

Part II

Discrete-Parts Manufacturing

Manufacturing, in its broadest form, refers to “the design, fabrication (production), and, when needed, assembly of a product.” In its narrower form, however, the term has been frequently used to refer to the actual physical creation of the product. In this latter context, the manufacturing of a product based on its design specifications is carried out in a discrete-parts mode (e.g., car engines) or a continuous-production mode (e.g., powder-form ceramic). In this part of the book, our focus is on the manufacturing (i.e., fabrication and assembly) of discrete parts. Continuous-production processes used in some metal, chemical, petroleum, and pharmaceutical industries will not be addressed herein.

In [Chap. 6](#), three distinct fusion-based production processes are described for the net-shape fabrication of three primary engineering materials: casting for metals, powder processing for ceramics and high-melting-point metals and their alloys (e.g., cermets), and molding for plastics. In [Chap. 7](#), several forming processes, such as forging and sheet forming, are discussed as net-shape fabrication techniques alternative to casting and powder processing of metals. One must note, however, that it is the manufacturing engineer’s task to evaluate and choose the optimal fabrication process among all alternatives based on the specifications of the product at hand.

In Chap. 8, several traditional material-removal techniques, such as turning, milling, and grinding, collectively termed as “machining,” are described. These techniques can yield parts that are dimensionally more accurate than those achievable by net-shape-fabrication methods. In practice, for mass-production cases, it is common to fabricate rough-shaped “blank” parts using casting or forming prior to their machining.

In Chap. 9, the emphasis is on nontraditional fabrication methods, such as electrical-discharge machining, lithography, and laser cutting, for part geometries and materials that are difficult to fabricate using traditional machining and/or forming techniques. Rapid layered fabrication of prototypes is also addressed in this chapter. A common constraint to all nontraditional (material-removal or material-additive) techniques is their restriction to one-of-a-kind or small-batch production.

In Chap. 10, several joining methods, such as mechanical fastening, adhesive bonding, welding, brazing, and soldering, are described as part of an overall discussion on product assembly. Automatic population of electronic boards and automatic assembly of small mechanical parts are also described in this chapter as exemplary applications of assembly.

In Chap. 11, workholding (fixturing) principles are discussed for the accurate and secure holding of workpieces in manufacturing. Numerous fixed-configuration (i.e., dedicated) jig and fixture examples are discussed for machining and assembly. Furthermore, several modular and reconfigurable systems are highlighted for flexible manufacturing.

In Chap. 12, common material-handling technologies, such as powered trucks, automated guided vehicles, and conveyors, targeted for the transportation of unit goods between manufacturing workcells, are described. The role of industrial robots in the movement of workpieces and tools within a workcell is also discussed in this chapter. The assembly of automobiles is addressed as an exemplary application area.

6

Metal Casting, Powder Processing, and Plastics Molding

This chapter presents net shape fabrication processes for three primary classes of engineering materials: casting for metals, powder processing for ceramics and (high-melting-temperature) metal alloys, and molding for plastics.

6.1 METAL CASTING

Casting is a term normally reserved for the net shape formation of a metal object by pouring (or forcing) molten (metal) material into a mold (or a die) and allowing it to solidify. The molten metal takes the shape of the cavity as it solidifies. Cast objects may be worked on further through other metal-forming or machining processes in order to obtain more intricate shapes, better mechanical properties, as well as higher tolerances. Over its history, casting has also been referred to as a founding process carried out at foundries.

6.1.1 Brief History of Casting

Casting of metals can be traced back in history several thousand years. Except in several isolated cases, however, these activities were restricted to the processing of soft metals with low melting temperatures (e.g., silver and

gold used for coins or jewellery). An isolated case of using iron in casting has been traced to China, which is claimed to be possible owing to the high phosphorus content of the ore, which allowed melting at lower temperatures.

Casting of iron on the European continent has been traced back to the period A.D. 1200–1300, the time of the first mechanized production of metal objects, in contrast to earlier manual forming of metals. During the period A.D. 1400–1600, the primary customers of these castings were the European armies, in their quest of improving on the previously forged cannons and cannon balls. However, owing to their enormous weight, the large cannon had to be poured at their expected scene of operation.

The first two commercial foundries in North America are claimed to be the Braintree and Hammersmith ironworks of New England in early 1600s. Most of their castings were manufactured by solidifying molten metal in trenches on the foundry floor (for future forging) or poured into loam- or sand-based molds. Wood-based patterns were commonly used in the shaping of the cavities.

Despite the existence of numerous foundries in America, one of the world's most famous castings, the Liberty Bell (originally called the Province Bell) was manufactured in London, England, in 1775, owing to a local scarcity of bronze in the U.S.A. The bell, which cracked in 1835, has been examined and classified as a “poor casting” (being gassy and of poor surface finish). Cannon and bells were followed by the use of castings in the making of stoves and steam-engine parts. Next came the extensive use of castings by the American railroad companies and the Canadian Pacific Railroad. Their locomotives widely utilized cast-iron-based wheel centers, cylinders and brakes, among many other parts. Although the railroad continues to use castings, since the turn of the 20th century, the primary user of cast parts has been the automotive industry.

6.1.2 Casting Materials

The most common casting material is iron. The widely used generic term cast iron refers to the family of alloys comprising different proportions of alloying material for iron—carbon and silicon, primarily, as well as manganese, sulphur, and phosphorus:

Gray cast iron: The chemical composition of gray cast iron contains 2.5–4% carbon, 1–3% silicon, and 0.4–1% manganese. Due to its casting characteristics and cost, it is the most commonly used material (by weight). Its fluidity makes it a desirable material for the casting of thin and intricate features. Gray cast iron also has a lower shrinkage rate, and it is easier to machine. A typical application is its use in the manufacture of engine blocks. Gray cast iron can be further alloyed with chromium, molybdenum, nickel,

copper, or even titanium for increased mechanical properties—strength, resistance to wear, corrosion, abrasion, etc.

Ductile cast iron: The chemical composition of ductile cast iron (also known as nodular or spheroidal graphite cast iron) contains 3–4% carbon, 1.8–2.8% silicon, and 0.15–0.9% manganese. First introduced in the late 1940s, this material can also be cast into thin sections (though not as well as gray cast iron). It is superior in machinability to gray cast iron at equivalent hardness. Its corrosion and wear resistance is superior to steel and equivalent to gray cast iron. Typical uses of ductile cast iron include gears, crankshafts, and cams.

Malleable iron: The chemical composition of malleable iron contains 2–3.3% carbon, 0.6–1.2% silicon, and 0.25–0.65% manganese. It can normally be obtained by heat-treating white iron castings. The high strength of malleable iron combined with its ductility makes it suitable for applications such as camshaft brackets, differential carriers, and numerous housings. One must note that malleable iron must be hardened in order to increase its relatively low wear resistance.

Other typical casting materials include

Aluminum and magnesium alloys: Aluminum is a difficult material to cast and needs to be alloyed with other metals, such as copper, magnesium, and zinc, as well as with silicon (up to 12–14%). In general, such alloys provide good fluidity, low shrinkage, and good resistance to cracking. The mechanical properties obtainable for aluminum alloys depend on the content of the alloying elements as well as on heat-treatment processes. Magnesium is also a difficult material to cast in its pure form and is normally alloyed with aluminum, zinc, and zirconium. Such alloys can have excellent corrosion resistance and moderate strengths.

Copper-based alloys: Copper may be alloyed with many different elements, including tin, lead, zinc, and nickel to yield, among others, a common engineering alloy known as bronze (80–90% copper, 5–20% tin, and less than 1–2% of lead, zinc, phosphorous, nickel, and iron).

Steel castings: These castings have isotropic uniformity of properties, regardless of direction of loading, when compared to cast iron. However, the strength and ductility of steel becomes a problem for the casting process, for example, causing high shrinkage rates. Low-carbon steel castings (< 0.2% carbon) can be found in numerous automotive applications, whereas high-carbon cast steels (0.5% carbon) are used for tool and die making.

6.1.3 Sand Casting

Numerous advantages make casting a preferred manufacturing process over other metal fabrication processes. Intricate and complex geometry parts can

be cast as single pieces, avoiding or minimizing subsequent forming and/or machining operations and occasionally even assembly operations; parts can be cast for mass production as well as for batch sizes of only several units and extremely large and heavy parts (thousands of kilograms) may be cast (as the only economically viable process of fabrication).

Among the numerous available techniques, sand casting is the most common casting process for ferrous metals (especially for large size objects such as automotive engine blocks). In sand casting, patterns are used for the preparation of the cavities, and cores are placed in the mold thereafter for obtaining necessary internal details. Due to the mostly mass production nature of the utilization of sand casting, the mold-making process and subsequent filling of the cavities is highly mechanized (usually in flow-line environments).

Pattern Making

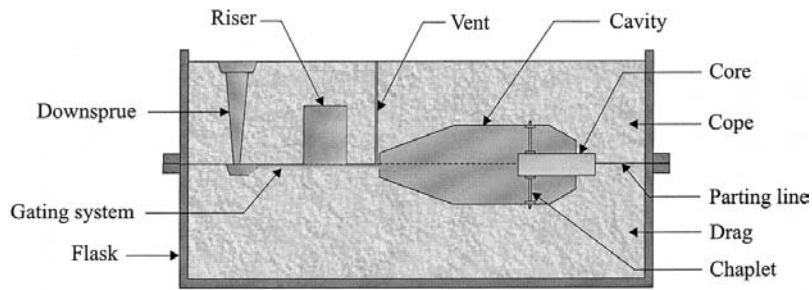
Pattern making is the first step in the construction of a mold, with the exception of die-casting molds. Historically, mold cavities have been generated by building the mold, in an iterative manner, around a given pattern made of wear-resistance metal (for repeated use), plastics (for limited use), or wax (for one-time use). These patterns have been either manually prepared (i.e., cut or carved) by industrial designers or machined by numerous material removal techniques (Chap. 8) based on the object's CAD data. (The latest technology used in pattern making is layered manufacturing—one such commercially available rapid prototyping technology is *stereolithography*, commonly used for the fabrication of thermoset plastic parts—Chap. 9).

During pattern making, one can also include the gating system, through which the molten metal flows into the cavities, as part of the pattern (Fig. 1). Furthermore, patterns can be manufactured in two halves (called the “cope” and the “drag” patterns, or halves, of the mold), as opposed to a single-piece pattern, for the individual production of the two halves of the mold.

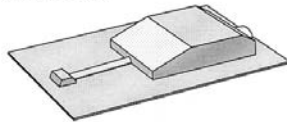
Although a pattern is used to produce the mold cavity, neither the pattern nor the cavity are dimensionally identical to the casting we intend to manufacture. Patterns must allow for shrinkage during solidification, for possible subsequent machining (namely, removal of some material to achieve better surface accuracy and finish), for distortion in large plates or thin-walled objects, and for ease of removal from the mold prior to casting.

Pattern making is followed by core making. Cores are patterns that are placed into the mold cavities and remain there during the casting process in order to yield the interior details of objects cast (Fig. 1). Naturally, they should be easily removable from the casting after the cooling period. In sand casting, cores are manufactured of sand aggregates.

One can realise that, for die casting applications, the pattern exists only in the virtual domain—i.e., as a CAD solid model. In such cases, the



Drag Pattern



Cope Pattern

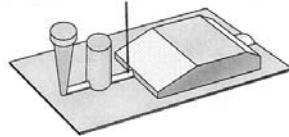


FIGURE 1 Sand mold.

mold is designed in the computer and its manufacturing operations are also planned in the same CAD domain.

Mold Making

As mentioned above, the sand casting mold is normally made of two halves—the cope and the drag. The sand used in making the mold is a carefully proportioned mixture of sand grains, clay, organic stretches, and a collection of synthetic binders. The basic steps of making a sand mold with two half patterns are as follows (Fig. 2):

1. The (half) pattern is placed inside the walls of the cope half of the mold.
2. The cope is filled with sand, which is subsequently rammed for maximum tightness around the pattern as well as around the gating system.
3. The pattern is removed.

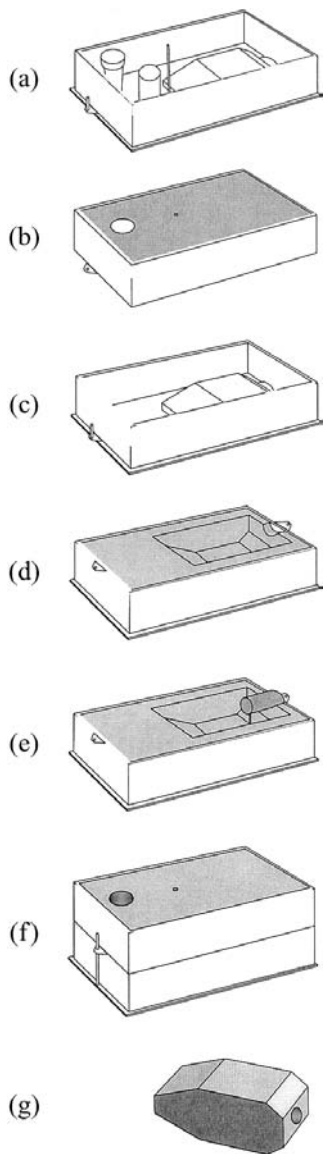


FIGURE 2 Mold-making and sand-casting process. (a) Cope pattern: ready to be filled with sand. (b) Cope filled with sand; pattern removed. (c) Drag pattern; ready to be filled with sand. (d) Drag filled with sand; pattern removed from drag. (e) Core placed inside drag. (f) Cope and drag assembled; molten metal poured into mold. (g) Metal cools and solidifies; casting removed from mold. Machining employed to remove the gating system; final product.

4. The second (half) pattern is placed inside the walls of the drag half of the mold.
5. The drag is filled with sand, which is subsequently rammed for maximum tightness around the pattern.
6. The pattern is removed and cores are placed if necessary.
7. The two mold halves are clamped together for subsequent filling of the cavities with molten metal.
8. The mold is opened after the cooling of the part and the surrounding sand (including the cores) are shaken out (through forced vibration or shot blasting).

Most sand cast parts would need subsequent machining operations for improved dimensional tolerances and better surface quality, which would normally be in the range of 0.015 to 0.125 in (app. 0.4 to 4 mm) for tolerance and 250 to 2000 μin (app. 6 to 50 μm) for surface roughness (R_a) (Chap. 16). However, one must note that sand casting can yield a high rate of production—hundreds of parts per hour.

6.1.4 Investment Casting

The investment casting process is also known as the lost wax process because of the expendable pattern (usually made of wax) used in forming the cavities. Although more costly than other casting processes, investment casting can yield parts with intricate geometries and excellent surface quality (15 to 150 μin , or approximately 1 to 6 μm). The term investment refers to the refractory mold that surrounds the wax pattern.

The basic steps of investment casting (mold making and casting) are as follows (Fig. 3):

1. An accurate metal die is manufactured and used for the large-scale production of wax patterns and gating systems.
2. The patterns are assembled into a multipart tree form and dipped into a slurry of a refractory coating material (silica, water and other binding agents). The tree is continuously lifted out and rotated to produce uniform coating and drainage of excessive slurry.
3. The tree is sprinkled with silica sand and allowed to dry.
4. The tree is invested in a mold with a slurry and allowed to harden (several hours to a day).
5. The mold is placed in an oven and the wax is melted off the investment casting mold (up to a day).
6. Molten metal is poured into the cavities while the mold is still at a high temperature.
7. The shells are broken and the castings cleaned.

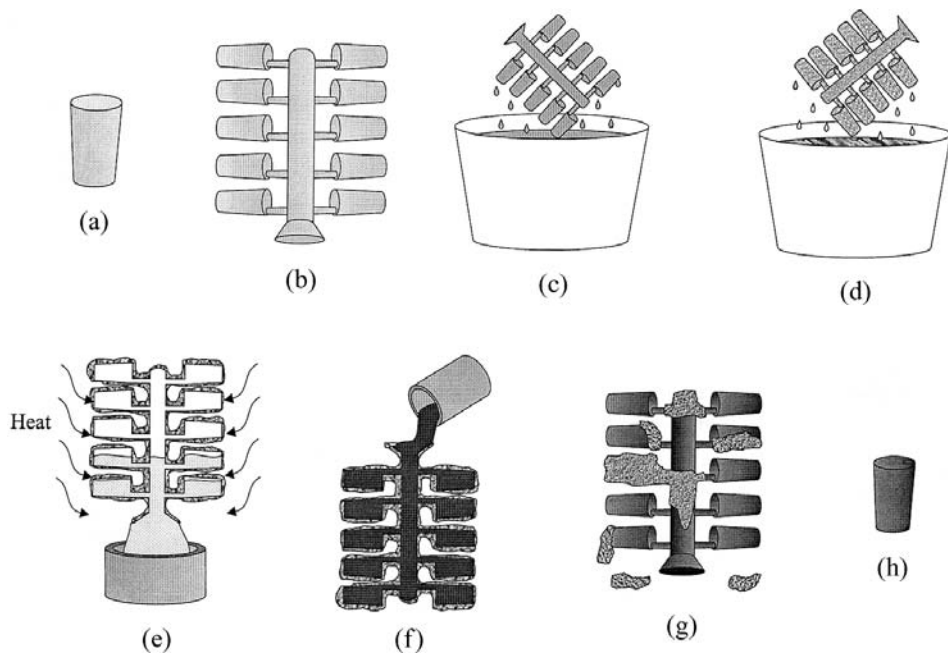


FIGURE 3 Investment casting. (a) Wax pattern. (b) Patterns attached to wax sprue. (c) Patterns and sprue coated in slurry. (d) Patterns and sprue coated in stucco. (e) Pattern melt-out. (f) Molten metal poured into mold; solidification. (g) Mold broken away from casting; finishing part removed from sprue. (h) Finished part.

Robots have been commonly used in the automation of the mold making process for investment casting: manufacture of wax patterns, assembly of trees, shell buildup, dewaxing, firing, casting, and cleaning.

6.1.5 Die Casting

Molds for multiuse must be made of comparably durable material (for example, tool-grade steel) and utilized for long runs in order to be economically viable. During the casting process, such molds would be sprayed (with silica-type fluid) prior to pouring of the molten metal, primarily to reduce wear. Molds are also be equipped with cooling systems in order to reduce cycle times, as well as to control the mechanical properties of the die cast part.

In the above context, die casting is a permanent mold process, where the molten metal is forced into the mold under high pressure, as opposed to pouring it in (under gravitational force). Die casting offers low cost, excellent dimensional tolerances and surface finish, and mass production capability (with low cycle times).

Die casting fabrication processes can be traced back to the mid-1880s, when it was used for the automatic production of metal letters. The development of the automotive industry in the early 1900s, however, is accepted as the turning point for die casting that first started with the production of bearings. Today, many automotive parts (door handles, radiator grills, cylinder heads, etc.) are manufactured through die casting (at rates of several thousands per hour). Most such parts are made of zinc alloys, aluminum alloys, or magnesium alloys.

As in other cases, a die casting mold comprises two halves. In this case one of the halves is fixed and the other is moving (the “ejector” half). After solidification, the casting remains in the moving half when the mold is opened. It is then ejected by (mechanically or hydraulically activated) pins. In order to prevent excessive friction with the fixed half and ease of ejection from the moving half, the part should have appropriate draft angles. Internal or external fins can be achieved by utilizing loose or moving die cores in the fixed half of the die. (Average wall thicknesses of die cast parts range from 1.0 to 2.5 mm for different alloys.)

There exist two primary die casting processes, whose names are derivatives of the machine configuration, more specifically, the locations of the molten metal storage units (Fig. 4): in the hot chamber machine, the molten metal storage unit is submerged in a large vat of molten material and supplies the die casting machine with an appropriate amount of molten metal on demand; on the other hand, for the cold chamber machine, a specific amount of molten metal is poured into the (cold) injection chamber that is an integral part of the die casting machine. Subsequently, this material is forced into the die under high pressure (typically, up to 150 MPa, or 20 ksi).

High-pressure cold chamber machines were originally supplied (ladled) manually by transferring molten metal from a holding furnace. However, since the 1970s, this process has been automated using mechanical ladles or machines that utilize pneumatic (vacuum) dispensers or electromagnetic pumps. Other automation applications in die casting have included the automatic lubrication of the die cavities by utilizing fixed or moving spray heads, as well as the use of robotic manipulators (ASEA, GM Fanuc and others) in the removal of parts from the dies (extraction), such as gasoline engines found in lawn mowers, snowmobiles, and garden tractors, and automotive fuel injection components.

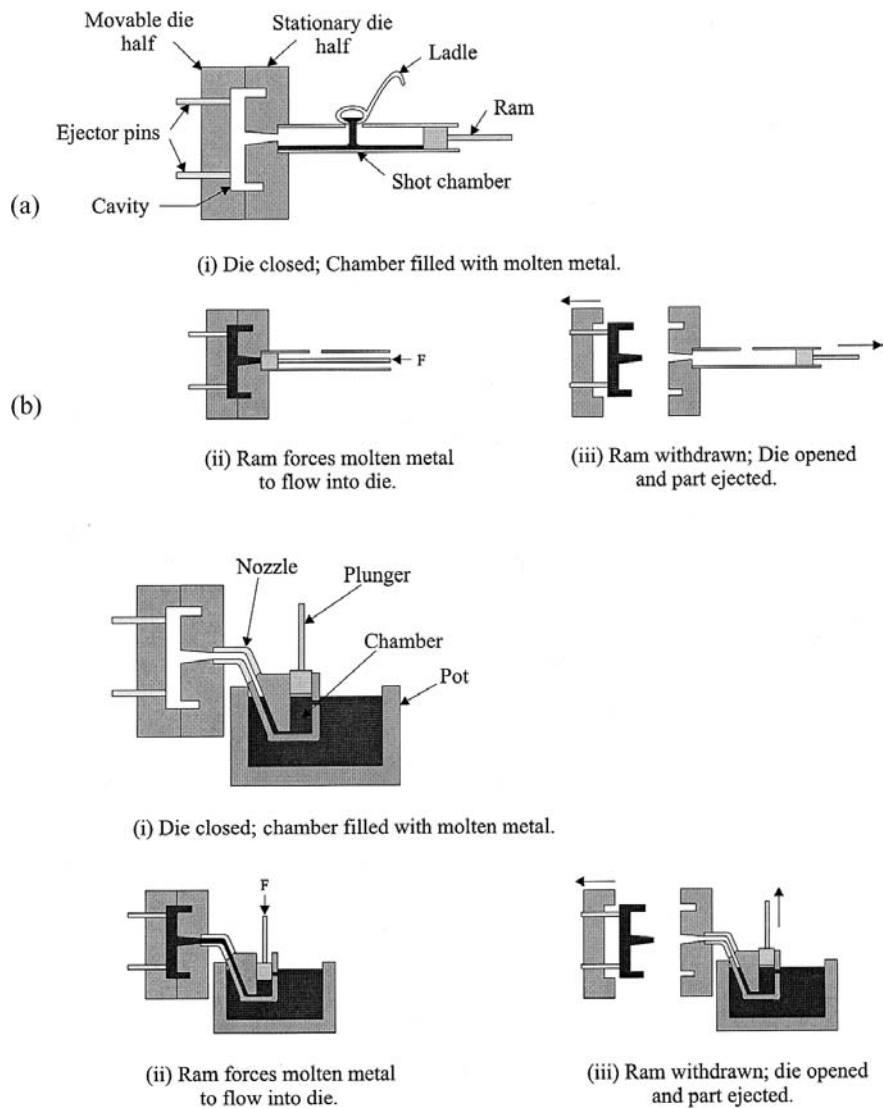


FIGURE 4 Die casting. (a) Cold chamber; (b) Hot chamber casting.

6.1.6 Design for Casting

The mechanical properties of a casting are of paramount concern to the user. Thus engineers must carefully design their parts and molds concurrently for optimizing a casting's performance. For example, parts can be designed to favor directional solidification for maximum strength and minimum chance of defects—columnar growth of dendrites would create weaknesses at sharp corners and must be avoided through the use of fillets. Furthermore, some metals are more susceptible to shrinkage during cooling and certain harmful shrinkage cavities—“hot spots.” Such problems are more apparent at junctions, especially owing to changing wall thicknesses: they could be alleviated by utilizing small nonfunctional holes that would not affect the overall strength of the part (Fig. 5).

Some other casting-design guidelines are

Adjacent thin and thick sections cause porosity when cooling. Thus fillets and tapering should be used for projections, and when

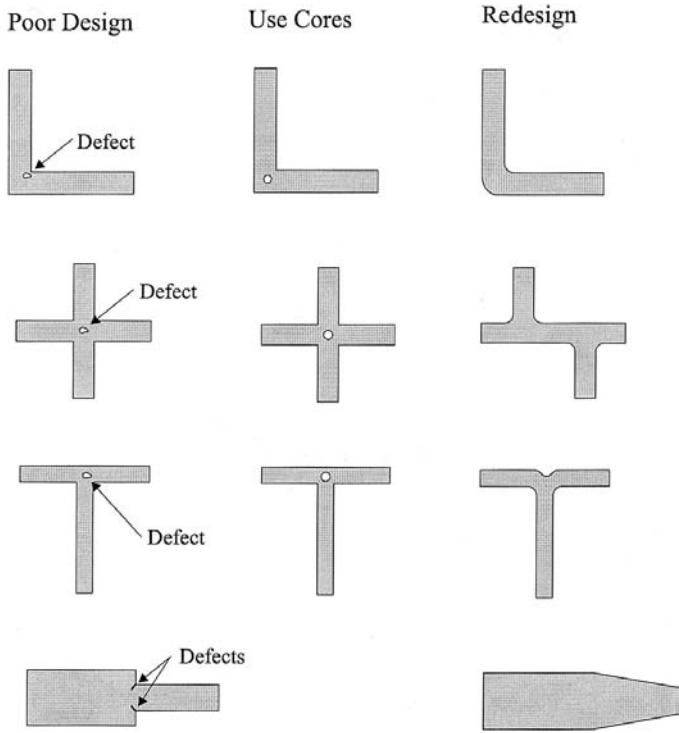


FIGURE 5 Hot spots in castings.

necessary local chilling should be employed as an additional measure.

It is generally more economical to drill out holes rather than using cores (especially for smaller holes).

Parting lines should be as straight as possible in order to prevent increased mold costs.

Casting threads (especially external) is more economical than machining.

Raised letters on parts (i.e., depressed shapes in the cavity) are cheaper to manufacture.

6.2 POWDER PROCESSING

Powder metallurgy, sintering, and powder processing have been synonymously used to describe the formation of discrete parts in mold/die cavities by compacting a mass of particles (< 150 microns) under pressure. This net shape fabrication process is normally reserved for mass production of materials whose melting point makes them unsuitable for fusion techniques, such as casting. Here, the term powder processing will be utilized (versus the other two common terms) since we will discuss materials that are metal as well as nonmetal, and since sintering is only one of the primary steps in powder processing.

The basic steps of powder processing are powder production, compacting of powder, and sintering. The last phase involves heating the “preform” part to a temperature below its melting point, when the powder particles lose their individual characteristics through an interdiffusion process and give the part its own overall physical and mechanical properties. Sintering lowers the surface energy of the particles by reducing their (surface) areas through interparticle bonding.

6.2.1 Brief History of Powder Processing

The powder processing of ceramic pottery and platinum jewelry can be traced back several thousands years. With the introduction of forging and casting, powder processing took a pause until the early 1900s, except for occasional revival attempts along the way. The first commercially viable process in the early 1900s was the manufacture of tungsten wires used in electric (incandescent) bulbs. The production of tungsten carbide (with cobalt) followed in the 1920s. The next significant development was the fabrication of porous, self-lubricating bronze (90% copper and 10% tin powder) bearings (impregnated with oil) in the late 1920s.

The second half of the 20th century saw an explosive spread in the use of powder-processed modern materials, including a variety of cemented carbides, artificial diamonds, and cermets (ceramic alloys of metals). Today, such powder-processed components are used by many industries: aerospace (turbine blades), automotive (gears, bushings, connecting rods), and household (sprinklers, electrical components, pottery). Recent developments in efficient production techniques (such as powder injection molding and plasma spraying) promise a successful future for powder processing of light and complex geometry parts with excellent mechanical properties.

6.2.2 Powder Processing Materials

Materials for powder processed products are many, and new alloys are proposed yearly. In this chapter, only a representative subset will be discussed with the emphasis being on hard particles with high-melting temperatures.

Metals

Metal powders commonly used today for powder processing include iron and steel, aluminum alloys, titanium and tungsten alloys, and cemented carbides. There are numerous techniques for the production of metal powder:

Mechanical means can be effectively used to reduce the size of metal particles: Milling and grinding of (solid-state) metals rely on the fracture of the larger particles.

Melt atomization of metals can be classified as liquid or gas atomization. The former utilizes a liquid (normally, water) jet stream, which is fed with the molten metal, for the formation of droplets of metal (that has a low affinity to oxygen). Gas atomization is similar to liquid atomization, but it uses gases such as nitrogen, argon, or helium for melt disintegration.

Chemical reduction can also be used for the fabrication of metal powders from their (commonly) original solid state (for example, through the use of hydrogen).

Iron and steel are the most commonly (by weight) powder processed materials. Steels and alloyed steels are utilized for the production of bearings and gears in automotive vehicles, of connecting rods in internal combustion engines, and even of cutting tools and dies (high-speed steels, HSS). Powder processed steel parts can have homogenous distribution of (high-content) carbides with excellent isotropic properties for increased lifetime—a characteristic that cannot be easily obtained through casting or forming.

Although a preferred manufacturing technique for titanium alloy products is through melting, complex-geometry parts can be produced via

powder processing. Tungsten products, on the other hand, are exclusively fabricated through powder processing owing to tungsten's high melting point ($> 3400^{\circ}\text{C}$).

Cemented carbides (also known as hard metals), first developed in Germany in the 1920s, combine at least one hard compound and a binder metal—for example, tungsten carbide particles in a cobalt matrix. The hard metal provides the parts with high hardness and wear resistance, while the binder matrix provides them with mechanical and thermal shock resistance (toughness). The most common use for such carbides are cutting tools for the machining industry (and even for the mining industry).

Cermets

Cermet is a compound word indicating that the composition of the material contains at least one ceramic and one metallic component. Such materials have been fabricated since the mid-1900s. (The component with the highest volume fraction is considered to be the matrix.) Cermets are very suitable for high-temperature environments (e.g., metal-cutting tools, brake linings, and clutch facings). Metal-bonded diamond grinding wheels can be used to grind refractory materials, such as granite, fused alumina, and cemented carbides.

Ceramic powders can be produced through chemical reactions (solid–solid, solid–gas, and liquid–liquid). Some secondary mechanical processes (e.g., milling) can also be used for powder-size reduction.

6.2.3 Compacting

Bulk powder can be (automatically) transformed into (“green”) preforms of desired geometry and density through compacting prior to their sintering. The first step in this process is effective mixing of the multimaterial powder. At this stage, lubricant, in the form of fine powder, is also added to the mixture (for reduced friction) if the powder is going to be formed in a closed die.

Most compacting operations, with the exception of processes such as slip casting and spray forming, are carried out under pressure: die compacting, isostatic compacting, powder rolling, extrusion of powder, and powder injection molding (PIM). Pressure-assisted compacting can be further categorized into cold (at ambient temperature) and hot (material-dependent enhanced-temperature) compactions.

Bulk powders are compressible materials—as the pressure is increased, the fraction of voids in the powder rapidly diminishes and the particles deform under (first elastic and then) plastic mechanisms (Fig. 6). The denser the preform is, the better are its mechanical properties and the less dimensional variation during sintering.

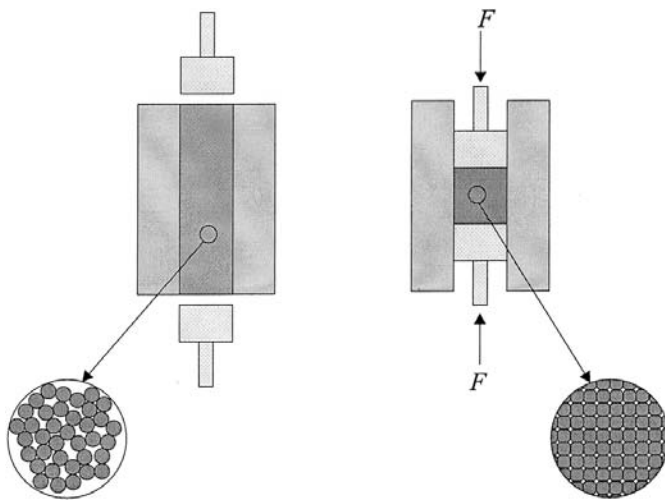
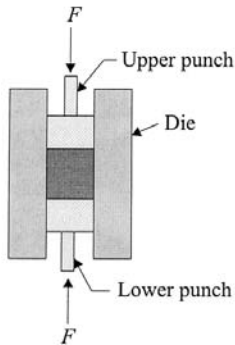


FIGURE 6 Compacting of powder.

Cold Compacting

Cold compacting (pressing), axial (rigid die) or isostatic (flexible die), is the most commonly utilized powder compacting method (Fig. 7). It requires only small amounts (and sometimes no amount) of lubricant or binder additions. In axial rigid die pressing, the powder is compacted by axially loading punches (one or several depending on the cross-sectional variations

Rigid-die compacting



Flexible-mold compacting

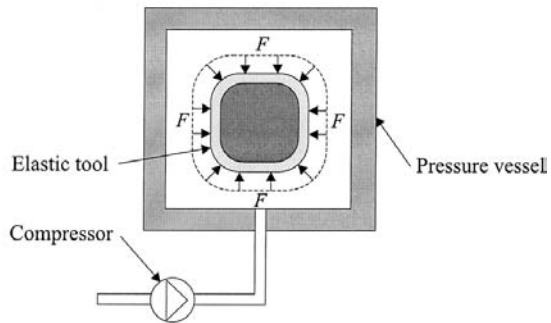


FIGURE 7 Rigid-die versus flexible-mold compacting.

of the part geometry), which are operated through mechanical or hydraulic presses. In isostatic compaction, a uniform pressure is applied to all the external surfaces of a powder body sealed in a flexible (elastomeric) envelope/mold. Incompressible liquids are normally utilized for exerting the required pressure. Although hydrostatic pressure would yield excellent uniformity in density, dimensional accuracy of the (green) preform is considerably less than it would be if manufactured in a rigid die.

Roll compacting can be utilized to fabricate (green) strips (or sheets) of powderprocessed (thin-walled) products. The powder can be fed into the rollers in vertical, inclined, or horizontal configurations (Fig. 8). Owing to the continuous nature of this process, however, the green product is usually fed (immediately) into a furnace on a rolling conveyor configuration. Frequently, the sintered product must be rolled again in order to reduce porosity.

Hot Compacting

The main hot compacting techniques are the axial and isostatic pressing processes and hot extrusion. Heating of the material in axial presses is achieved through direct heating of the powder or through heat transfer from the (heated) tool. In isostatic pressing, heating can be achieved by placing heating elements in the liquid enveloping the flexible mold.

Hot compacting of metals should be reserved for a select set of materials whose mechanical properties can indeed be improved during a heat-induced and pressurized compacting process. The process is expensive and difficult to operate and maintain. However, complex-shape products, when produced through such a technique, may be worth the effort—for example, jet-engine turbine disks fabricated from nickel-base superalloy powders. Temperatures in hot compacting can be as high as 1050–1100°C for beryllium and 1400°C for cemented carbides, or even higher (up to 2500°C for other materials).

Injection molding of powders, although occasionally considered as a hot compacting technique because of the elevated temperature of the plastic binding material (150° to 200°C), should be treated as a cold compacting

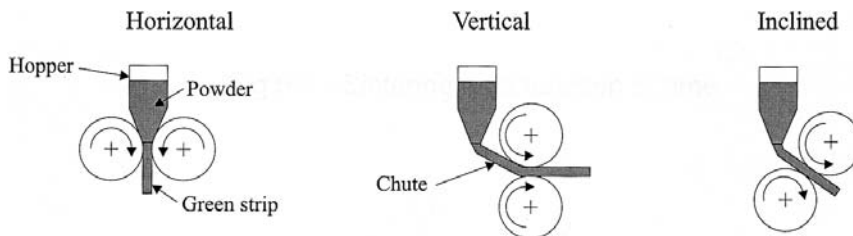


Figure 8 Roll compacting.

technique. The formation of green parts through this technique will be discussed following the presentation of the injection molding technique for polymers in Sec. 6.3 below.

6.2.4 Sintering

Sintering, the last stage in powder processing, is the thermal bonding of particles into a coherent, primarily solid structure. The mechanical properties of the original green compacted part are significantly improved through the elimination of the pores and the increase in density. However, it should be noted that the former phenomenon occurs at the expense of shrinkage and undesired dimensional changes. Thus maximum densities should be obtained at the presintering compaction phase.

Most sintering processes are carried out in pressureless environments and involve a partial liquid phase of the matrix component for multi-component materials. The presence of liquid (even for very short periods of time) improves the mass-transport rates and creates capillary pull. The application of heat can occur in batch or conveyor-type furnaces. Batch furnaces are easier to utilize, since the heating–cooling cycle is only dependent on the time a batch of parts spends in the furnace. In a continuous sintering furnace, the speed of the conveyor has to be carefully controlled, where parts are either placed on trays or directly on a metal screen belt. Sintered parts can be unloaded from furnaces using industrial robots.

Single-Phase Sintering

Sintering forms solid bonds between the particles, reducing the surface energy through grain growth and elimination of pores. Individual grain boundaries normally disappear by the end of the sintering process, and what remains behind is a solid cross section with distributed pores (Fig. 9). As is further shown in Fig. 10, individual grain boundaries are assumed to disappear through a neck growth process, in which two particles coalesce into a single larger particle.

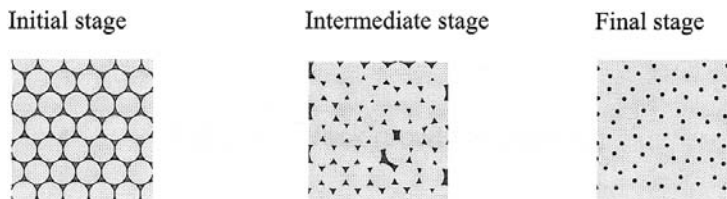


FIGURE 9 Sintering as a function of time.

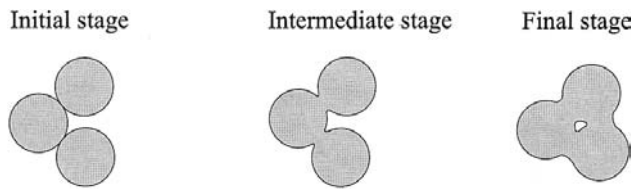


FIGURE 10 Neck growth in sintering.

Two mass-transport mechanisms contribute to grain bonding: surface transport and bulk transport. The former yields neck growth at lower temperatures without a change in particle spacing. Although bulk transport also contributes to neck growth, mass densification is the primary characteristic of this mechanism, which is achieved through volume diffusion, plastic flow, and viscous flow at high temperatures.

Sintering of multicomponent powder mixtures is normally carried out in the presence of a liquid phase of one of these components, as discussed below. However, sintering of mixtures can also be carried out in a single-phase (sintering) environment. In this case, neck growing predominantly occurs for the component with the lower melting temperature. Even if sintering times were prolonged for better mechanical properties, the individual rates of diffusion of the different powders would result in higher percentages of pores than those in single-component preforms.

Liquid-Phase Sintering

The presence of a liquid phase significantly increases the rate of sintering. Thus this process is commonly used in industry for both metal and ceramic alloys (e.g., cemented carbide cutting tools). Substantially full densities can be obtained through good wetting of the liquid on the solid particles, thus eliminating porosity. In this multistage process, the powder's temperature is first raised until the melting of one of the components. During this stage, solid-state sintering is already initiated. Subsequently, in the presence of the liquid phase, densification occurs through rearrangements (due to capillary forces), solution reprecipitation (i.e., grain growth), and final solid-state sintering.

6.2.5 Design for Powder Processing

As with casting, parts produced by powder processing are considered net shape and require few additional finishing processes. Due to processing requirements, especially the necessary high pressure for compacting, powder processed parts should not be too large. Thin geometrical details should also be avoided for ease of powder flow. The overall part geometry

should be as simple and as uniform as possible. High length-to-diameter ratios (> 3) should be avoided. Sharp corners and edges weaken the part's mechanical properties. Undercuts and side holes, as well as threads, interfere with the ejection of the parts and should be machined after the parts have been sintered.

6.3 PLASTICS PROCESSING

Plastics have been one of the most controversial material groups of the 20th century. Despite their wide use in a large number of household and industrial products, they have been seen as a serious threat to the world's environment. However, as will be noted in this section, a large percentage of plastics are recyclable with minimum effort (in terms of having lower melting temperatures when compared to those of metals). Thermoplastic polymers constitute 85% of plastics in use—they can be recycled many times by simply repeating the heating and cooling cycle. Thermoset polymers, on the other hand, constitute the remaining 15% of plastics in use today and cannot be recycled.

Their resistance to corrosive degradation combined with their light weight have made plastics very suitable for use in industries such as construction, automotive, aerospace, and household products. They can be manufactured in continuous form (e.g., extrusion) or discrete form (e.g., injection molding). In the past several decades, plastics have also been reinforced with glass and carbon fibers to increase significantly their mechanical properties (strength and rigidity) to complement their excellent electrical and chemical properties.

6.3.1 Brief History of Plastics

The production of plastic products in modern times can be traced to the 1860s in England, where small moldings made of cellulose nitrate were made by A. Parkes. The 1930s witnessed the development of nylon and polyethylene by W. Carothers (working for DuPont de Nemours & Co.) and by ICI, England, respectively. The first uses of these products were in self-lubricating bearings and wire insulation. Today, plastics are used in the production of bottles, drums, toys, pipe fittings, wires, aircraft structures, and a variety of automotive parts.

Polymers and polymer composites have been used in automotive applications since the 1930s and 1950s, respectively. Today, approximately 8% (by weight) of material used in a North American automotive vehicle is plastics based. This percentage is also approximately 8% for European vehicles and 6% for Asian vehicles. Generally, 30% of plastics are used in the exterior of the car, 40% in the interior, 10% under the hood, and 20%

other (including structural components). Some examples include engine intake manifolds, instrument panels, side doors and door handles, fuel tanks, and fuel lines. It is expected that by 2015, the plastics content in a vehicle could rise to 12 to 15% (by weight). However, there are two competing factors that could affect this predicted composition: legislative recycling initiatives could keep the percentages at current levels or even force reductions, while legislative fuel-economy initiatives could force manufacturers to increase the usage of plastics up to 15 to 20% (by weight) in order to reduce the overall vehicle weight.

6.3.2 Engineering Plastics

Plastics refer to the family of polymers (organic materials), which are made of repeated collection of monomers produced through polymerization. The word polymer derives from the Greek words of *poly*, meaning many, and *meros*, meaning part. (Polyethylene, for example, comprises chains of ethylene, CH_2 , monomers, as many as 10^6 of them per molecule.)

Polymers are classified based on their structures: linear chains, linear-branched chains and cross linked. The first two are called thermoplastic polymers; they can be solidified or softened (molten state) reversibly by changing their temperature. Cross-linked thermoset polymers, on the other hand, have their networks set after solidification and cannot be remelted, but only burned.

Thermoplastics

The four major low-cost, high-volume thermoplastic polymers are polyethylene, polypropylene, polystyrene, and polyvinyl chloride.

Polyethylene (PE) is a polymer comprising ethylene monomers. It has excellent chemical resistance to acids, bases, and salts. It is also easy to process (mostly through injection molding or extrusion), free from odor and toxicity, and reasonably clear when in thin film form. Major product lines of PE include bottles, toys, food containers, bags, conduits and wires, and shrink wraps.

Polypropylene (PP) is a fast growing low-cost polymer. Its heat resistance, stiffness, and chemical resistance is superior to those of PE. PP films can also be glass clear and be very suitable for food packaging when in coated (biaxially oriented) grade. Major product lines for PP include medical containers, luggage, washing-machine parts, and various auto parts (e.g., battery cases, accelerator pedals, door frames).

Polyvinyl chloride (PVC) is a polymer comprising vinyl and chloride monomers. It is always utilized with fillers and/or plasticizers (nonvolatile solvents), or even with pigments, lubricants, and extenders (e.g., paraffins and

oil extracts). PVC is the most versatile polymer; it can be rigid or flexible (when plasticized), it is resistant to alkalis and dilute mineral acids, and it can be a good electrical insulator. Major product lines of PVC include kitchen upholstery, bathroom curtains, floor tiles, blood bags, and pipes and fittings.

Polystyrene (PS) is a polymer comprising styrene monomers. It is the lowest-cost thermoplastic. Its major characteristics are rigidity, transparency, low water absorption, good electrical insulation, and ease of coloring. A significant limitation, however, is its brittleness—thus its rubber-modified grade of high-impact PS (containing up to 15% rubber). Its major product lines include mouldings for appliances, containers, disposable cutlery and dishes, lenses, footwear heels, and toys.

Thermosets

The four major thermoset polymers are polyester, epoxy, polyurethane, and phenolic. Although phenolics are historically the oldest thermosets, the largest thermoset family used today is the polyesters. Thermosetting polyesters are almost always combined with fillers, such as glass fibers, for yielding reinforced plastics with good mechanical properties. The automotive market is probably the largest consumer of such products. The high strength-to-weight ratio of polyester-glass laminates have led to their use also in aircraft parts manufacturing.

Composites

Composite plastics have two primary ingredients, the (thermoplastic or thermoset) polymer matrix and the reinforcement fibers/flakes/fillers/etc. The modulus and strength of the reinforced plastic is determined by the stiffness and the strength of the reinforcements and the bonding between them and the polymer matrix.

The most commonly used reinforcing material is glass fibers. They can be continuous fibers (woven into a laminated structure through filament winding) or (chopped) short fibers (mixed with the liquid polymer prior to being processed). E-glass (54% SiO₂) is the most widely used reinforcement: it has 76 GPa tensile modulus and 1.5 GPa tensile strength. Other reinforcing materials include carbon fibers, synthetic polymer fibers, and even silicon carbide fibers. DuPont's aramid polymer fiber (Kevlar 49) has found a niche market in aerospace and sports products, where superior performance is needed and cost is not a limiting factor. Kevlar's tensile modulus and strength are almost as twice those of E-glass fibers.

In the automotive industry, many companies (Ford, GM, Chrysler, Honda, etc.) have concentrated on the use of composite parts since the early 1980s, even in the primary vehicle structures, as a replacement for steel. The revolutionary car of the future could comprise 50% (by weight) aluminum

and 50% composite plastics, thus achieving a 30 to 50% weight reduction in comparison to today's steel-based cars.

6.3.3 Thermoplastic Processes

The most widely used manufacturing processes for thermoplastic polymers are injection molding, extrusion, blow molding, rotational molding, and calendaring. (Some of these can also be used for thermoset polymers, such as injection molding.) Extrusion, injection molding, and blow molding will be briefly reviewed here.

Extrusion

Although the focus of this book is on discrete parts manufacturing, the extrusion of plastics, which is a continuous process, is reviewed here because it is utilized in other plastics manufacturing processes to plasticize the polymer. The three primary elements of an extruder are the hopper, the barrel, which houses the screw, and the die (Fig. 11). Generally, the material (in granular form, pellets) is allowed to flow freely from the hopper into the throat of the extruder barrel (under gravity). As the screw turns in the heated barrel, a forward flow is generated. Frictional forces that develop within the barrel are the primary contributors to the melting (plasticizing) of the polymer. The molten material is fed into a die and exits the extruder (as it cools) assuming the cross-sectional shape of the die.

Besides pipes, tubes, and sheets, extruders can make hollow objects for blow molding (such as bottles) and provide injection molding machines with plasticized melt. In (noncontinuous) blow molding production, the resin flowing out of the extruder is fed into a mold and cut to dimension for yielding individual preforms (parisons), which are subsequently enlarged (and thinned in wall thickness) through blowing, as will be discussed below.

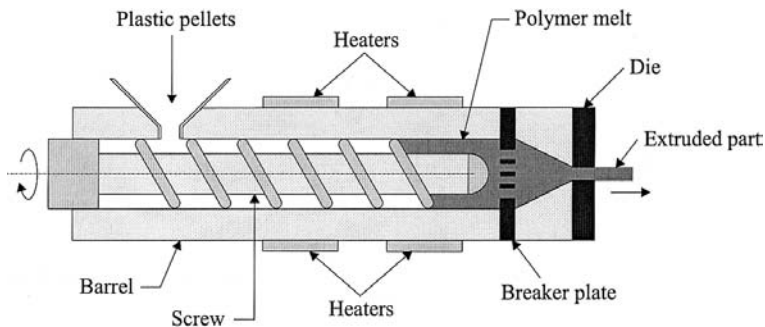


FIGURE 11 Plastics extrusion.

Blow Molding

Blow molding is primarily aimed at the production of thin-walled hollow plastic products. However, the process can be utilized for the fabrication of toys and even automotive parts. The basic steps of this process are: (1) the formation of a parison (a tube-like preform shape) in the molten state of the polymer, (2) sealing of one end of the parison and its inflation with blowing air injected from the other end—the parison then assumes the shape of the cavity of the mold, and (3) cooling and ejection from the mold (Fig. 12). The parison can be fabricated via a continuous or intermittent extrusion process linked to the blow molding machine. Parisons can also be injection molded in a cavity (of an injection mold) and then transferred to a second blowing mold.

Injection Molding

Injection molding is the most widely used process for thermoplastics in discrete parts manufacturing industries. The basic steps of injection molding are: (1) the transfer of resin (pure polymer or composite mixture) into a plasticizing chamber, (2) plasticizing of the resin and its transfer to the injection chamber (utilizing an extrusion screw or a cylinder), (3) pressurized

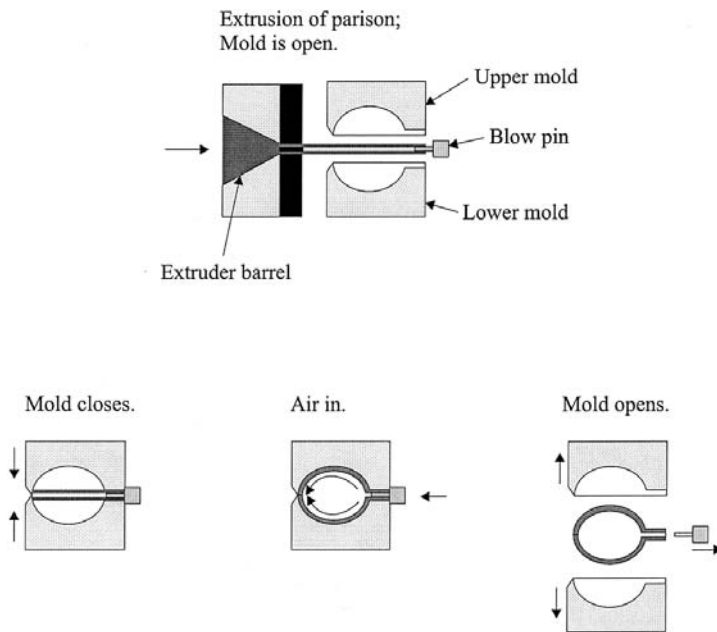


FIGURE 12 Blow molding.

injection of molten material into a closed mold (held tightly shut under great clamping forces), (4) solidification and cooling in the mold, and (5) ejection of parts from the cavities (Fig. 13).

Mold designs for injection molding are affected by many factors: the type of material to be molded and part geometry—affecting gating and

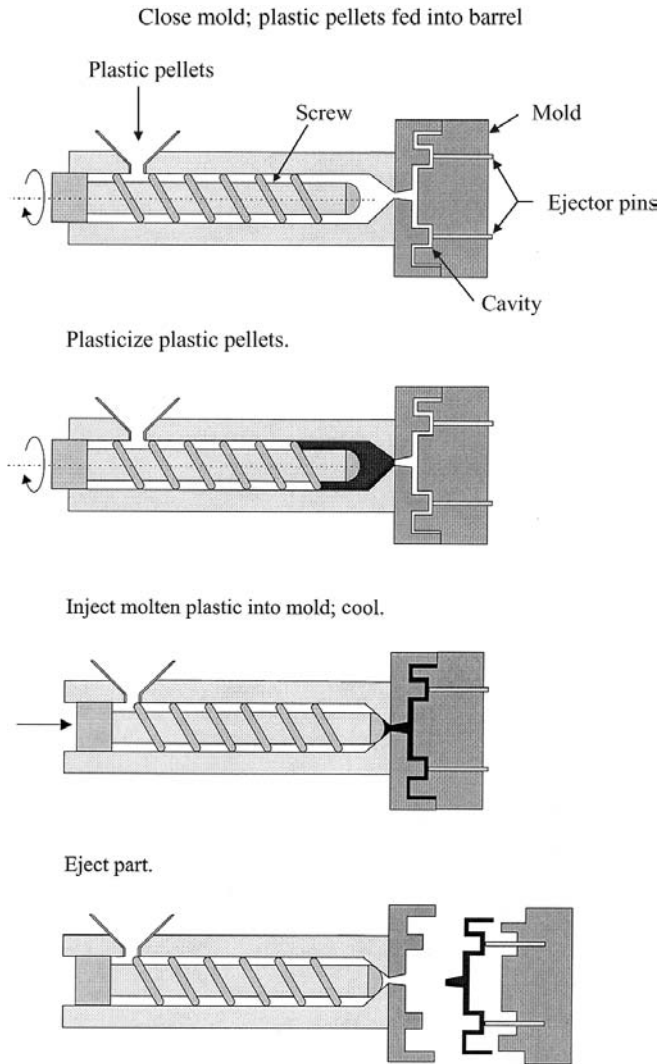


FIGURE 13 Injection molding.

ejection configurations, and production requirements—which dictate number of cavities, cooling rates, and mechanization. The mold may have two or three plates: one (or two) movable plates and one stationary plate. In two-plate molds, mold cavities are placed on the stationary plate and the ejectors on the moving plate (Fig. 14).

Injection molding can also be used for the fabrication of thermoset plastics. However, for such materials, the screw in the extrusion barrel must have a zero compression ratio—i.e., the depth of flight is uniform throughout the length of the screw. The materials themselves (most commonly phenolics) must also be modified for timely plasticization within the extruder. Normally, these thermoset materials are reinforced with short glass fibers, whose shrinkage characteristics must be considered during molding.

Recently, metal and ceramic powders have been also mixed with thermoplastic polymers for the fabrication of “compacts” (preforms) prior to a sintering phase in powder processing (Sec. 6.2). The polymer (commonly

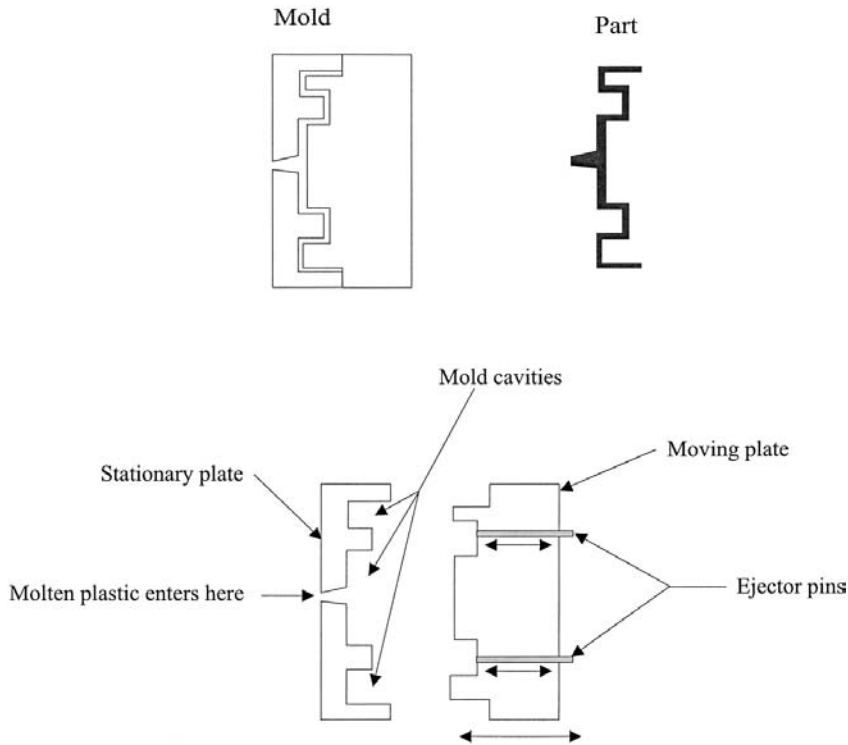


FIGURE 14 Injection mold design.

polyethylene) acts as a binder and is removed from the compact through thermal debinding or through the use of solvents. This injection molding process is commonly referred to as powder injection molding (PIM).

6.3.4 Thermoset Processes

Thermoset resins require higher temperatures (than do thermoplastics) to initiate polymerization (for the forming of a cross-linked matrix). Once processed, these plastics are temperature and chemical resistant, though they are also very brittle. Thus thermosets are seldom used without a reinforcement agent (such as fibers, glass, or synthetic polymers). As a result of these additives, processes for thermoset plastics must accommodate for the processing of two-phase mixtures (liquid matrix and solid additives). The three most widely used mold-based processes are compression molding, transfer molding, and, as mentioned above, injection molding. Other open-mold processes would include spray up, filament winding, and centrifugal casting.

Industrial robots are commonly used in spray up (or its derivative processes), where the robotic manipulator holds a spray gun that sprays catalyzed polyester resin mixed with chopped glass fibers onto a mold surface. Robots are also widely used in the removal of large parts from molds and in transferring them to other postcuring locations.

Compression Molding

Compression molding is the oldest method for the mass production of plastic products (thermoset as well as some polyethylene thermoplastics). This simple process includes two steps: (1) a controlled amount of resin (in pellet form) is placed into the cavity of a heated mold (150°C to 200°C) (2) the mold is subsequently closed under pressure and the resin is allowed to flow (to assume the shape of the cavity). Once ejected, parts can be transferred to a finishing area for the removal of flash (Fig. 15).

Compression molding can be used for high-reinforcement-content materials, with large surface areas and thicknesses, and it provides excellent uniformity in mechanical properties (isotropy). Also, since the polymer flows over short distances, concerns for large “frozen-in” stresses is reduced. Furthermore, the resin does not have to flow through a gating system (gate, sprue, and runners layout). However, the process is labor intensive (unless people are replaced by robots) and causes material waste (flash).

Transfer Molding

Transfer molding is a relatively new process developed (by L. E. Shaw) in response to the shortcomings of compression molding—especially for the production of parts with holes and recesses. The term “transfer” is in

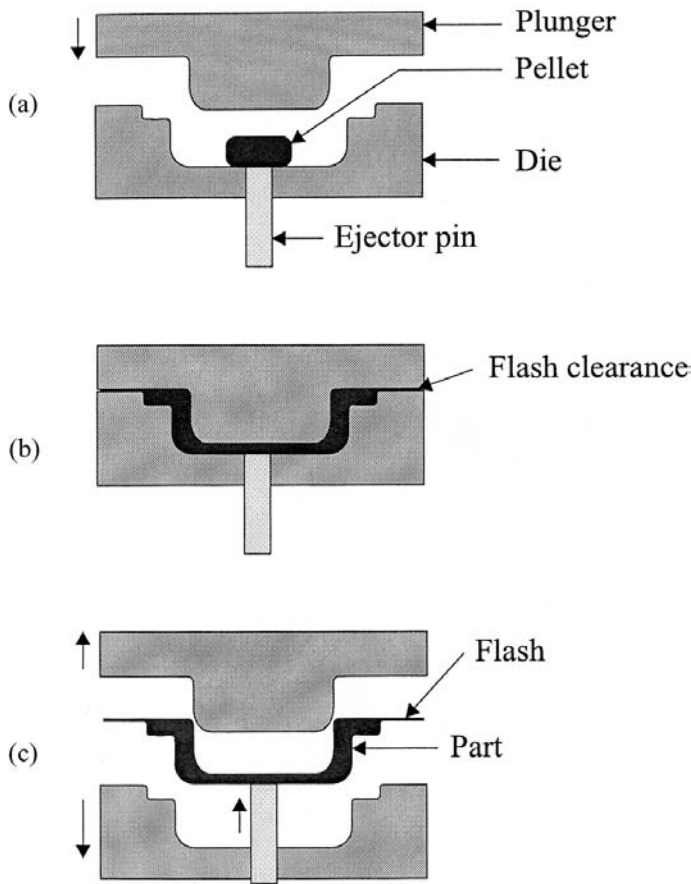


FIGURE 15 Compression molding. (a) Pallet loaded; mold closed. (b) Curing stage. (c) Mold opened; part ejected.

reference to the transfer of the molten resin, held in a middle plate of a three-plated mold, into the cavities, in the fixed plate of the mold, under pressure, through a gating system (Fig. 16). The process can be further automated by the utilization of an extruder screw that would provide the transfer molding press with controlled amounts of molten (plasticized) resin on demand.

In comparison to compression molding, transfer molding has the following advantages: good control of part thicknesses (owing to a totally-closed mold), production of intricate geometrical details, and better mechanical

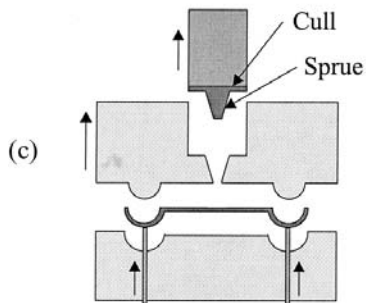
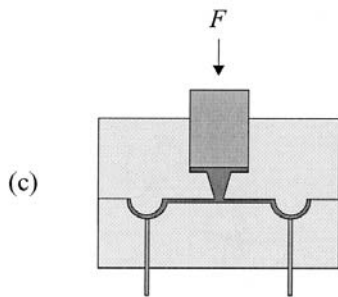
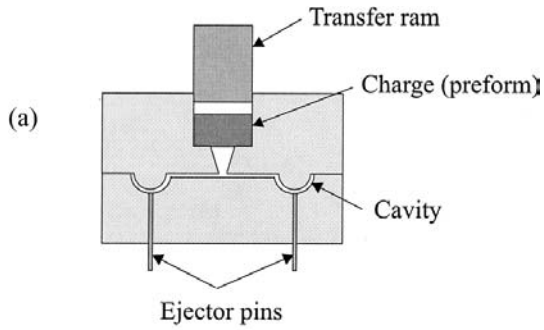


FIGURE 16 Transfer molding. (a) Charge loaded; (b) softened polymer pressed into cavity and cured; (c) part ejected.

properties (owing to less damage to fibers and furthermore their preferential alignment). However, material wastage in the gating system is greater here.

6.3.5 Design for Plastics Processing

The first step in designing a plastic product is the selection of an appropriate polymer (and reinforcing material, when needed). Factors in choosing a material for a specific application include mechanical properties, thermal and chemical properties (for example, resistance to ultraviolet sunlight), hazards (e.g., toxicity, flammability), appearance (e.g., transparency), and economics (including manufacturing costs). For the automotive parts industry, for example, engine parts must be resistant to automotive fluids and high temperatures. Similarly, body panels must be resistant to high paint-oven temperatures or, when not painted, they must have extra resistance to water absorption and UV light. Ski bindings, on the other hand, must be resilient to low temperatures and be very rigid.

From a manufacturing perspective, since most parts are fabricated in molds, part design strongly impacts on mold design and thus manufacturability. As discussed in [Chaps. 3 and 5](#), the filling of the mold as well as the cooling of the part within the mold can be simulated using computer-aided engineering (CAE) analysis tools for better part design. Such analyses will remind designers to refrain from using sharp corners and/or sudden wall thickness changes that would disrupt the uniform flow of the resin in the cavities. Changes in wall thicknesses also result in additional shrinkage problems, such as stress concentrations, warpage, and even sink marks ([Fig. 17](#)). Sink marks predominantly occur opposite to ribs, flanges, and bosses, which are used for increasing stiffness and strength without adding weight to the part. Thus a rule of thumb is to have their thickness be 50 to 75% of the wall thickness they are reinforcing.

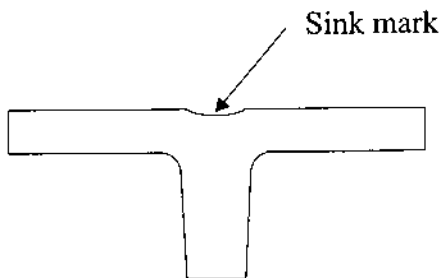


FIGURE 17 Sink mark.

Shrinkage problems are of major concern in the design of thermoset plastics. Mold design should accommodate for significant shrinkages in the curing of such materials. The problem is further complicated for composite parts, where fiber wetting as well as uniform fiber volume distribution are major concerns. A list of design guidelines for thermoset plastics and composites, which is also applicable to thermoplastic parts, is given here:

Wall thicknesses must be kept as uniform as possible with gradual changes between sections through the use of fillets, tapers, etc.

Tapers should be used for ease of removal from the mold.

Side holes and/or undercuts should be avoided for low-cost molds.

Holes must not be placed too near to edges/faces to avoid fracture.

Fine screw threads should be avoided in composite part design, since even short fibers (less than 3 mm in length) would not be present at the threads.

Raised letters can be manufactured more easily (through engravings in the mold cavity).

REVIEW QUESTIONS

1. What is net shape (or near-net shape) fabrication? Identify several household products that are, or could have been, manufactured using a net shape process.
2. Why do casting/powder processing/plastics molding processes yield parts with mechanical properties better than those obtained with layered manufacturing (or lamination-type) processes?
3. What important property makes certain materials favorable for casting and not others?
4. Why is sand casting normally viewed as a process that lends itself easily to automation and mass production? Would you recommend sand casting for small-batch-size or one-of-a-kind production environments? Discuss both sides of the argument.
5. Why should one try to include the gating system into the pattern in sand casting? Furthermore, discuss the advantages/disadvantages of using halved patterns versus single-piece ones.
6. Discuss the investment casting process. Would you recommend investment casting for small-batch-size or one-of-a-kind production environments? Discuss both sides of the argument.
7. Define the two primary die casting processes and compare their uses.
8. Shrinkage is normally seen as a primary design concern in metal casting. How could one deal with this problem analytically?

9. What are the three basic steps of powder processing?
10. Why would one need to use powder processing instead of casting? If both processes were to be applicable, which one would you recommend?
11. What is a cermet?
12. Discuss the cold versus hot compacting of powder.
13. What is sintering? Why would one use a liquid-phase sintering process?
14. Thermoplastic polymers constitute 85% of plastics in use. They can be recycled many times by simply repeating the heating and cooling cycle. Thermoset polymers, on the other hand, constitute the remaining 15% of plastics in use today and cannot be recycled. Despite these facts, why do industries continue to manufacture thermoset-based products, including composites?
15. Describe the blow molding process.
16. Describe the injection molding process. What is powder injection molding (PIM)?
17. Discuss the fluid flow and cooling issues in plastics molding. You may refer to [Chap. 5](#) for further information.

DISCUSSION QUESTIONS

1. Casting has commonly been used as a mass production technique. For example, in sand casting, highly accurate patterns and (when needed) mass produced cores are utilized for the production of thousands of identical parts. Review several of the common casting processes and discuss ways of using them profitably in high-variety production, for example by utilizing rapid prototyping techniques in the manufacture of patterns and cores.
2. Material removal techniques, as the name implies, are based on removing material from a given blank for the fabrication of the final geometry of a part. Compare material removal techniques to near-net shape production techniques, such as casting, powder processing, and forming, in the context of product geometry, material properties, and economics in mass production versus small-batch production environments.
3. Composite materials have been increasingly developed and used widely owing to their improved mechanical/electrical/chemical properties when compared to their base (matrix) material. For example, the use of glass, carbon, and Kevlar fibers in polymer base composites has significantly increased their employment in the automotive and sports products industries. Composite materials, however, may be in direct conflict with environmental and other concerns, which advocate that products should

be designed so that material mix is minimized or totally avoided for ease of manufacturing and/or recycling (including decomposition) purposes. Discuss the above issues in favor of continuing to use composite materials, otherwise propose alternatives.

4. In the mid part of the 20th century, design, planning, and control of manufacturing processes were argued to be activities that had more to do with the application of experience/knowledge gathered by experts in contrast to the use of any mathematical models or systematic analysis techniques. As a contrary argument, discuss the basic physical phenomena (e.g., non-Newtonian fluid mechanics and heat transfer) that govern common manufacturing processes (e.g., casting of metals and molding of plastics) and their use in the design, planning, and control of these processes. Furthermore discuss the role of computer-aided engineering (CAE) in these analyses.
5. Discuss potential postprocess defect identification schemata/technologies for parts that are manufactured using a casting or powder processing method. Furthermore, discuss possible sensing technologies that can be incorporated into different casting or powder-processing equipment for the on-line monitoring and control of the manufacturing process, while the parts are being formed.
6. Single-minute exchange of dies (SMED) is a manufacturing strategy developed for allowing mixed production (e.g., multimodel cars) within the same facility in small batches. The primary objective has always been to minimize the time spent on setting up a process while the machine is idle. This objective has been achieved (1) by converting as many on-line operations as possible to off-line ones (i.e., those that can be carried out while the machine is working on a different batch), and (2) by minimizing the time spent on on-line setup operations. Discuss the effectiveness of using SMED or equivalent strategies in the mass manufacturing of multimodel products, the mass manufacturing of customized products, and the manufacturing of small batch-size or one-of-a-kind products.

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