.

- **Levitation melting** involves *magnetic suspension* of the molten metal. An induction coil simultaneously heats a solid billet and stirs and confines the melt, thus eliminating the need for a crucible (which could be a source of contamination with oxide inclusions). The molten metal flows downward into an investment-casting mold placed directly below the coil. Investment castings made with this method are free of refractory inclusions and of gas porosity and have a uniform fine-grained structure.

11.9 Foundries and Foundry Automation

Casting operations usually are carried out in **foundries** (from the Latin *fundere*, meaning melting and pouring). Although these operations traditionally have involved much manual labor, modern foundries have automated and computer-integrated facilities for all aspects of their operations. They produce a wide variety and sizes of castings at high production rates, with good quality control and at low cost.

As outlined in Fig. 11.2, foundry operations initially involve two separate groups of activities. The first group is pattern and mold making. Computer-aided design and manufacturing (Chapter 38) and rapid-prototyping techniques (Chapter 20) are now used to minimize trial and error and thus improve efficiency. A variety of automated machinery is used to minimize labor costs, which can be significant in the production of castings. The second group of activities is melting the metals, controlling their composition and impurities, and pouring them into molds.

The rest of the operations, such as pouring into molds carried along conveyors, shakeout, cleaning, heat treatment, and inspection, also are automated. Automation minimizes labor, reduces the possibility of human error, increases the production rate, and attains higher quality levels. Industrial robots (Section 37.6) are now used extensively in foundry operations, such as cleaning, riser cutting, mold venting, mold spraying, pouring, sorting, and inspection. Automatic storage and retrieval systems for cores and patterns using automated guided vehicles (Section 37.5) are other operations.

SUMMARY

- Expendable-mold, permanent-pattern processes include sand, shell-mold, plaster-mold, and ceramic-mold casting. These processes require the destruction of the mold for each casting produced, but mold production is facilitated by a reusable pattern.
- Expendable-mold, expendable-pattern processes include lost-foam and investment casting. In these processes, a pattern is consumed for each mold produced and the mold is destroyed after each casting.
- Permanent-mold processes have molds or dies that can be used to produce a large number of castings. Common permanent-mold processes include slush casting, pressure casting, die casting, and centrifugal casting.
- The molds used in permanent-mold casting are made of metal or graphite and are used repeatedly to produce a large number of parts. Because metals are good heat conductors, but do not allow gases to escape, permanent molds fundamentally have different effects on casting than sand or other aggregate mold materials.

- In permanent-mold casting, die and equipment costs are relatively high, but the processes are economical for large production runs. Scrap loss is low, dimensional accuracy is relatively high, and good surface detail can be achieved.
- Other casting processes include squeeze casting (a combination of casting and forging), semisolid-metal forming, rapid solidification (for the production of amorphous alloys), and the casting of single-crystal components (such as turbine blades and silicon ingots for integrated-circuit manufacture).
- Melting processes and their control also are important factors in casting operations. They include proper melting of the metals; preparation for alloying; removal of slag and dross; and pouring the molten metal into the molds. Inspection of castings for possible internal or external defects also is important.
- Castings are generally subjected to additional processing (such as heat treatment and machining operations) to produce the final desired shapes and surface characteristics and to achieve the required surface finish and dimensional accuracy.

KEY TERMS

Binders
Centrifugal casting
Ceramic-mold casting
Chaplets
Composite mold
Core print
Cores
Crystal growing
Die casting
Evaporative-pattern casting
Expendable mold
Expendable-pattern casting
Fluxes
Foundry
Green molding sand
Insert molding
Investment casting
Levitation melting
Lost-foam process
Lost-wax process
Parting agent
Patterns
Permanent mold
Permanent-mold casting
Plaster-mold casting
Precision casting
Pressure casting
Rammed-graphite molding
Rapid prototyping
Rapid solidification
Rheocasting
Sand casting
Semisolid-metal forming
Shell-mold casting
Slush casting
Sodium-silicate process
Squeeze casting
Thixotropy
Vacuum casting

BIBLIOGRAPHY

Allsop, D.F., and Kennedy, D., **Pressure Die Casting—Part II: The Technology of the Casting and the Die**, Pergamon, 1983.

Ammen, C.W., **Metalcasting**, McGraw-Hill, 2000.

An Introduction to Die Casting, American Die Casting Institute, 1981.

Andresen, W., **Die Cast Engineering: A Hydraulic, Thermal and Mechanical Process**, CRC Press, 2005.

ASM Handbook, Vol. 15: **Casting**, ASM International, 2008.

Beeley, P., **Foundry Technology**, Butterworth-Heinemann, 2002.

Brooks, N., **Mouldmaking and Casting**, Crowood Press, 2005.

Campbell, J., **Castings**, 2nd ed., Butterworth-Heinemann, 2003.

Chastain, S., **Metal Casting: A Sand Casting Manual for the Small Foundry** (2 vols), Chastain Publishing, 2004.

Clegg, A.J., **Precision Casting Processes**, Pergamon, 1991.

Investment Casting Handbook, Investment Casting Institute, 1997.

Martin, A., **The Essential Guide to Mold Making & Slip Casting**, Lark Books, 2007.

Otooni, M.A. (ed.), **Elements of Rapid Solidification: Fundamentals and Applications**, Springer, 1999.

Product Design for Die Casting, Diecasting Development Council, 1988.

Sias, F.R., **Lost-Wax Casting**, Woodsmere Press, 2006.

Steel Castings Handbook, 6th ed., ASM International, 1995.

The Metallurgy of Die Castings, Society of Die Casting Engineers, 1986.

Viarcik, E.J., **High Integrity Die Casting**, Wiley, 2002.

Young, K.P., **Semi-solid Processing**, Chapman & Hall, 1997.