# 11 Metal Casting Processes

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Metal casting processes divide into two categories, based on mold type: (1) expendable mold and (2) permanent mold. In expendable mold casting operations, the mold is sacrificed in order to remove the cast part. Since a new mold is required for each new casting, production rates in expendable-mold processes are often limited by the time required to make the mold rather than the time to make the casting itself. However, for certain part geometries, sand molds can be produced and castings made at rates of 400 parts per hour and higher. In permanent mold casting processes, the mold is fabricated out of metal (or other durable material) and can be used many times to make many castings. Accordingly, these processes possess a natural advantage in terms of higher production rates.

The discussion of casting processes in this chapter is organized as follows: (1) sand casting, (2) other expendable mold casting processes, and (3) permanent mold casting processes. The chapter also includes casting equipment and practices used in foundries. Another section deals with inspection and quality issues. Product design guidelines are presented in the final section.

## 11.1 Sand Casting

Sand casting is the most widely used casting process, accounting for a significant majority of the total tonnage cast. Nearly all casting alloys can be sand cast; indeed, it is one of the few processes that can be used for metals with high melting temperatures, such as steels, nickels, and titaniums. Its versatility permits the casting of parts ranging in size from small to very large and in production quantities from one to millions. Figure 11.1 shows a cast iron sand casting of a pump housing that has been partially machined to create accurate holes and surfaces.

***Sand casting***, also known as ***sand-mold casting***, consists of pouring molten metal into a sand mold, allowing the metal to solidify, and then breaking up the mold to remove the casting. The casting must then be cleaned and inspected, and heat treatment is sometimes required

**FIGURE 11.1** A sand casting for an industrial pump. Holes and surfaces have been machined. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

to improve metallurgical properties. The cavity in the sand mold is formed by packing sand around a pattern (an approximate duplicate of the part to be cast), and then removing the pattern by separating the mold into two halves. The mold also contains the gating and riser system. In addition, if the casting is to have internal surfaces (e.g., hollow parts or parts with holes), a core must be included in the mold. Since the mold is sacrificed to remove the casting, a new sand mold must be made for each part that is produced. From this brief description, sand casting is seen to include not only the casting operation itself, but also the fabrication of the pattern and the making of the mold. The production sequence is outlined in Figure 11.2.

### 11.1.1 PATTERNS AND CORES

Sand casting requires a ***pattern***—a full-sized model of the part, enlarged to account for shrinkage and machining allowances in the final casting. Materials used to make patterns include wood, plastics, and metals. Wood is a common pattern material because it is easily shaped. Its disadvantages are that it tends to warp, and it is abraded by the sand being compacted around it, thus limiting the number of times it can be reused. Metal patterns are more expensive to make, but they last much longer. Plastics represent a compromise between wood and metal. Selection of the appropriate pattern material depends to a large extent on the total quantity of castings to be made.

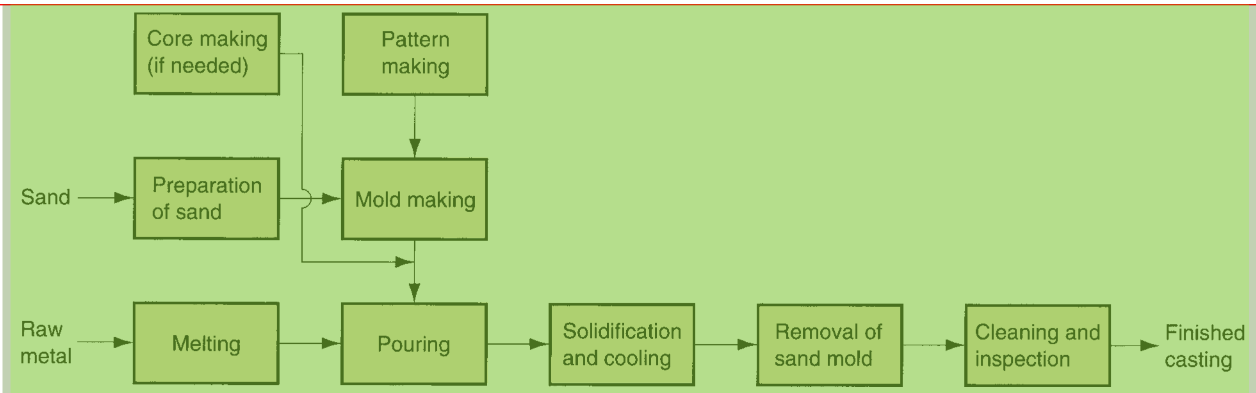


**FIGURE 11.2** Steps in the production sequence in sand casting. The steps include not only the casting operation but also pattern making and mold making.

There are various types of patterns, as illustrated in Figure 11.3. The simplest is made of one piece, called a ***solid pattern***—same geometry as the casting, adjusted in size for shrinkage and machining. Although it is the easiest pattern to fabricate, it is not the easiest to use in making the sand mold. Determining the location of the parting line between the two halves of the mold for a solid pattern can be a problem, and incorporating the gating system and sprue into the mold is left to the judgment and skill of the foundry worker. Consequently, solid patterns are generally limited to very low production quantities.

***Split patterns*** consist of two pieces, dividing the part along a plane coinciding with the parting line of the mold. Split patterns are appropriate for complex part geometries and moderate production quantities. The parting line of the mold is predetermined by the two pattern halves, rather than by operator judgment.

For higher production quantities, match-plate patterns or cope-and-drag patterns are used. In ***match-plate*** patterns, the two pieces of the split pattern are attached to opposite sides of a wood or metal plate. Holes in the plate allow the top and bottom (cope and drag) sections of the mold to be aligned accurately. ***Cope-and-drag patterns*** are similar to match-plate patterns except that split pattern halves are

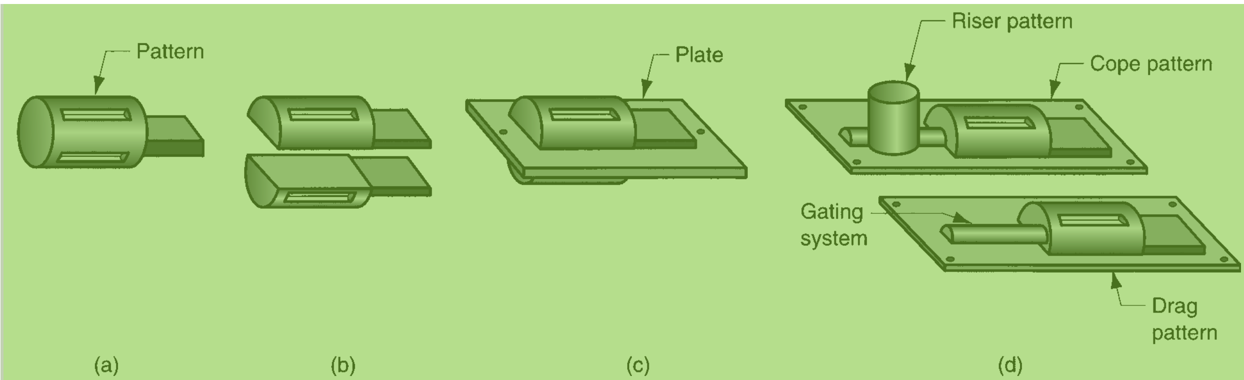


**FIGURE 11.3** Types of patterns used in sand casting: (a) solid pattern, (b) split pattern, (c) match-plate pattern, and (d) cope and drag pattern.

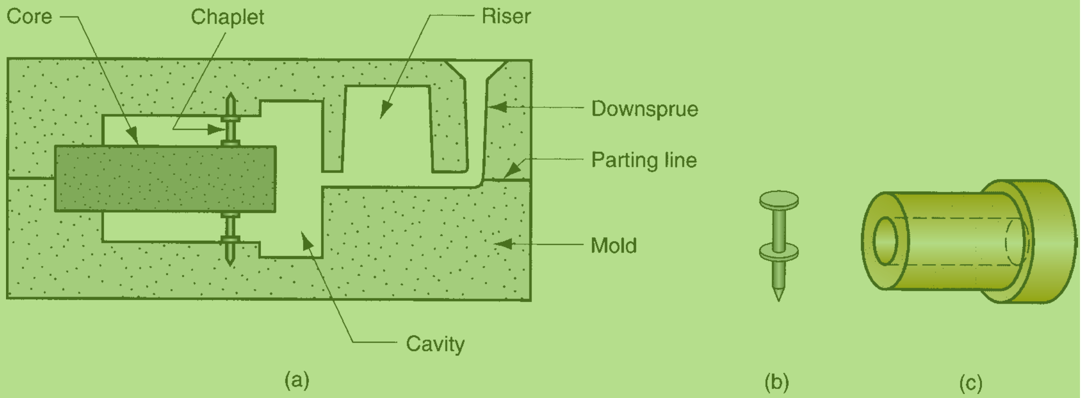


**FIGURE 11.4** (a) Core held in place in the mold cavity by chaplets, (b) possible chaplet design, and (c) casting with internal cavity.

attached to separate plates, so that the cope and drag sections of the mold can be fabricated independently, instead of using the same tooling for both. Part (d) of the figure includes the gating and riser system in the cope-and-drag patterns.

Patterns define the external shape of the cast part. If the casting is to have internal surfaces, a core is required. A ***core*** is a full-scale model of the interior surfaces of the part. It is inserted into the mold cavity prior to pouring, so that the molten metal will flow and solidify between the mold cavity and the core to form the casting's external and internal surfaces. The core is usually made of sand, compacted into the desired shape. As with the pattern, the actual size of the core must include allowances for shrinkage and machining. Depending on the geometry of the part, the core may or may not require supports to hold it in position in the mold cavity during pouring. These supports, called ***chaplets***, are made of a metal with a higher melting temperature than the casting metal. For example, steel chaplets would be used for cast iron castings. On pouring and solidification, the chaplets become bonded into the casting. A possible arrangement of a core in a mold using chaplets is sketched in Figure 11.4. The portion of the chaplet protruding from the casting is subsequently cut off.

## 11.1.2 MOLDS AND MOLD MAKING

Foundry sands are silica ($SiO_2$) or silica mixed with other minerals. The sand should possess good refractory properties—capacity to stand up under high temperatures without melting or otherwise degrading. Other important features of the sand include grain size, distribution of grain size in the mixture, and shape of the individual grains (Section 15.1). Small grain size provides a better surface finish on the cast part, but large grain size is more permeable (to allow escape of gases during pouring). Molds made from grains of irregular shape tend to be stronger than molds of round grains because of interlocking, yet interlocking tends to restrict permeability.

In making the mold, the grains of sand are held together by a mixture of water and bonding clay. A typical mixture (by volume) is 90% sand, 3% water, and 7% clay. Other bonding agents can be used in place of clay, including organic resins (e.g., phenolic resins) and inorganic binders (e.g., sodium silicate and phosphate).

Besides sand and binder, additives are sometimes combined with the mixture to enhance properties such as strength and/or permeability of the mold.

To form the mold cavity, the traditional method is to compact the molding sand around the pattern for both cope and drag in a container called a ***flask***. The packing process is performed by various methods. The simplest is hand ramming, accomplished manually by a foundry worker. In addition, various machines have been developed to mechanize the packing procedure. These machines operate by any of several mechanisms, including (1) squeezing the sand around the pattern by pneumatic pressure; (2) a jolting action in which the sand, contained in the flask with the pattern, is dropped repeatedly in order to pack it into place; and (3) a slinging action, in which the sand grains are impacted against the pattern at high speed.

An alternative to traditional flasks for each sand mold is ***flaskless molding***, which refers to the use of one master flask in a mechanized system of mold production. Each sand mold is produced using the same master flask. Mold production rates up to 600 per hour are claimed for this more automated method [8].

Several indicators are used to determine the quality of the sand mold [7]: (1) ***strength***—the mold's ability to maintain its shape and resist erosion caused by the flow of molten metal; it depends on grain shape, adhesive qualities of the binder, and other factors; (2) ***permeability***—capacity of the mold to allow hot air and gases from the casting operation to pass through the voids in the sand; (3) ***thermal stability***—ability of the sand at the surface of the mold cavity to resist cracking and buckling upon contact with the molten metal; (4) ***collapsibility***—ability of the mold to give way and allow the casting to shrink without cracking the casting; it also refers to the ability to remove the sand from the casting during cleaning; and (5) ***reusability***—can the sand from the broken mold be reused to make other molds? These measures are sometimes incompatible; for example, a mold with greater strength is less collapsible.

Sand molds are often classified as green-sand, dry-sand, or skin-dried molds. ***Green-sand molds*** are made of a mixture of sand, clay, and water, the word ***green*** referring to the fact that the mold contains moisture at the time of pouring. Green-sand molds possess sufficient strength for most applications, good collapsibility, good permeability, good reusability, and are the least expensive of the molds. They are the most widely used mold type, but they are not without problems. Moisture in the sand can cause defects in some castings, depending on the metal and geometry of the part. A ***dry-sand mold*** is made using organic binders rather than clay, and the mold is baked in a large oven at temperatures ranging from 200°C to 320°C (400°F–600°F) [8]. Oven baking strengthens the mold and hardens the cavity surface. A dry-sand mold provides better dimensional control in the cast product, compared to green-sand molding. However, dry-sand molding is more expensive, and production rate is reduced because of drying time. Applications are generally limited to medium and large castings in low to medium production rates. In a ***skin-dried mold***, the advantages of a dry-sand mold is partially achieved by drying the surface of a green-sand mold to a depth of 10 to 25 mm (0.4–1 in) at the mold cavity surface, using torches, heating lamps, or other means. Special bonding materials must be added to the sand mixture to strengthen the cavity surface.

The preceding mold classifications refer to the use of conventional binders consisting of either clay-and-water or ones that require heating to cure. In addition to these classifications, chemically bonded molds have been developed that are not based on either of these traditional binder ingredients. Some of the binder materials

TABLE • 11.1 Densities of selected casting alloys.

| Metal | Density g/cm³ | Density lb/in³ | Metal | Density g/cm³ | Density lb/in³ |
|---|---|---|---|---|---|
| Aluminum (99% = pure) | 2.70 | 0.098 | Cast iron, gray[a] | 7.16 | 0.260 |
| Aluminum-silicon alloy | 2.65 | 0.096 | Copper (99% = pure) | 8.73 | 0.317 |
| Aluminum-copper (92% Al) | 2.81 | 0.102 | Lead (pure) | 11.30 | 0.410 |
| Brass[a] | 8.62 | 0.313 | Steel | 7.82 | 0.284 |

Source: [7].
[a]Density depends on composition of alloy; value given is typical.

used in these "no-bake" systems include furan resins (consisting of furfural alcohol, urea, and formaldehyde), phenolics, and alkyd oils. No-bake molds are growing in popularity due to their good dimensional control in high production applications.

### 11.1.3 THE CASTING OPERATION

After the core is positioned (if one is used) and the two halves of the mold are clamped together, then casting is performed. Casting consists of pouring, solidification, and cooling of the cast part (Sections 10.2 and 10.3). The gating and riser system in the mold must be designed to deliver liquid metal into the cavity and provide for a sufficient reservoir of molten metal during solidification shrinkage. Air and gases must be allowed to escape.

One of the hazards during pouring is that the buoyancy of the molten metal will displace the core. Buoyancy results from the weight of molten metal being displaced by the core, according to Archimedes' principle. The force tending to lift the core is equal to the weight of the displaced liquid less the weight of the core itself. Expressing the situation in equation form,

$$F_b = W_m - W_c \tag{11.1}$$

where $F_b$ = buoyancy force, N (lb); $W_m$ = weight of molten metal displaced, N (lb); and % $W_c$ = weight of the core, N (lb). Weights are determined as the volume of the core multiplied by the respective densities of the core material (typically sand) and the metal being cast. The density of a sand core is approximately 1.6 g/cm³ (0.058 lb/in³). Densities of several common casting alloys are given in Table 11.1.

**Example 11.1 Buoyancy in sand casting**

A sand core has a volume = 1875 cm³ and is located inside a sand mold cavity. Determine the buoyancy force tending to lift the core during pouring of molten lead into the mold.

**Solution:** Density of the sand core is 1.6 g/cm³. Weight of the core is 1875(1.6) = 3000 g = 3.0 kg. Density of lead, based on Table 11.1, is 11.3 g/cm³. The weight of lead displaced by the core is 1875(11.3) = 21,188 g = 21.19 kg. The difference = 21.19 − 3.0 = 18.19 kg. Given that 1 kg = 9.81 N, the buoyancy force is therefore $F_b$ = 9.81(18.19) = **178.4 N**.

Following solidification and cooling, the sand mold is broken away from the casting to retrieve the part. The part is then cleaned—gating and riser system are separated, and sand is removed. The casting is then inspected (Section 11.5).

# 11.2 Other Expendable-Mold Casting Processes

As versatile as sand casting is, there are other casting processes that have been developed to meet special needs. The differences between these methods are in the composition of the mold material, or the manner in which the mold is made, or in the way the pattern is made.

## 11.2.1 SHELL MOLDING

Shell molding is a casting process in which the mold is a thin shell (typically 9 mm or 3/8 in) made of sand held together by a thermosetting resin binder. Developed in Germany during the early 1940s, the process is described and illustrated in Figure 11.5.

There are many advantages to the shell-molding process. The surface of the shell-mold cavity is smoother than a conventional green-sand mold, and this smoothness permits easier flow of molten metal during pouring and better surface finish on the final casting. Finishes of 2.5 $\mu$m (100 $\mu$-in) can be obtained. Good

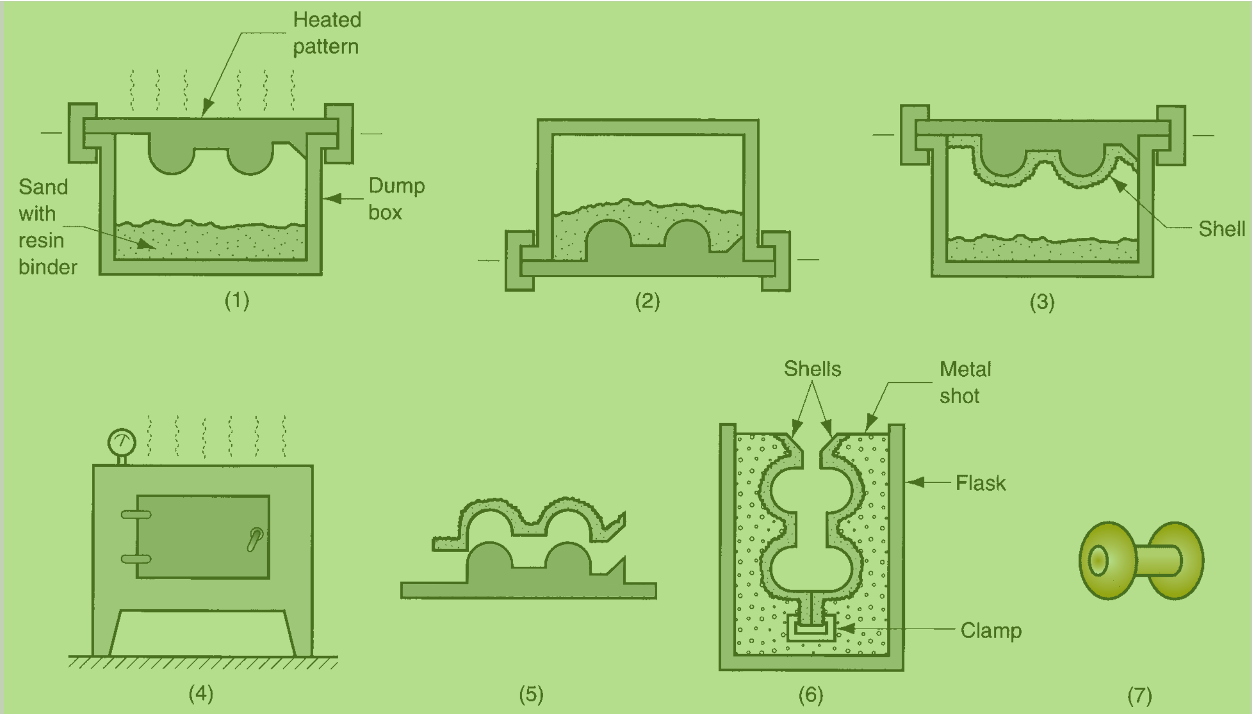


**FIGURE 11.5** Steps in shell-molding: (1) a match-plate or cope-and-drag metal pattern is heated and placed over a box containing sand mixed with thermosetting resin; (2) box is inverted so that sand and resin fall onto the hot pattern, causing a layer of the mixture to partially cure on the surface to form a hard shell; (3) box is repositioned so that loose, uncured particles drop away; (4) sand shell is heated in oven for several minutes to complete curing; (5) shell mold is stripped from the pattern; (6) two halves of the shell mold are assembled, supported by sand or metal shot in a box, and pouring is accomplished. The finished casting with sprue removed is shown in (7).

dimensional accuracy is also achieved, with tolerances of ±0.25 mm (±0.010 in) possible on small-to-medium-sized parts. The good finish and accuracy often precludes the need for further machining. Collapsibility of the mold is generally sufficient to avoid tearing and cracking of the casting.

Disadvantages of shell molding include a more expensive metal pattern than the corresponding pattern for green-sand molding. This makes shell molding difficult to justify for small quantities of parts. Shell molding can be mechanized for mass production and is very economical for large quantities. It seems particularly suited to steel castings of less than 20 lb. Examples of parts made using shell molding include gears, valve bodies, bushings, and camshafts.

### 11.2.2 VACUUM MOLDING

Vacuum molding, also called the ***V-process***, was developed in Japan around 1970. It uses a sand mold held together by vacuum pressure rather than by a chemical binder. Accordingly, the term ***vacuum*** in this process refers to the making of the mold rather than the casting operation itself. The steps of the process are explained in Figure 11.6.

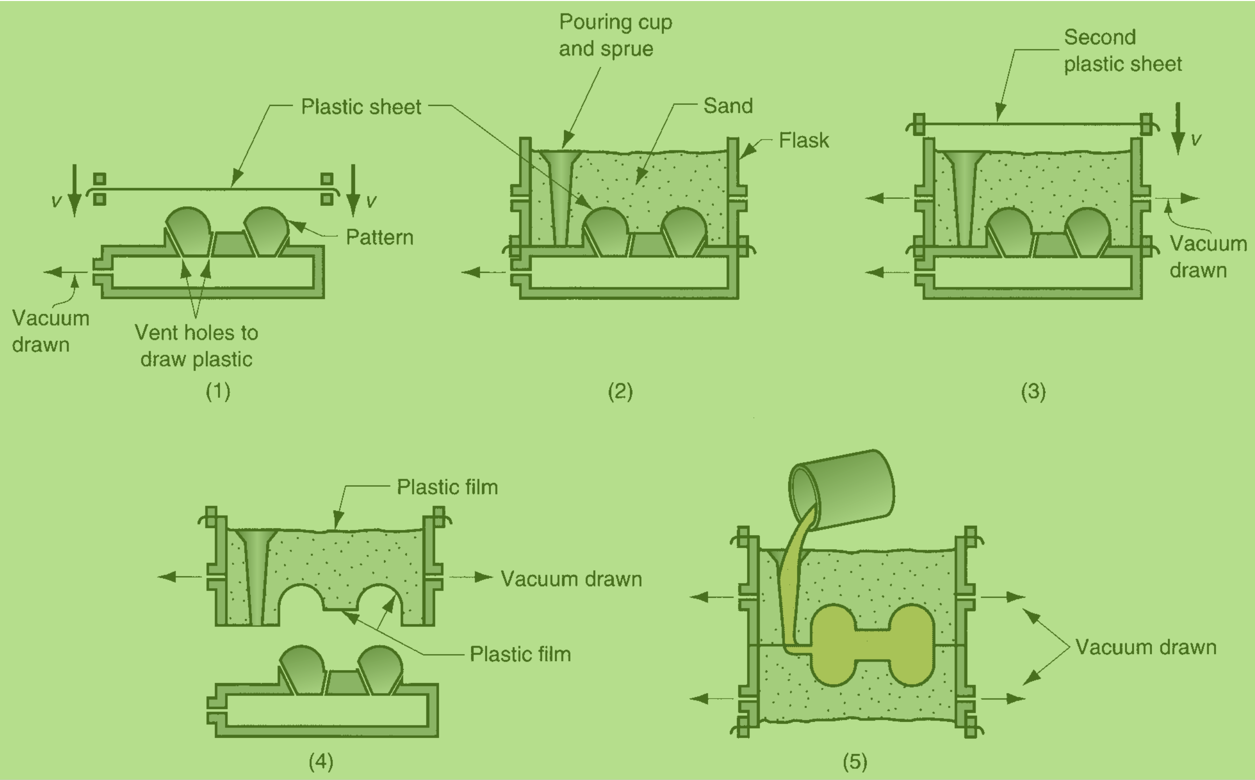


**FIGURE 11.6** Steps in vacuum molding: (1) a thin sheet of preheated plastic is drawn over a match-plate or cope-and-drag pattern by vacuum—the pattern has small vent holes to facilitate vacuum forming; (2) a specially designed flask is placed over the pattern plate and filled with sand, and a sprue and pouring cup are formed in the sand; (3) another thin plastic sheet is placed over the flask, and a vacuum is drawn that causes the sand grains to be held together, forming a rigid mold; (4) the vacuum on the mold pattern is released to permit the pattern to be stripped from the mold; (5) this mold is assembled with its matching half to form the cope and drag, and with vacuum maintained on both halves, pouring is accomplished. The plastic sheet quickly burns away on contacting the molten metal. After solidification, nearly all of the sand can be recovered for reuse.

Because no binders are used, the sand is readily recovered in vacuum molding. Also, the sand does not require extensive mechanical reconditioning normally done when binders are used in the molding sand. Since no water is mixed with the sand, moisture-related defects are absent from the product. Disadvantages of the V-process are that it is relatively slow and not readily adaptable to mechanization.

### 11.2.3 EXPANDED POLYSTYRENE PROCESS

The expanded polystyrene casting process uses a mold of sand packed around a polystyrene foam pattern that vaporizes when the molten metal is poured into the mold. The process and variations of it are known by other names, including ***lost-foam process***, ***lost-pattern process***, ***evaporative-foam process***, and ***full-mold process*** (the last being a trade name). The foam pattern includes the sprue, risers, and gating system, and it may also contain internal cores (if needed), thus eliminating the need for a separate core in the mold. Also, since the foam pattern itself becomes the cavity in the mold, considerations of draft and parting lines can be ignored. The mold does not have to be opened into cope and drag sections. The sequence in this casting process is illustrated and described in Figure 11.7. Various methods for making the pattern can be used, depending on the quantities of castings to be produced. For one-of-a-kind castings, the foam is manually cut from large strips and assembled to form the pattern. For large production runs, an automated molding operation can be set up to mold the patterns prior to making the molds for casting. The pattern is normally coated with a refractory compound to provide a smoother surface on the pattern and to improve its high temperature resistance. Molding sands usually include bonding agents. However, dry sand is used in certain processes in this group, which aids recovery and reuse.

A significant advantage for this process is that the pattern need not be removed from the mold. This simplifies and expedites mold making. In a conventional green-sand mold, two halves are required with proper parting lines, draft allowances must be provided in the mold design, cores must be inserted, and the gating and riser system must be added. With the expanded polystyrene process, these steps

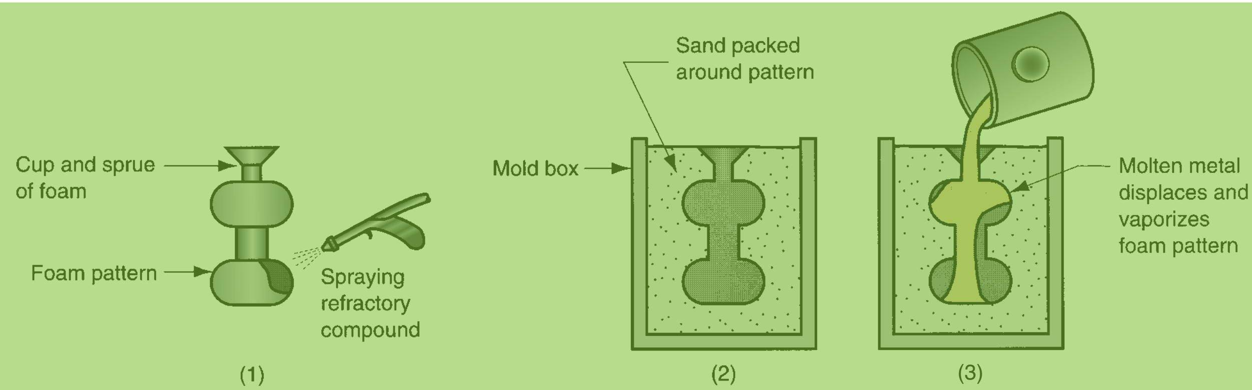


**FIGURE 11.7** Expanded polystyrene casting process: (1) pattern of polystyrene is coated with refractory compound; (2) foam pattern is placed in mold box, and sand is compacted around the pattern; and (3) molten metal is poured into the portion of the pattern that forms the pouring cup and sprue. As the metal enters the mold, the polystyrene foam is vaporized ahead of the advancing liquid, thus allowing the resulting mold cavity to be filled.

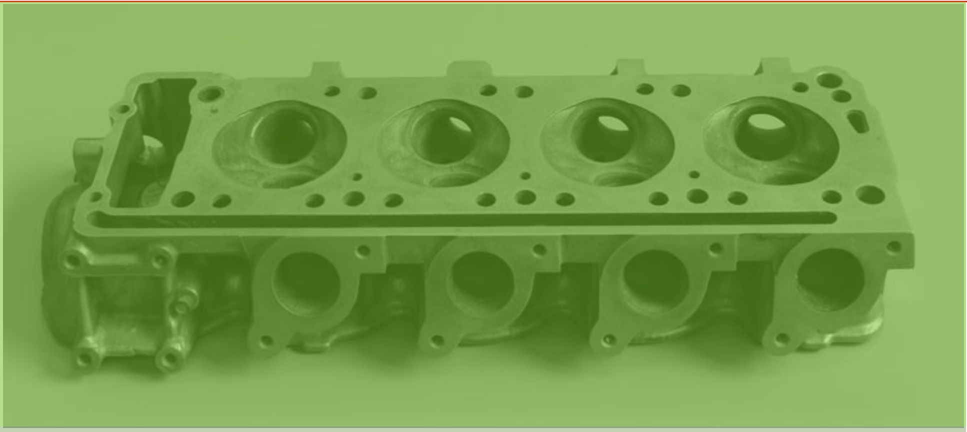

**FIGURE 11.8** An aluminum engine head produced by the expanded polystyrene casting process. The holes and certain surfaces have been machined. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

are built into the pattern itself. A new pattern is needed for every casting, so the economics of the expanded polystyrene casting process depend largely on the cost of producing the patterns. The process has been applied to mass produce castings for automobiles engines. Automated production systems are installed to mold the polystyrene foam patterns for these applications. Figure 11.8 shows an aluminum engine head that was cast by the expanded polystyrene process (the holes and some surfaces have been machined).

## 11.2.4 INVESTMENT CASTING

In investment casting, a pattern made of wax is coated with a refractory material to make the mold, after which the wax is melted away prior to pouring the molten metal. The term ***investment*** comes from one of the less familiar definitions of the word ***invest***, which is "to cover completely," this referring to the coating of the refractory material around the wax pattern. It is a precision casting process, because it is capable of making castings of high accuracy and intricate detail. The process dates back to ancient Egypt (Historical Note 11.1) and is also known as the ***lost-wax process***, because the wax pattern is lost from the mold prior to casting.

### Historical Note 11.1 *Investment casting*

The lost wax casting process was developed by the ancient Egyptians some 3,500 years ago. Although written records do not identify when the invention occurred or the artisan responsible, historians speculate that the process resulted from the close association between pottery and molding in early times. It was the potter who crafted the molds that were used for casting. The idea for the lost wax process must have originated with a potter who was familiar with the casting process. As he was working one day on a ceramic piece—perhaps an ornate vase or bowl—it occurred to him that the article might be more attractive and durable if made of metal. So he fashioned a core in the general shape of the piece, but smaller than the desired final dimensions, and coated it with wax to establish the size. The wax proved to be an easy material to form, and intricate designs and shapes could be created by the craftsman. On the wax surface, he carefully plastered several layers of clay and devised a means of holding the resulting components together. He then baked the mold in a kiln, so that the clay hardened and the wax melted and drained out to form a cavity. At last, he poured molten bronze into the cavity and, after the casting had solidified and cooled, broke away the mold to recover the part. Considering the education and experience of this early pottery maker and the tools he had to work with, development of the lost wax casting process demonstrated great innovation and insight. "No other process can be named by archeologists so crowded with deduction, engineering ability and ingenuity" [14].

Steps in investment casting are described in Figure 11.9. Since the wax pattern is melted off after the refractory mold is made, a separate pattern must be made for every casting. Pattern production is usually accomplished by a molding operation—pouring or injecting the hot wax into a ***master die*** that has been designed with proper allowances for shrinkage of both wax and subsequent metal casting. In cases where the part geometry is complicated, several separate wax pieces must be joined to make the pattern. In high-production operations, several patterns are attached to a sprue, also made of wax, to form a ***pattern tree***; this is the geometry that will be cast out of metal.

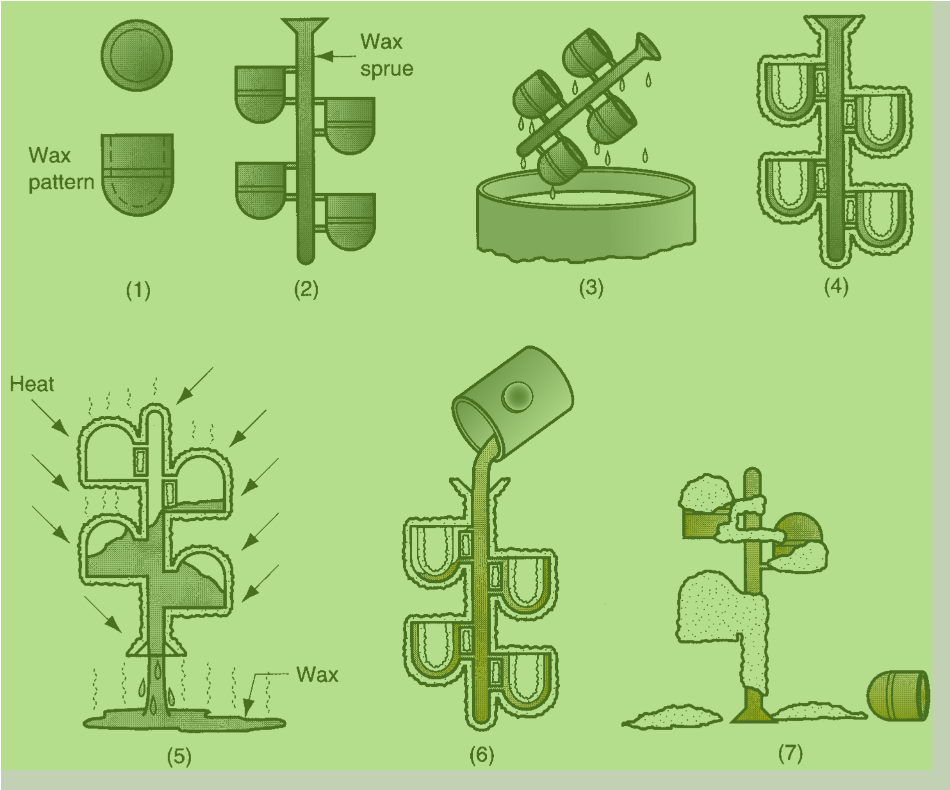


**FIGURE 11.9** Steps in investment casting: (1) wax patterns are produced; (2) several patterns are attached to a sprue to form a pattern tree; (3) the pattern tree is coated with a thin layer of refractory material; (4) the full mold is formed by covering the coated tree with sufficient refractory material to make it rigid; (5) the mold is held in an inverted position and heated to melt the wax and permit it to drip out of the cavity; (6) the mold is preheated to a high temperature, which ensures that all contaminants are eliminated from the mold; it also permits the liquid metal to flow more easily into the detailed cavity; the molten metal is poured; it solidifies; and (7) the mold is broken away from the finished casting. Parts are separated from the sprue.

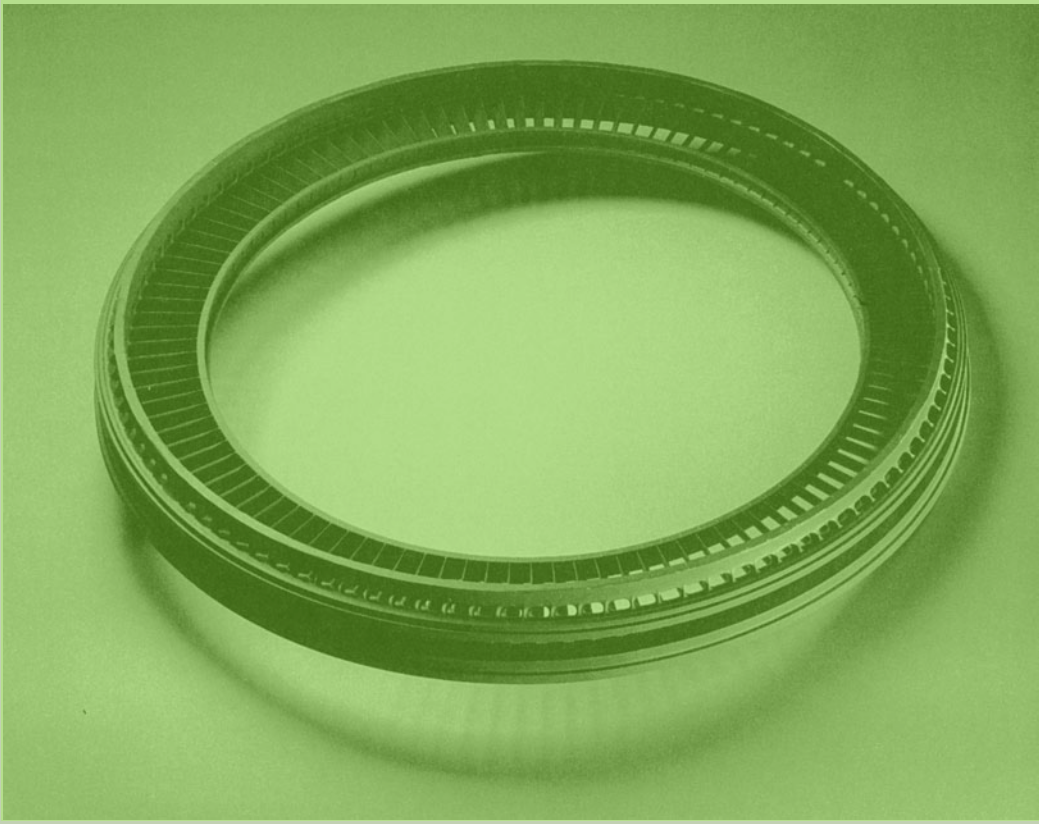

**FIGURE 11.10** A one-piece compressor stator with 108 separate airfoils made by investment casting. (Courtesy of Alcoa Howmet.)

Coating with refractory (step 3) is usually accomplished by dipping the pattern tree into a slurry of very fine grained silica or other refractory (almost in powder form) mixed with plaster to bond the mold into shape. The small grain size of the refractory material provides a smooth surface and captures the intricate details of the wax pattern. The final mold (step 4) is accomplished by repeatedly dipping the tree into the refractory slurry or by gently packing the refractory around the tree in a container. The mold is allowed to air dry for about 8 hours to harden the binder.

Advantages of investment casting include: (1) parts of great complexity and intricacy can be cast; (2) close dimensional control—tolerances of ±0.075 mm (±0.003 in) are possible; (3) good surface finish is possible; (4) the wax can usually be recovered for reuse; and (5) additional machining is not normally required—this is a net shape process. Because many steps are involved in this casting operation, it is a relatively expensive process. Investment castings are normally small in size, although parts with complex geometries weighing up to 75 lb have been successfully cast. All types of metals, including steels, stainless steels, and other high temperature alloys, can be investment cast. Examples of parts include complex machinery parts, blades, and other components for turbine engines, jewelry, and dental fixtures. Shown in Figure 11.10 is a part illustrating the intricate features possible with investment casting.

### 11.2.5 PLASTER-MOLD AND CERAMIC-MOLD CASTING

Plaster-mold casting is similar to sand casting except that the mold is made of plaster of Paris (gypsum—$CaSO_4$—$2H_2O$) instead of sand. Additives such as talc and silica flour are mixed with the plaster to control contraction and setting time, reduce cracking, and increase strength. To make the mold, the plaster mixture combined with water is poured over a plastic or metal pattern in a flask and allowed to set. Wood patterns are generally unsatisfactory due to the extended contact with water in the plaster. The fluid consistency permits the plaster mixture to readily flow around the pattern, capturing its details and surface finish. Thus, the cast product in plaster molding is noted for these attributes.

Curing of the plaster mold is one of the disadvantages of this process, at least in high production. The mold must set for about 20 minutes before the pattern is stripped. The mold is then baked for several hours to remove moisture. Even with the baking, not all of the moisture content is removed from the plaster. The dilemma faced by foundrymen is that mold strength is lost when the plaster becomes too dehydrated, and yet moisture content can cause casting defects in the product. A balance must be achieved between these undesirable alternatives. Another disadvantage with the plaster mold is that it is not permeable, thus limiting escape of gases from the mold cavity. This problem can be solved in a number of ways: (1) evacuating air from the mold cavity before pouring; (2) aerating the plaster slurry prior to mold making so that the resulting hard plaster contains finely dispersed voids; and (3) using a special mold composition and treatment known as the ***Antioch process***. This process involves using about 50% sand mixed with the plaster, heating the mold in an autoclave (an oven that uses superheated steam under pressure), and then drying. The resulting mold has considerably greater permeability than a conventional plaster mold.

Plaster molds cannot withstand the same high temperatures as sand molds. They are therefore limited to the casting of lower-melting-point alloys, such as aluminum, magnesium, and some copper-base alloys. Applications include metal molds for plastic and rubber molding, pump and turbine impellers, and other parts of relatively intricate geometry. Casting sizes range from about 20 g (less than 1 oz) to more than 100 kg (more than 200 lb). Parts weighing less than about 10 kg (20 lb) are most common. Advantages of plaster molding for these applications are good surface finish and dimensional accuracy and the capability to make thin cross sections in the casting.

***Ceramic-mold casting*** is similar to plaster-mold casting, except that the mold is made of refractory ceramic materials that can withstand higher temperatures than plaster. Thus, ceramic molding can be used to cast steels, cast irons, and other high-temperature alloys. Its applications (relatively intricate parts) are similar to those of plaster mold casting except for the metals cast. Its advantages (good accuracy and finish) are also similar.

## 3 Permanent-Mold Casting Processes

The economic disadvantage of any of the expendable mold processes is that a new mold is required for every casting. In permanent-mold casting, the mold is reused many times. In this section, permanent-mold casting is treated as the basic process in the group of casting processes that all use reusable metal molds. Other members of the group include die casting and centrifugal casting.

### 11.3.1 THE BASIC PERMANENT-MOLD PROCESS

Permanent-mold casting uses a metal mold constructed of two sections that are designed for easy, precise opening and closing. These molds are commonly made of steel or cast iron. The cavity, with gating system included, is machined into the two halves to provide accurate dimensions and good surface finish. Metals commonly cast in permanent molds include aluminum, magnesium, copper-base alloys, and cast iron. However, cast iron requires a high pouring temperature, 1250°C to 1500°C (2300°F–2700°F), which takes a heavy toll on mold life. The very high pouring temperatures of steel make permanent molds unsuitable for this metal, unless the mold is made of refractory material.

Cores can be used in permanent molds to form interior surfaces in the cast product. The cores can be made of metal, but either their shape must allow for removal from the casting or they must be mechanically collapsible to permit removal. If withdrawal of a metal core would be difficult or impossible, sand cores can be used, in which case the casting process is often referred to as ***semipermanent-mold casting***.

Steps in the basic permanent mold casting process are described in Figure 11.11. In preparation for casting, the mold is first preheated and one or more coatings are

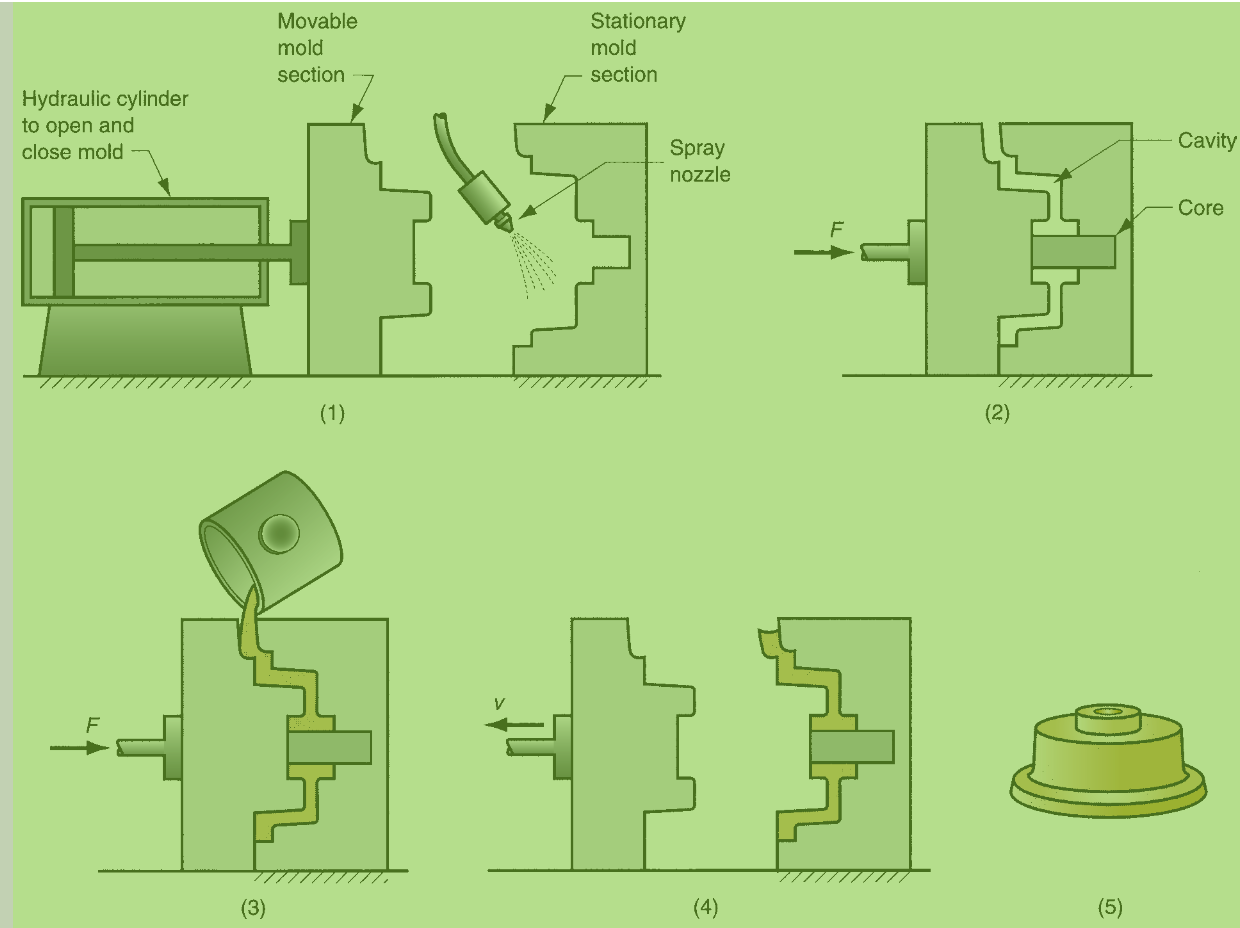


**FIGURE 11.11** Steps in permanent-mold casting: (1) mold is preheated and coated; (2) cores (if used) are inserted, and mold is closed; (3) molten metal is poured into the mold; and (4) mold is opened. Finished part is shown in (5).

sprayed on the cavity. Preheating facilitates metal flow through the gating system and into the cavity. The coatings aid heat dissipation and lubricate the mold surfaces for easier separation of the cast product. After pouring, as soon as the metal solidifies, the mold is opened and the casting is removed. Unlike expendable molds, permanent molds do not collapse, so the mold must be opened before appreciable cooling contraction occurs in order to prevent cracks from developing in the casting.

Advantages of permanent-mold casting include good surface finish and close dimensional control, as previously indicated. In addition, more rapid solidification caused by the metal mold results in a finer grain structure, so stronger castings are produced. The process is generally limited to metals of lower melting points. Other limitations include simple part geometries compared to sand casting (because of the need to open the mold), and the expense of the mold. Because mold cost is substantial, the process is best suited to high-volume production and can be automated accordingly. Typical parts include automotive pistons, pump bodies, and certain castings for aircraft and missiles.

## 11.3.2 VARIATIONS OF PERMANENT-MOLD CASTING

Several casting processes are quite similar to the basic permanent-mold method. These include slush casting, low-pressure casting, and vacuum permanent-mold casting.

**Slush Casting** Slush casting is a permanent mold process in which a hollow casting is formed by inverting the mold after partial freezing at the surface to drain out the liquid metal in the center. Solidification begins at the mold walls because they are relatively cool, and it progresses over time toward the middle of the casting (Section 10.3.1). Thickness of the shell is controlled by the length of time allowed before draining. Slush casting is used to make statues, lamp pedestals, and toys out of low-melting-point metals such as zinc and tin. In these items, the exterior appearance is important, but the strength and interior geometry of the casting are minor considerations.

**Low-Pressure Casting** In the basic permanent mold casting process and in slush casting, the flow of metal into the mold cavity is caused by gravity. In low-pressure casting, the liquid metal is forced into the cavity under low pressure—approximately 0.1 MPa (15 lb/in$^2$)—from beneath so that the flow is upward, as illustrated in Figure 11.12. The advantage of this approach over traditional pouring is that clean molten metal from the center of the ladle is introduced into the mold, rather than metal that has been exposed to air. Gas porosity and oxidation defects are thereby minimized, and mechanical properties are improved.

**Vacuum Permanent-Mold Casting** Not to be confused with vacuum molding (Section 11.2.2), this process is a variation of low-pressure casting in which a vacuum is used to draw the molten metal into the mold cavity. The general configuration of the vacuum permanent-mold casting process is similar to the low-pressure casting operation. The difference is that reduced air pressure from the vacuum in the mold is used to draw the liquid metal into the cavity, rather than forcing it by positive air pressure from below. There are several benefits of the vacuum technique relative to low-pressure casting: air porosity and related defects are reduced, and greater strength is given to the cast product.

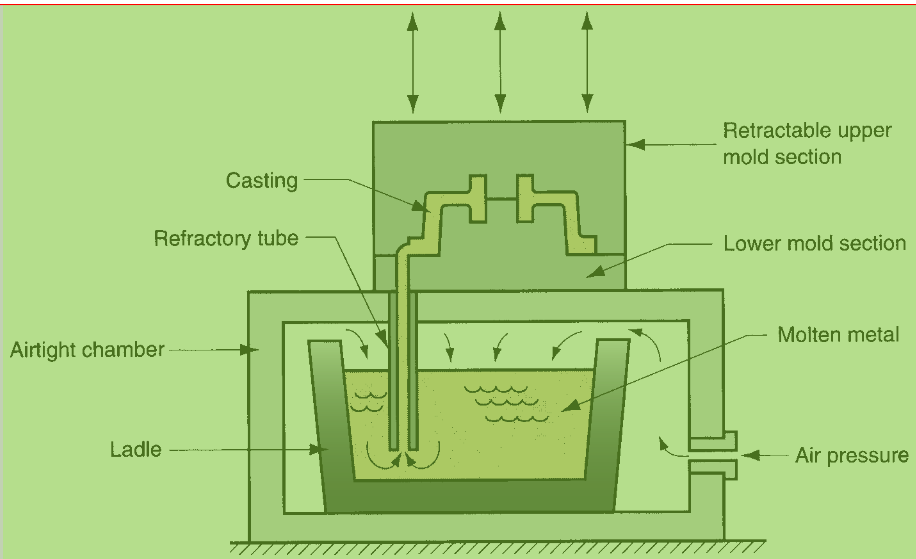


**FIGURE 11.12** Low-pressure casting. The diagram shows how air pressure is used to force the molten metal in the ladle upward into the mold cavity. Pressure is maintained until the casting has solidified.

### 11.3.3 DIE CASTING

Die casting is a permanent-mold casting process in which the molten metal is injected into the mold cavity under high pressure. Typical pressures are 7 to 350 MPa (1000–50,000 lb/in$^2$). The pressure is maintained during solidification, after which the mold is opened and the part is removed. Molds in this casting operation are called dies; hence the name die casting. The use of high pressure to force the metal into the die cavity is the most notable feature that distinguishes this process from others in the permanent mold category.

Die-casting operations are carried out in special die-casting machines (Historical Note 11.2), which are designed to hold and accurately close the two halves of the mold, and keep them closed while the liquid metal is forced into the cavity. The general configuration is shown in Figure 11.13. There are two main types of die-casting machines: (1) hot-chamber and (2) cold-chamber, differentiated by how the molten metal is injected into the cavity.

#### Historical Note 11.2 *Die-casting machines*

The modern die-casting machine has its origins in the printing industry and the need in the mid- to late 1800s to satisfy an increasingly literate population with a growing appetite for reading. The linotype, invented and developed by O. Mergenthaler in the late 1800s, is a machine that produces printing type. It is a casting machine because it casts a line of type characters out of lead to be used in preparing printing plates. The name ***linotype*** derives from the fact that the machine produces a line of type characters during each cycle of operation. The machine was first used successfully on a commercial basis in New York City by ***The Tribune*** in 1886.

The linotype proved the feasibility of mechanized casting machines. The first die-casting machine was patented by H. Doehler in 1905 (this machine is displayed in the Smithsonian Institute in Washington, D.C.). In 1907, E. Wagner developed the first die-casting machine to utilize the hot-chamber design. It was first used during World War I to cast parts for binoculars and gas masks.

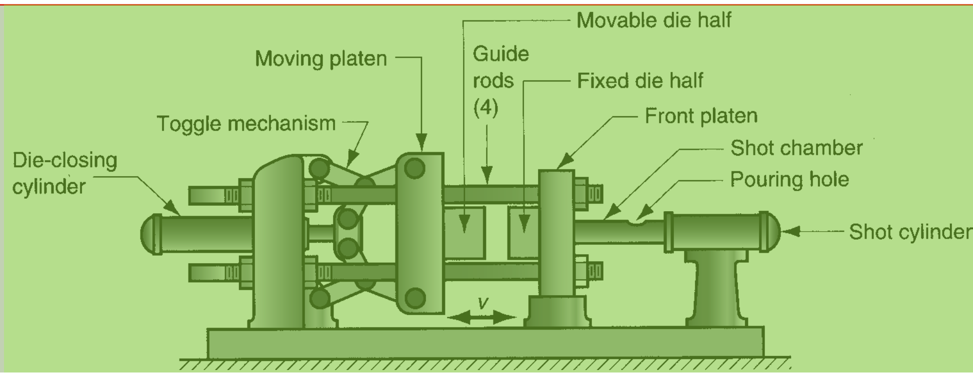


**FIGURE 11.13** General configuration of a (cold-chamber) die-casting machine.

In ***hot-chamber machines***, the metal is melted in a container attached to the machine, and a piston is used to inject the liquid metal under high pressure into the die. Typical injection pressures are 7 to 35 MPa (1000–5000 lb/in$^2$). The casting cycle is summarized in Figure 11.14. Production rates up to 500 parts per hour are not uncommon. Hot-chamber die casting imposes a special hardship on the injection system because much of it is submerged in the molten metal. The process is therefore limited in its applications to low-melting-point metals that do not chemically attack the plunger and other mechanical components. The metals include zinc, tin, lead, and sometimes magnesium.

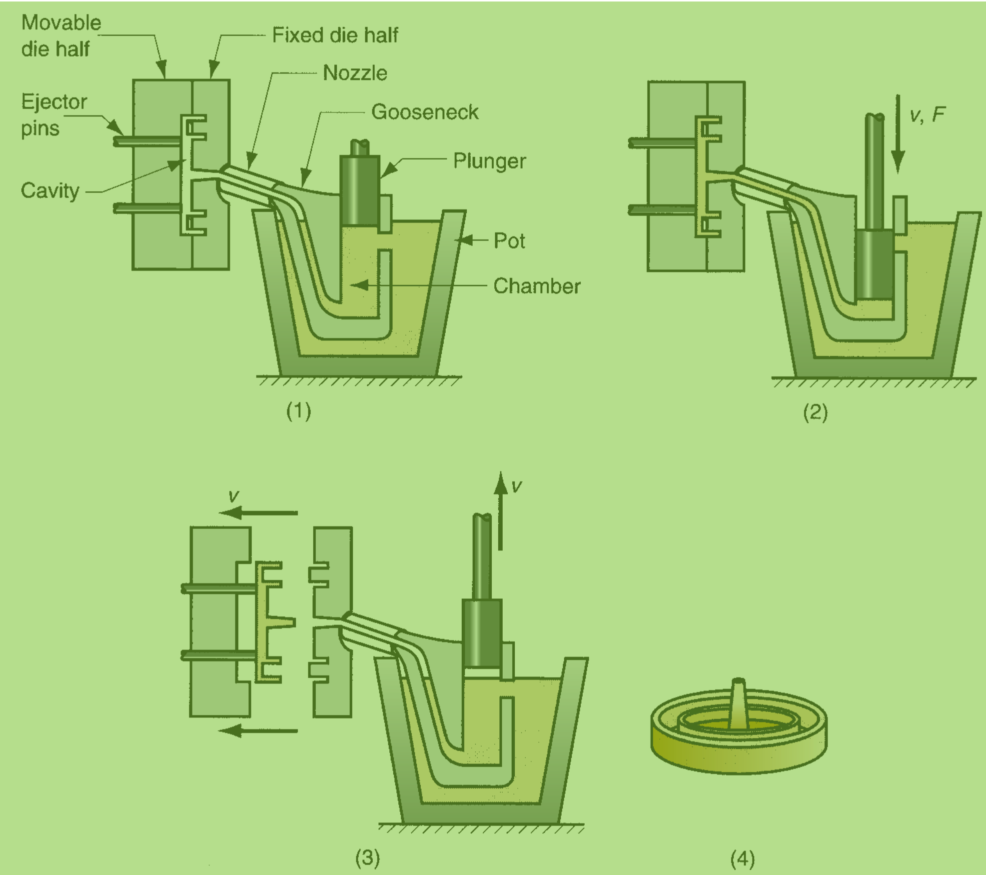


**FIGURE 11.14** Cycle in hot-chamber casting: (1) with die closed and plunger withdrawn, molten metal flows into the chamber; (2) plunger forces metal in chamber to flow into die, maintaining pressure during cooling and solidification; and (3) plunger is withdrawn, die is opened, and solidified part is ejected. Finished part is shown in (4).

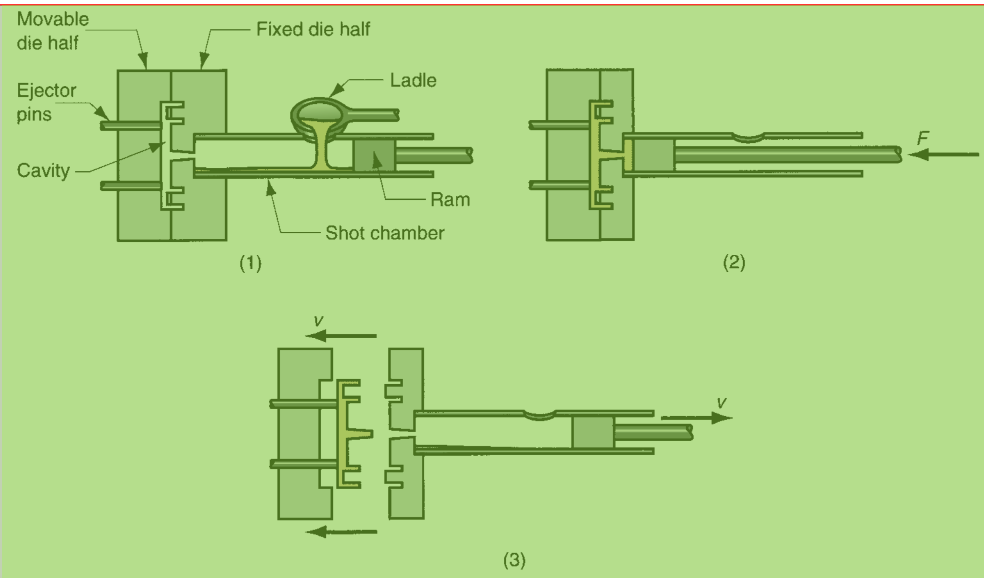


**FIGURE 11.15** Cycle in cold-chamber casting: (1) with die closed and ram withdrawn, molten metal is poured into the chamber; (2) ram forces metal to flow into die, maintaining pressure during cooling and solidification; and (3) ram is withdrawn, die is opened, and part is ejected. (Gating system is simplified.)

In ***cold-chamber die-casting machines***, molten metal is poured into an unheated chamber from an external melting container, and a piston is used to inject the metal under high pressure into the die cavity. Injection pressures used in these machines are typically 14 to 140 MPa (2000–20,000 lb/in$^2$). The production cycle is explained in Figure 11.15. Compared to hot-chamber machines, cycle rates are not usually as fast because of the need to ladle the liquid metal into the chamber from an external source. Nevertheless, this casting process is a high production operation. Cold-chamber machines are typically used for casting aluminum, brass, and magnesium alloys. Low-melting-point alloys (zinc, tin, lead) can also be cast on cold-chamber machines, but the advantages of the hot-chamber process usually favor its use on these metals. A large die casting produced by a cold-chamber machine is shown in Figure 11.16.

Molds used in die-casting operations are usually made of tool steel, mold steel, or maraging steel. Tungsten and molybdenum with good refractory qualities are also being used, especially in attempts to die cast steel and cast iron. Dies can be single-cavity or multiple-cavity. Single-cavity dies are shown in Figures 11.14 and 11.15. Ejector pins are required to remove the part from the die when it opens, as shown in the diagrams. These pins push the part away from the mold surface so that it can be removed. Lubricants must also be sprayed into the cavities to prevent sticking.

Because the die materials have no natural porosity and the molten metal rapidly flows into the die during injection, venting holes and passageways must be built into the dies at the parting line to evacuate the air and gases in the cavity. The vents are quite small; yet they fill with metal during injection. This metal must later be trimmed from the part. Also, formation of ***flash*** is common in die casting, in which the liquid metal under high pressure squeezes into the small space between the die halves at the parting line or into the clearances around the cores and ejector pins. This flash must be trimmed from the casting, along with the sprue and gating system.

Advantages of die casting include (1) high production rates possible; (2) economical for large production quantities; (3) close tolerances possible, on the order

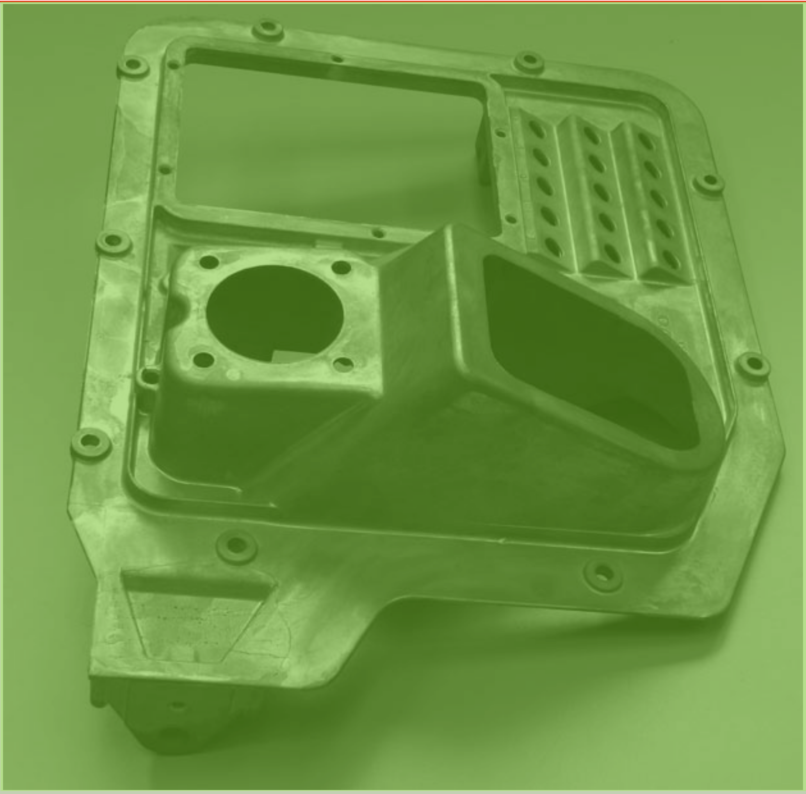

**FIGURE 11.16** A large die casting measuring about 400 mm diagonally for a truck cab floor. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

of ±0.076 mm (±0.003 in) for small parts; (4) good surface finish; (5) thin sections are possible, down to about 0.5 mm (0.020 in); and (6) rapid cooling provides small grain size and good strength to the casting. The limitation of this process, in addition to the metals cast, is the shape restriction. The part geometry must allow for removal from the die cavity.

### 11.3.4 SQUEEZE CASTING AND SEMI-SOLID METAL CASTING

These are two processes that are often associated with die casting. ***Squeeze casting*** is a combination of casting and forging (Section 18.3) in which a molten metal is poured into a preheated lower die, and the upper die is closed to create the mold cavity after solidification begins. This differs from the usual permanent-mold casting process in which the die halves are closed prior to pouring or injection. Owing to the hybrid nature of the process, it is also known as ***liquid–metal forging***. The pressure applied by the upper die in squeeze casting causes the metal to completely fill the cavity, resulting in good surface finish and low shrinkage. The required pressures are significantly less than in forging of a solid metal billet and much finer surface detail can be imparted by the die than in forging. Squeeze casting can be used for both ferrous and non-ferrous alloys, but aluminum and magnesium alloys are the most common due to their lower melting temperatures. Automotive parts are a common application.

***Semi-solid metal casting*** is a family of net-shape and near net-shape processes performed on metal alloys at temperatures between the liquidus and solidus (Section 10.3.1). Thus the alloy is a mixture of solid and molten metals during casting, like a slurry; it is in the mushy state. In order to flow properly, the mixture must consist of solid metal globules in a liquid rather than the more typical dendritic solid shapes that form during freezing of a molten metal. This is achieved by forcefully stirring the slurry to prevent dendrite formation and instead encourage the spherical shapes, which in turn reduces the viscosity of the work metal. Advantages of semi-solid metal casting include the following [16]: (1) complex part geometries, (2) thin walls in parts, (3) close tolerances, (4) zero or low porosity, resulting in high strength of the casting.

There are several forms of semi-solid metal casting. When applied to aluminum, the terms thixocasting and rheocasting are used. The prefix in thixocasting is derived from the word ***thixotropy***, which refers to the decrease in viscosity of some fluid-like materials when agitated. The prefix in rheocasting comes from ***rheology***, the science that relates deformation and flow of materials. In ***thixocasting***, the starting work material is a pre-cast billet that has a non-dendritic microstructure; this is heated into the semi-solid temperature range and injected into a mold cavity using die casting equipment. In ***rheocasting***, a semi-solid slurry is injected into the mold cavity by a die casting machine, very much like conventional die casting. The difference is that the starting metal in rheocasting is at a temperature between the solidus and liquidus rather than above the liquidus. And the mushy mixture is agitated to prevent dendrite formation.

When applied to magnesium, the term is ***thixomolding***, which utilizes equipment similar to an injection-molding machine (Section 13.6.3). Magnesium alloy granules are fed into a barrel and propelled forward by a rotating screw as they are heated into the semi-solid temperature range. The required globular form of the solid phase is accomplished by the mixing action of the rotating screw. The slurry is then injected into the mold cavity by a linear forward movement of the screw.

## 11.3.5 CENTRIFUGAL CASTING

Centrifugal casting refers to several casting methods in which the mold is rotated at high speed so that centrifugal force distributes the molten metal to the outer regions of the die cavity. The group includes (1) true centrifugal casting, (2) semicentrifugal casting, and (3) centrifuge casting.

**True Centrifugal Casting** In true centrifugal casting, molten metal is poured into a rotating mold to produce a tubular part. Examples of parts made by this process include pipes, tubes, bushings, and rings. One possible setup is illustrated in Figure 11.17. Molten metal is poured into a horizontal rotating mold at one end. In some operations, mold rotation commences after pouring has occurred rather than beforehand. The high-speed rotation results in centrifugal forces that cause the metal to take the shape of the mold cavity. Thus, the outside shape of the casting can be round, octagonal, hexagonal, and so on. However, the inside shape of the casting is (theoretically) perfectly round, due to the radially symmetric forces at work.

Orientation of the axis of mold rotation can be either horizontal or vertical, the former being more common. The question is, how fast must the mold be rotated

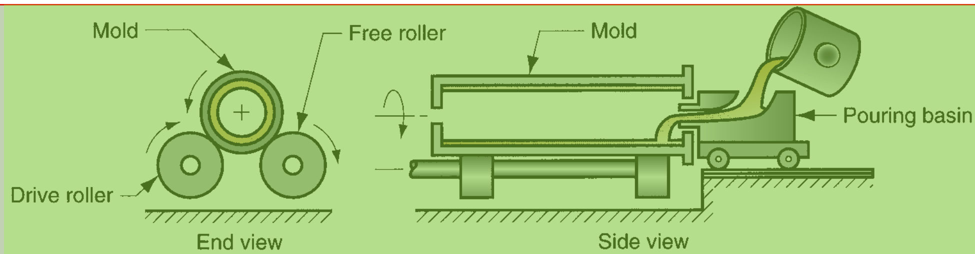


**FIGURE 11.17** Setup for true centrifugal casting.

for the process to work successfully? Consider ***horizontal centrifugal casting*** first. Centrifugal force is defined by this physics equation:

$$F = \frac{mv^2}{R} \tag{11.2}$$

where $F$ = force, N (lb); $m$ = mass, kg (lbm); $v$ = velocity, m/s (ft/sec); and $R$ = inside radius of the mold, m (ft). The force of gravity is its weight $W = mg$, where $W$ is given in kg (lb), and $g$ = acceleration of gravity, 9.8 m/s² (32.2 ft/sec²). The so-called G-factor $GF$ is the ratio of centrifugal force divided by weight:

$$GF = \frac{F}{W} = \frac{mv^2}{Rmg} = \frac{v^2}{Rg} \tag{11.3}$$

Velocity $v$ can be expressed as $2\pi RN/60 = \pi RN/30$, where the constant 60 converts seconds to minutes; so that $N$ = rotational speed, rev/min. Substituting this expression into Equation (11.3),

$$GF = \frac{\left(\frac{\pi RN}{30}\right)^2}{Rg} = \frac{R\left(\frac{\pi N}{30}\right)^2}{g} \tag{11.4}$$

Rearranging this to solve for rotational speed $N$, and using diameter $D$ rather than radius in the resulting equation,

$$N = \frac{30}{\pi}\sqrt{\frac{gGF}{R}} = \frac{30}{\pi}\sqrt{\frac{2gGF}{D}} \tag{11.5}$$

where $D$ = inside diameter of the mold, m (ft). If the G-factor is too low in centrifugal casting, the liquid metal will not remain forced against the mold wall during the upper half of the circular path but will "rain" inside the cavity. Slipping occurs between the molten metal and the mold wall, which means that the rotational speed of the metal is less than that of the mold. On an empirical basis, values of $GF$ = 60 to 80 are found to be appropriate for horizontal centrifugal casting [2], although this depends to some extent on the metal being cast.

**Example 11.2 Rotation speed in true centrifugal casting**

A true centrifugal casting operation is to be performed horizontally to make copper tube sections with $OD$ = 25 cm and $ID$ = 22.5 cm. What rotational speed is required if a G-factor of 65 is used to cast the tubing?

**Solution:** The inside diameter of the mold $D$ = $OD$ of the casting = 25 cm = 0.25 m. The required rotational speed can be computed from Equation (11.5) as follows:

$$N = \frac{30}{\pi}\sqrt{\frac{2(9.8)(65)}{0.25}} = \mathbf{681.7\ rev/min}$$

In ***vertical centrifugal casting***, the effect of gravity acting on the liquid metal causes the casting wall to be thicker at the base than at the top. The inside profile of the casting wall takes on a parabolic shape. The difference in inside radius between top and bottom is related to speed of rotation as follows:

$$N = \frac{30}{\pi}\sqrt{\frac{2gL}{R_t^2 - R_b^2}} \tag{11.6}$$

where $L$ = vertical length of the casting, m (ft); $R_t$ = inside radius at the top of the casting, m (ft); and $R_b$ = inside radius at the bottom of the casting, m (ft). Equation (11.6) can be used to determine the required rotational speed for vertical centrifugal casting, given specifications on the inside radii at top and bottom. One can see from the formula that for $R_t$ to equal $R_b$, the speed of rotation $N$ would have to be infinite, which is impossible of course. As a practical matter, part lengths made by vertical centrifugal casting are usually no more than about twice their diameters. This is quite satisfactory for bushings and other parts that have large diameters relatively to their lengths, especially if machining will be used to accurately size the inside diameter.

Castings made by true centrifugal casting are characterized by high density, especially in the outer regions of the part where $F$ is greatest. Solidification shrinkage at the exterior of the cast tube is not a factor, because the centrifugal force continually reallocates molten metal toward the mold wall during freezing. Any impurities in the casting tend to be on the inner wall and can be removed by machining if necessary.

**Semicentrifugal Casting** In this method, centrifugal force is used to produce solid castings, as in Figure 11.18, rather than tubular parts. The rotation speed in semicentrifugal casting is usually set so that G-factors of around 15 are obtained [2], and the molds are designed with risers at the center to supply feed metal. Density of metal in the final casting is greater in the outer sections than at the center of rotation. The process is often used on parts in which the center of the casting is machined away, thus eliminating the portion of the casting where the quality is lowest. Wheels and pulleys are examples of castings that can be made by this process. Expendable molds are often used in semicentrifugal casting, as suggested by the illustration of the process.

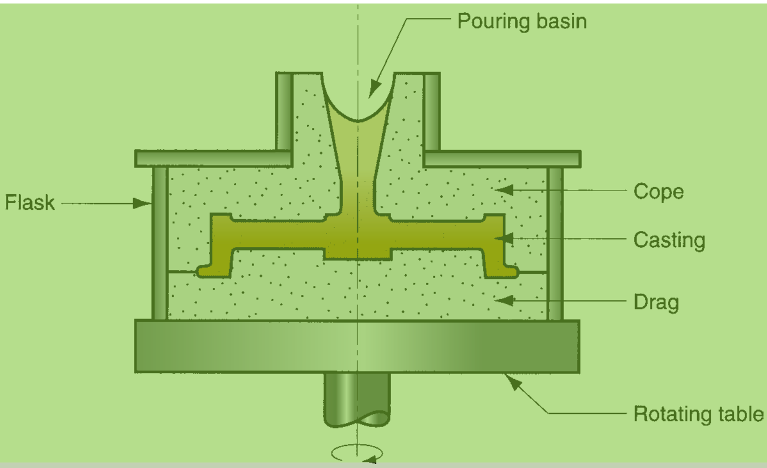


**FIGURE 11.18** Semicentrifugal casting.

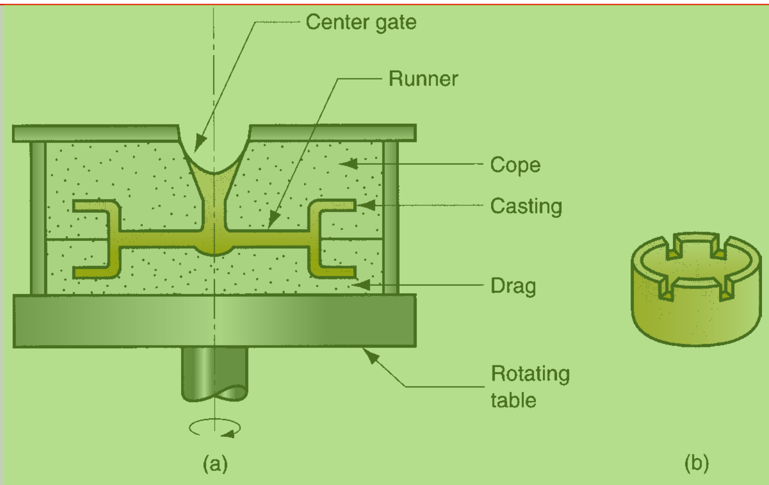


**FIGURE 11.19** (a) Centrifuge casting—centrifugal force causes metal to flow to the mold cavities away from the axis of rotation; and (b) the casting.

**Centrifuge Casting** In centrifuge casting, Figure 11.19, the mold is designed with part cavities located away from the axis of rotation, so that the molten metal poured into the mold is distributed to these cavities by centrifugal force. The process is used for smaller parts, and radial symmetry of the part is not a requirement as it is for the other two centrifugal casting methods.

# 11.4 Foundry Practice

In all casting processes, the metal must be heated to the molten state to be poured or otherwise forced into the mold. Heating and melting are accomplished in a furnace. This section covers the various types of furnaces used in foundries and the pouring practices for delivering the molten metal from furnace to mold.

## 11.4.1 FURNACES

The types of furnaces most commonly used in foundries are (1) cupolas, (2) direct fuel-fired furnaces, (3) crucible furnaces, (4) electric-arc furnaces, and (5) induction furnaces. Selection of the most appropriate furnace type depends on factors such as the casting alloy; its melting and pouring temperatures; capacity requirements of the furnace; costs of investment, operation, and maintenance; and environmental pollution considerations.

**Cupolas** A cupola is a vertical cylindrical furnace equipped with a tapping spout near its base. Cupolas are used only for melting cast irons, and although other furnaces are also used, the largest tonnage of cast iron is melted in cupolas. General construction and operating features of the cupola are illustrated in Figure 11.20. It consists of a large shell of steel plate lined with refractory. The "charge," consisting of iron, coke, flux, and possible alloying elements, is loaded through a charging door located less than halfway up the height of the cupola. The iron is usually a mixture of pig iron and scrap (including risers, runners, and sprues left over from previous castings). Coke is the fuel used to heat the furnace. Forced air is introduced through openings near the bottom of the shell for combustion of the coke. The flux is a basic

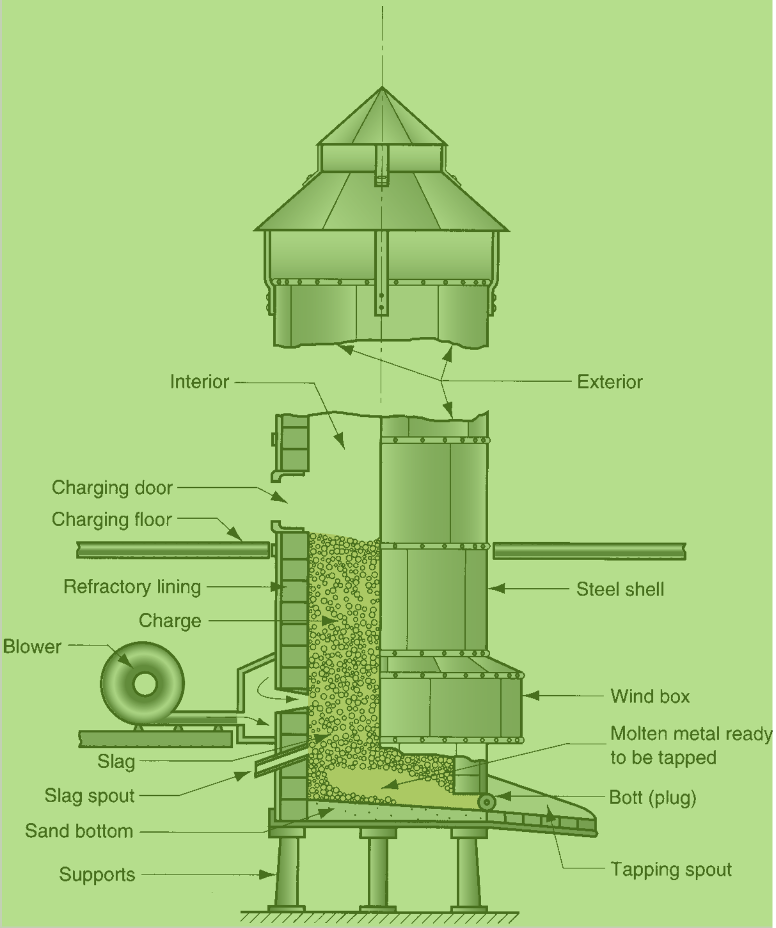


**FIGURE 11.20** Cupola used for melting cast iron. Furnace shown is typical for a small foundry and omits details of emissions control system required in a modern cupola.

compound such as limestone that reacts with coke ash and other impurities to form slag. The slag serves to cover the melt, protecting it from reaction with the environment inside the cupola and reducing heat loss. As the mixture is heated and melting of the iron occurs, the furnace is periodically tapped to provide liquid metal for the pour.

**Direct Fuel-Fired Furnaces** A direct fuel-fired furnace contains a small open hearth, in which the metal charge is heated by fuel burners located on the side of the furnace. The roof of the furnace assists the heating action by reflecting the flame down against the charge. Typical fuel is natural gas, and the combustion products exit the furnace through a stack. At the bottom of the hearth is a tap hole to release the molten metal. Direct fuel-fired furnaces are generally used in casting for melting nonferrous metals such as copper-base alloys and aluminum.

**Crucible Furnaces** These furnaces melt the metal without direct contact with a burning fuel mixture. For this reason, they are sometimes called ***indirect fuel-fired furnaces***. Three types of crucible furnaces are used in foundries: (a) lift-out type, (b) stationary, and (c) tilting, illustrated in Figure 11.21. They all utilize a container (the crucible) made out of a suitable refractory material (e.g., a clay–graphite mixture) or

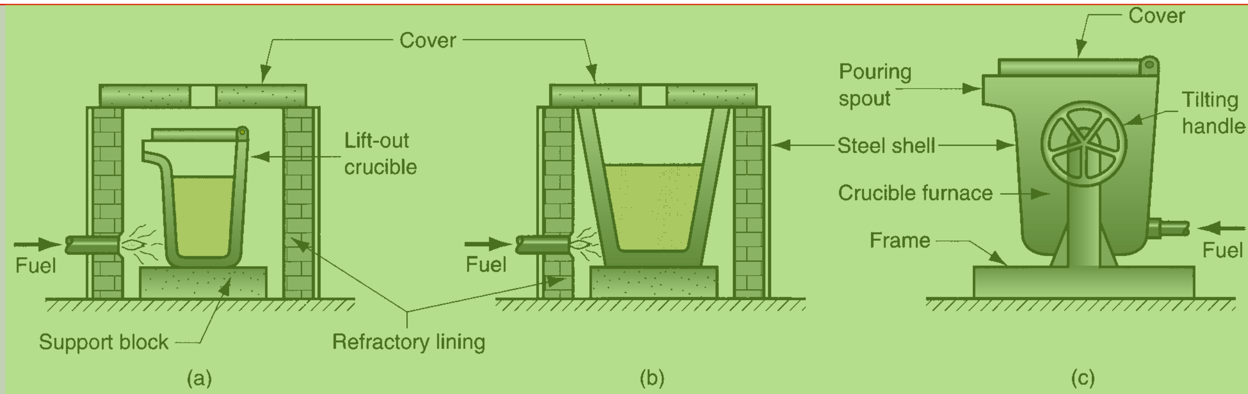


**FIGURE 11.21** Three types of crucible furnaces: (a) lift-out crucible, (b) stationary pot, and (c) tilting-pot furnace.

high-temperature steel alloy to hold the charge. In the ***lift-out crucible furnace***, the crucible is placed in a furnace and heated sufficiently to melt the metal charge. Oil, gas, or powdered coal are typical fuels for these furnaces. When the metal is melted, the crucible is lifted out of the furnace and used as a pouring ladle. The other two types, sometimes referred to as ***pot furnaces***, have the heating furnace and container as one integral unit. In the ***stationary pot furnace***, the furnace is stationary and the molten metal is ladled out of the container. In the ***tilting-pot furnace***, the entire assembly can be tilted for pouring. Crucible furnaces are used for nonferrous metals such as bronze, brass, and alloys of zinc and aluminum. Furnace capacities are generally limited to several hundred pounds.

**Electric-Arc Furnaces** In this furnace type, the charge is melted by heat generated from an electric arc. Various configurations are available, with two or three electrodes (Figure 6.9). Power consumption is high, but electric-arc furnaces can be designed for high melting capacity (23,000–45,000 kg/hr or 25–50 tons/hr), and they are used primarily for casting steel.

**Induction Furnaces** An induction furnace uses alternating current passing through a coil to develop a magnetic field in the metal, and the resulting induced current causes rapid heating and melting of the metal. Features of an induction furnace for foundry operations are illustrated in Figure 11.22. The electromagnetic

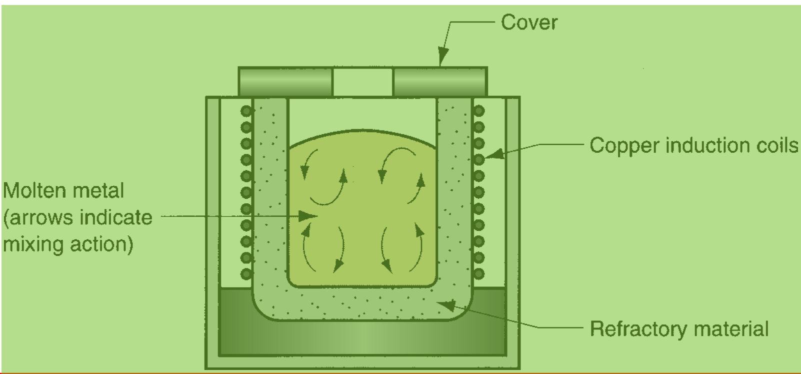


**FIGURE 11.22** Induction furnace.

force field causes a mixing action to occur in the liquid metal. Also, since the metal does not come in direct contact with the heating elements, the environment in which melting takes place can be closely controlled. All of this results in molten metals of high quality and purity, and induction furnaces are used for nearly any casting alloy when these requirements are important. Melting steel, cast iron, and aluminum alloys are common applications in foundry work.

### 11.4.2 POURING, CLEANING, AND HEAT TREATMENT

Moving the molten metal from the melting furnace to the mold is sometimes done using crucibles. More often, the transfer is accomplished by ***ladles*** of various kinds. These ladles receive the metal from the furnace and allow for convenient pouring into the molds. Two common ladles are illustrated in Figure 11.23, one for handling large volumes of molten metal using an overhead crane, and the other a "two-man ladle" for manually moving and pouring smaller amounts.

One of the problems in pouring is that oxidized molten metal can be introduced into the mold. Metal oxides reduce product quality, perhaps rendering the casting defective, so measures are taken to minimize the entry of these oxides into the mold during pouring. Filters are sometimes used to catch the oxides and other impurities as the metal is poured from the spout, and fluxes are used to cover the molten metal to retard oxidation. In addition, ladles have been devised to pour the liquid metal from the bottom, since the top surface is where the oxides accumulate.

After the casting has solidified and been removed from the mold, a number of additional steps are usually required. These operations include (1) trimming, (2) removing the core, (3) surface cleaning, (4) inspection, (5) repair, if required, and (6) heat treatment. Steps (1) through (5) are collectively referred to in foundry work as "cleaning." The extent to which these additional operations are required varies with casting processes and metals. When required, they are usually labor-intensive and costly.

***Trimming*** involves removal of sprues, runners, risers, parting-line flash, fins, chaplets, and any other excess metal from the cast part. In the case of brittle casting alloys and when the cross sections are relatively small, these appendages on the casting can be broken off. Otherwise, hammering, shearing, hack-sawing, band-sawing, abrasive wheel cutting, or various torch cutting methods are used.

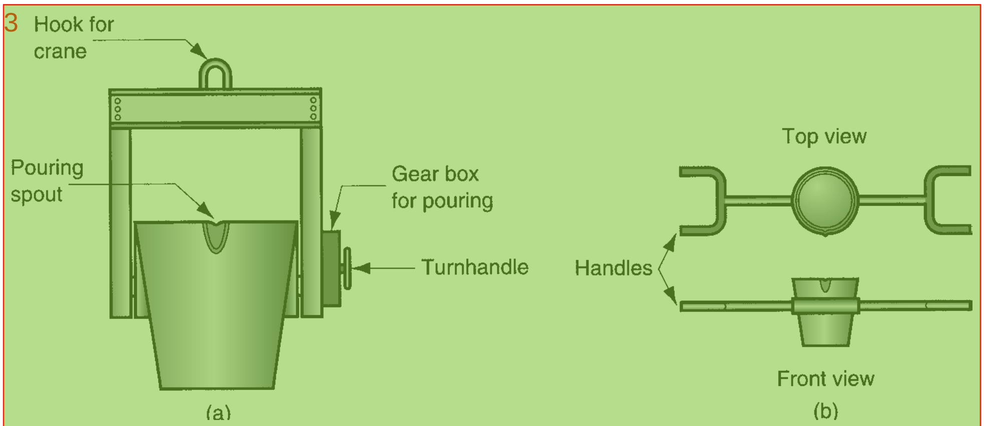


**FIGURE 11.23** Two common types of ladles: (a) crane ladle and (b) two-man ladle.

If cores have been used to cast the part, they must be removed. Most cores are chemically bonded or oil-bonded sand, and they often fall out of the casting as the binder deteriorates. In some cases, they are removed by shaking the casting, either manually or mechanically. In rare instances, cores are removed by chemically dissolving the bonding agent used in the sand core. Solid cores must be hammered or pressed out.

Surface cleaning is most important in the case of sand casting. In many of the other casting methods, especially the permanent mold processes, this step can be avoided. ***Surface cleaning*** involves removal of sand from the surface of the casting and otherwise enhancing the appearance of the surface. Methods used to clean the surface include tumbling, air-blasting with coarse sand grit or metal shot, wire brushing, and chemical pickling (Section 27.1).

Defects are possible in casting, and inspection is needed to detect their presence. These quality issues are considered in the following section.

Castings are often heat treated to enhance their properties, either for subsequent processing operations such as machining or to bring out the desired properties for application of the part.

## 11.5 Casting Quality

There are numerous opportunities for things to go wrong in a casting operation, resulting in quality defects in the cast product. In this section, the common defects that occur in casting are listed, and the inspection procedures to detect them are indicated.

**Casting Defects** Some defects are common to any and all casting processes. These defects are illustrated in Figure 11.24 and briefly described in the following:

(a) ***Misruns***, which are castings that solidify before completely filling the mold cavity. Typical causes include (1) fluidity of the molten metal is insufficient, (2) pouring temperature is too low, (3) pouring is done too slowly, and/or (4) cross section of the mold cavity is too thin.

(b) ***Cold Shuts***, which occur when two portions of the metal flow together but there is a lack of fusion between them due to premature freezing. Its causes are similar to those of a misrun.

(c) ***Cold shots***, which result from splattering during pouring, causing the formation of solid globules of metal that become entrapped in the casting. Pouring procedures and gating system designs that avoid splattering can prevent this defect.

(d) ***Shrinkage cavity*** is a depression in the surface or an internal void in the casting, caused by solidification shrinkage that restricts the amount of molten metal available in the last region to freeze. It often occurs near the top of the casting, in which case it is referred to as a "pipe." See Figure 10.8(3). The problem can often be solved by proper riser design.

(e) ***Microporosity*** consists of a network of small voids distributed throughout the casting caused by localized solidification shrinkage of the final molten metal in the dendritic structure. The defect is usually associated with alloys, because of the protracted manner in which freezing occurs in these metals.

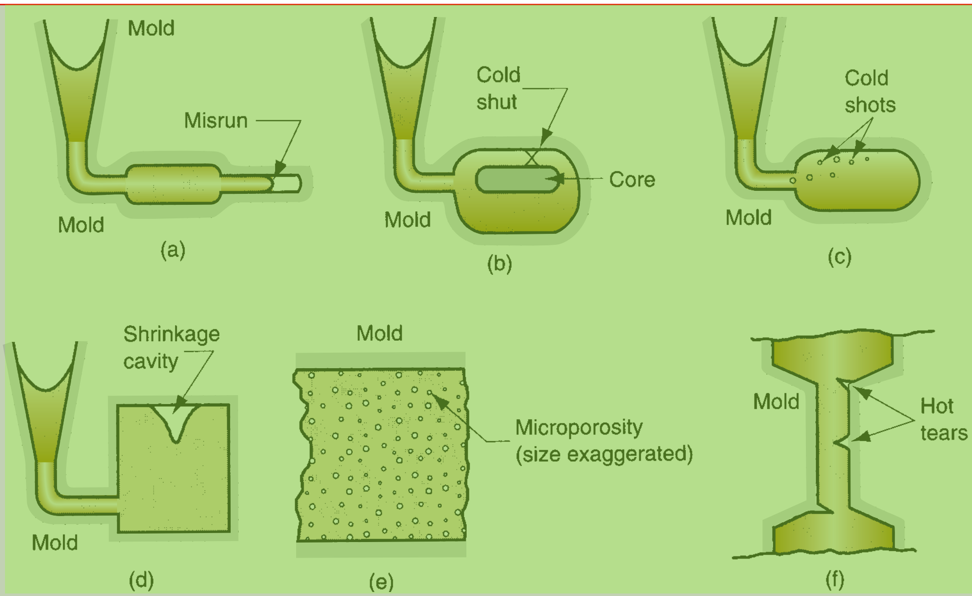


**FIGURE 11.24** Some common defects in castings: (a) misrun, (b) cold shut, (c) cold shot, (d) shrinkage cavity, (e) microporosity, and (f) hot tearing.

(f) ***Hot tearing***, also called ***hot cracking***, occurs when the casting is restrained from contraction by an unyielding mold during the final stages of solidification or early stages of cooling after solidification. The defect is manifested as a separation of the metal (hence, the terms ***tearing*** and ***cracking***) at a point of high tensile stress caused by the metal's inability to shrink naturally. In sand casting and other expendable-mold processes, it is prevented by compounding the mold to be collapsible. In permanent-mold processes, hot tearing is reduced by removing the part from the mold immediately after solidification.

Some defects are related to the use of sand molds, and therefore they occur only in sand castings. To a lesser degree, other expendable mold processes are also susceptible to these problems. Defects found primarily in sand castings are shown in Figure 11.25 and described here:

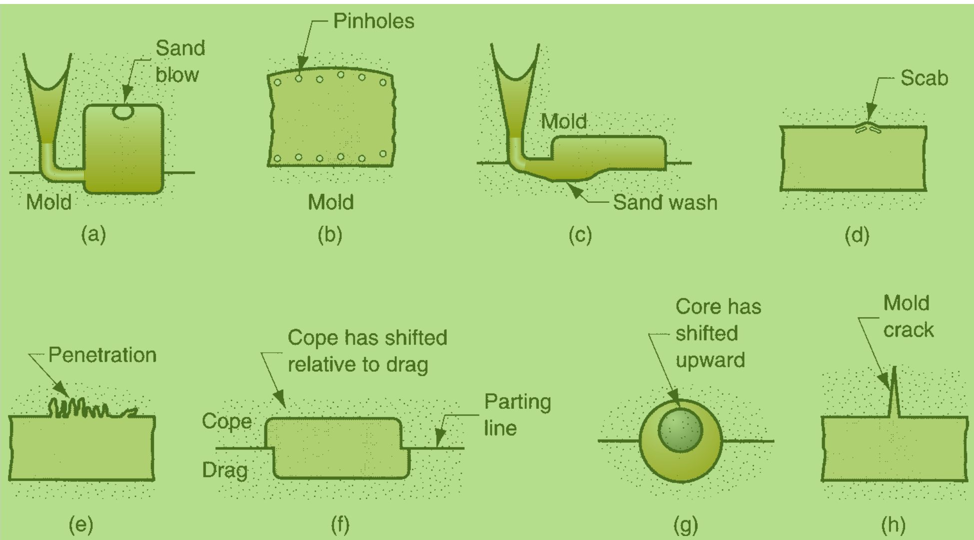


**FIGURE 11.25** Common defects in sand castings: (a) sand blow, (b) pin holes, (c) sand wash, (d) scabs, (e) penetration, (f) mold shift, (g) core shift, and (h) mold crack.

(a) ***Sand blow*** is a defect consisting of a balloon-shaped gas cavity caused by release of mold gases during pouring. It occurs at or below the casting surface near the top of the casting. Low permeability, poor venting, and high moisture content of the sand mold are the usual causes.

(b) ***Pinholes***, also caused by release of gases during pouring, consist of many small gas cavities formed at or slightly below the surface of the casting.

(c) ***Sand wash***, which is an irregularity in the surface of the casting that results from erosion of the sand mold during pouring, and the contour of the erosion is formed in the surface of the final cast part.

(d) ***Scabs*** are rough areas on the surface of the casting due to encrustations of sand and metal. It is caused by portions of the mold surface flaking off during solidification and becoming imbedded in the casting surface.

(e) ***Penetration*** refers to a surface defect that occurs when the fluidity of the liquid metal is high, and it penetrates into the sand mold or sand core. Upon freezing, the casting surface consists of a mixture of sand grains and metal. Harder packing of the sand mold helps to alleviate this condition.

(f) ***Mold shift*** refers to a defect caused by a sidewise displacement of the mold cope relative to the drag, the result of which is a step in the cast product at the parting line.

(g) ***Core shift*** is similar to mold shift, but it is the core that is displaced, and the displacement is usually vertical. Core shift and mold shift are caused by buoyancy of the molten metal (Section 11.1.3).

(h) ***Mold crack*** occurs when mold strength is insufficient, and a crack develops, into which liquid metal can seep to form a "fin" on the final casting.

**Inspection Methods** Foundry inspection procedures include (1) visual inspection to detect obvious defects such as misruns, cold shuts, and severe surface flaws; (2) dimensional measurements to ensure that tolerances have been met; and (3) metallurgical, chemical, physical, and other tests concerned with the inherent quality of the cast metal [7]. Tests in category (3) include: (a) pressure testing—to locate leaks in the casting; (b) radiographic methods, magnetic particle tests, the use of fluorescent penetrants, and supersonic testing—to detect either surface or internal defects in the casting; and (c) mechanical testing to determine properties such as tensile strength and hardness. If defects are discovered but are not too serious, it is often possible to save the casting by welding, grinding, or other salvage methods to which the customer has agreed.

## 11.6 Metals for Casting

Most commercial castings are made of alloys rather than pure metals. Alloys are generally easier to cast, and properties of the resulting product are better. Casting alloys can be classified as ferrous or nonferrous. The ferrous category is subdivided into cast iron and cast steel.

**Ferrous Casting Alloys: Cast Iron** Cast iron is the most important of all casting alloys (Historical Note 11.3). The tonnage of cast iron castings is several times that of all other metals combined. There are several types of cast iron: (1) gray cast iron, (2) nodular iron, (3) white cast iron, (4) malleable iron, and (5) alloy cast irons (Section 6.2.4). Typical pouring temperatures for cast iron are around 1400°C (2500°F), depending on composition.

### Historical Note 11.3 *Early cast iron products*

In the early centuries of casting, bronze and brass were preferred over cast iron as foundry metals. Iron was more difficult to cast, due to its higher melting temperatures and lack of knowledge about its metallurgy. Also, there was little demand for cast iron products. This all changed starting in the sixteenth and seventeenth centuries.

The art of sand casting iron entered Europe from China, where iron was cast in sand molds more than 2,500 years ago. In 1550 the first cannons were cast from iron in Europe. Cannon balls for these guns were made of cast iron starting around 1568. Guns and their projectiles created a large demand for cast iron. But these items were for military rather than civilian use. Two cast iron products that became significant to the general public in the sixteenth and seventeenth centuries were the cast iron stove and cast iron water pipe.

As unspectacular a product as it may seem today, the cast iron stove brought comfort, health, and improved living conditions to many people in Europe and America. During the 1700s, the manufacture of cast iron stoves was one of the largest and most profitable industries on these two continents. The commercial success of stove making was due to the large demand for the product and the art and technology of casting iron that had been developed to produce it.

Cast iron water pipe was another product that spurred the growth of the iron casting industry. Until the advent of cast iron pipes, a variety of methods had been tried to supply water directly to homes and shops, including hollow wooden pipes (which quickly rotted), lead pipes (too expensive), and open trenches (susceptible to pollution). Development of the iron-casting process provided the capability to fabricate water pipe sections at relatively low cost. Cast iron water pipes were used in France starting in 1664, and later in other parts of Europe. By the early 1800s, cast iron pipe lines were being widely installed in England for water and gas delivery. The first significant water pipe installation in the United States was in Philadelphia in 1817, using pipe imported from England.

**Ferrous Casting Alloys: Steel** The mechanical properties of steel make it an attractive engineering material, and the capability to create complex geometries makes casting an appealing process. However, great difficulties are faced by the foundry specializing in steel. First, the melting point of steel is considerably higher than for most other metals that are commonly cast. The solidification range for low carbon steels (Figure 6.4) begins at just under 1540°C (2800°F). This means that the pouring temperature required for steel is very high—about 1650°C (3000°F). At these high temperatures, steel is chemically very reactive. It readily oxidizes, so special procedures must be used during melting and pouring to isolate the molten metal from air. Also, molten steel has relatively poor fluidity, and this limits the design of thin sections in components cast out of steel.

Several characteristics of steel castings make it worth the effort to solve these problems. Tensile strength is higher than for most other casting metals, ranging upward from about 410 MPa (60,000 lb/in$^2$) [9]. Steel castings have better toughness than most other casting alloys. The properties of steel castings are isotropic; strength is virtually the same in all directions. By contrast, mechanically formed parts (e.g., rolling, forging) exhibit directionality in their properties. Depending on the requirements of the product, isotropic behavior of the material may be desirable. Another advantage of steel castings is ease of welding. They can be readily welded without significant loss of strength, to repair the casting, or to fabricate structures with other steel components.

**Nonferrous Casting Alloys** Nonferrous casting metals include alloys of aluminum, magnesium, copper, tin, zinc, nickel, and titanium (Section 6.3). ***Aluminum alloys*** are generally considered to be very castable. The melting point of pure aluminum is 660°C (1220°F), so pouring temperatures for aluminum casting alloys are low compared to cast iron and steel. Their properties make them attractive for castings: light weight, wide range of strength properties attainable through heat treatment, and ease of machining. ***Magnesium alloys*** are the lightest of all casting metals. Other properties include corrosion resistance, as well as high strength-to-weight and stiffness-to-weight ratios.

***Copper alloys*** include bronze, brass, and aluminum bronze. Properties that make them attractive include corrosion resistance, attractive appearance, and good bearing qualities. The high cost of copper is a limitation on the use of its alloys. Applications include pipe fittings, marine propeller blades, pump components, and ornamental jewelry.

Tin has the lowest melting point of the casting metals. ***Tin-based alloys*** are generally easy to cast. They have good corrosion resistant but poor mechanical strength, which limits their applications to pewter mugs and similar products not requiring high strength. ***Zinc alloys*** are commonly used in die casting. Zinc has a low melting point and good fluidity, making it highly castable. Its major weakness is low creep strength, so its castings cannot be subjected to prolonged high stresses.

***Nickel alloys*** have good hot strength and corrosion resistance, which make them suited to high-temperature applications such as jet engine and rocket components, heat shields, and similar components. Nickel alloys also have a high melting point and are not easy to cast. ***Titanium alloys*** for casting are corrosion resistant and possess high strength-to-weight ratios. However, titanium has a high melting point, low fluidity, and a propensity to oxidize at high temperatures. These properties make it and its alloys difficult to cast.

## 11.7 Product Design Considerations

If casting is selected by the product designer as the primary manufacturing process for a particular component, then certain guidelines should be followed to facilitate production of the part and avoid many of the defects enumerated in Section 11.5. Some of the important guidelines and considerations for casting are presented here.

- ***Geometric simplicity***. Although casting is a process that can be used to produce complex part geometries, simplifying the part design will improve its castability. Avoiding unnecessary complexities simplifies mold making, reduces the need for cores, and improves the strength of the casting.
- ***Corners***. Sharp corners and angles should be avoided, because they are sources of stress concentrations and may cause hot tearing and cracks in the casting. Generous fillets should be designed on inside corners, and sharp edges should be blended.

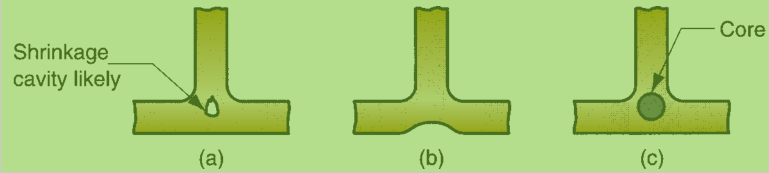


**FIGURE 11.26** (a) Thick section at intersection can result in a shrinkage cavity. Remedies include (b) redesign to reduce thickness and (c) use of a core.

- ➢ ***Section thicknesses***. Section thicknesses should be uniform in order to avoid shrinkage cavities. Thicker sections create ***hot spots*** in the casting, because greater volume requires more time for solidification and cooling. These are likely locations of shrinkage cavities. Figure 11.26 illustrates the problem and offers some possible solutions.
- ➢ ***Draft***. Part sections that project into the mold should have a draft or taper, as defined in Figure 11.27. In expendable mold casting, the purpose of this draft is to facilitate removal of the pattern from the mold. In permanent mold casting, its purpose is to aid in removal of the part from the mold. Similar tapers should be allowed if solid cores are used in the casting process. The required draft need only be about 1° for sand casting and 2° to 3° for permanent mold processes.
- ➢ ***Use of cores.*** Minor changes in part design can reduce the need for coring, as shown in Figure 11.27.
- ➢ ***Dimensional tolerances.*** There are significant differences in the dimensional accuracies that can be achieved in castings, depending on which process is used. Table 11.2 provides a compilation of typical part tolerances for various casting processes and metals.
- ➢ ***Surface finish.*** Typical surface roughness achieved in sand casting is around 6 $\mu$m (250 $\mu$-in). Similarly poor finishes are obtained in shell molding, while plaster-mold and investment casting produce much better roughness values: 0.75 $\mu$m (30 $\mu$-in). Among the permanent mold processes, die casting is noted for good surface finishes at around 1 $\mu$m (40 $\mu$-in).
- ➢ ***Machining allowances.*** Tolerances achievable in many casting processes are insufficient to meet functional needs in many applications. Sand casting is the most prominent example of this deficiency. In these cases, portions of the casting must be machined to the required dimensions. Almost all sand

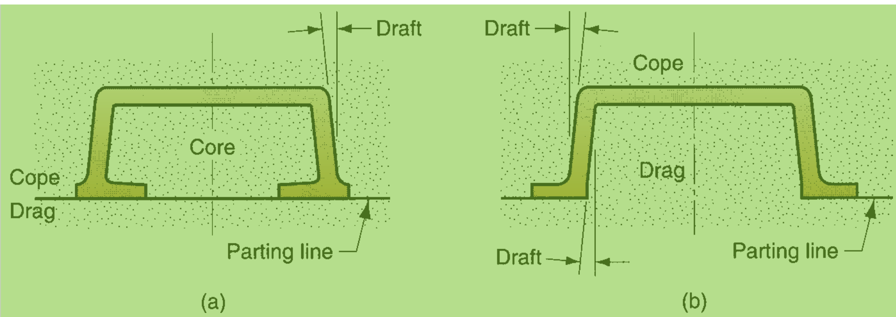


**FIGURE 11.27** Design change to eliminate the need for using a core: (a) original design and (b) redesign.

**TABLE • 11.2** Typical dimensional tolerances for various casting processes and metals.

| Casting Process | Part Size | Tolerance mm | Tolerance in | Casting Process | Part Size | Tolerance mm | Tolerance in |
|---|---|---|---|---|---|---|---|
| Sand casting | | | | Permanent mold | | | |
| Aluminum[a] | Small | ±0.5 | ±0.020 | Aluminum[a] | Small | ±0.25 | ±0.010 |
| Cast iron | Small | ±1.0 | ±0.040 | Cast iron | Small | ±0.8 | ±0.030 |
| | Large | ±1.5 | ±0.060 | Copper alloys | Small | ±0.4 | ±0.015 |
| Copper alloys | Small | ±0.4 | ±0.015 | Steel | Small | ±0.5 | ±0.020 |
| Steel | Small | ±1.3 | ±0.050 | Die casting | | | |
| | Large | ±2.0 | ±0.080 | Aluminum[a] | Small | ±0.12 | ±0.005 |
| Shell molding | | | | Copper alloys | Small | ±0.12 | ±0.005 |
| Aluminum[a] | Small | ±0.25 | ±0.010 | Investment | | | |
| Cast iron | Small | ±0.5 | ±0.020 | Aluminum[a] | Small | ±0.12 | ± 0.005 |
| Copper alloys | Small | ±0.4 | ±0.015 | Cast iron | Small | ±0.25 | ±0.010 |
| Steel | Small | ±0.8 | ±0.030 | Copper alloys | Small | ±0.12 | ±0.005 |
| Plaster mold | Small | ±0.12 | ±0.005 | Steel | Small | ±0.25 | ±0.010 |
| | Large | ±0.4 | ±0.015 | | | | |

Compiled from [7], [16], and other sources.
[a]Values for aluminum also apply to magnesium.

castings must be machined to some extent in order for the part to be made functional. Therefore, additional material, called the ***machining allowance***, is left on the casting for machining those surfaces where necessary. Typical machining allowances for sand castings range between 1.5 mm and 3 mm (1/16 in and 1/4 in).

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