PART II
Metal-casting Processes and Equipment

Several methods are available to shape metals into products. One of the oldest processes is **casting**, which basically involves pouring molten metal into a mold cavity; upon solidification, the metal takes the shape of the cavity. Two examples of cast parts are shown in Fig. II.1.

Casting was first used around 4000 B.C. to make ornaments, arrowheads, and various other simple objects. The process is now capable of producing intricate shapes, in one piece, and including those with internal cavities, such as engine blocks. Figure II.2 shows cast components in a typical automobile, a product that was used in the introduction to Part I to illustrate the selection and use of a variety of materials. The casting processes developed over the years are shown in Fig. II.3.

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

- Casting can produce complex shapes and can incorporate internal cavities or hollow parts.
- Very large parts can be produced in one piece.
- Casting can utilize materials that are difficult or uneconomical to process by other methods, such as hard metals that are difficult to machine or plastically deform.
- The casting process is less expensive than other manufacturing processes for the particular application being considered.

(a)

(b)

Figure II.1: (a) Examples of cast parts. (b) A tree of rings produced through investment casting. *Source:* (a) Shutterstock/Mr.1 (b) Courtesy of Romanoff, Inc.

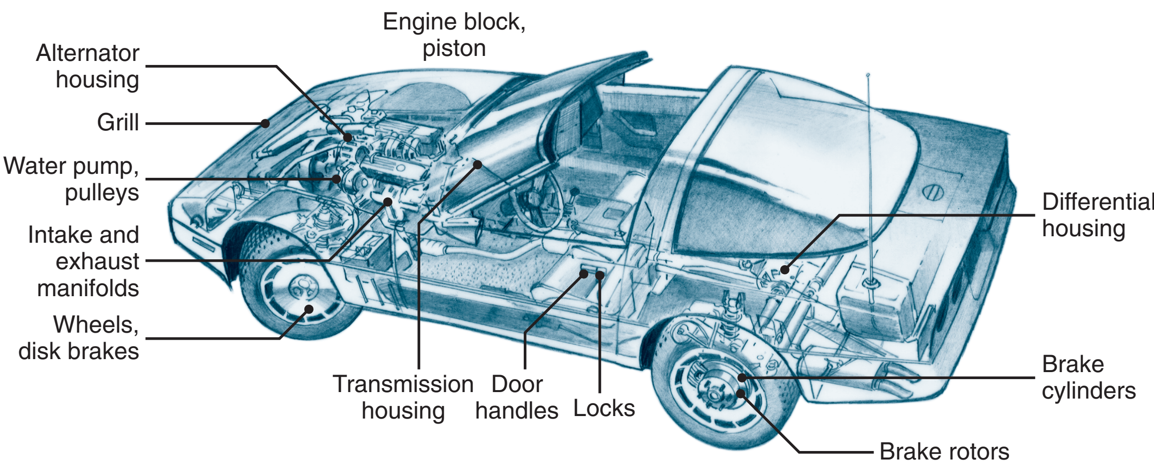

Figure II.2: Cast parts in a typical automobile.

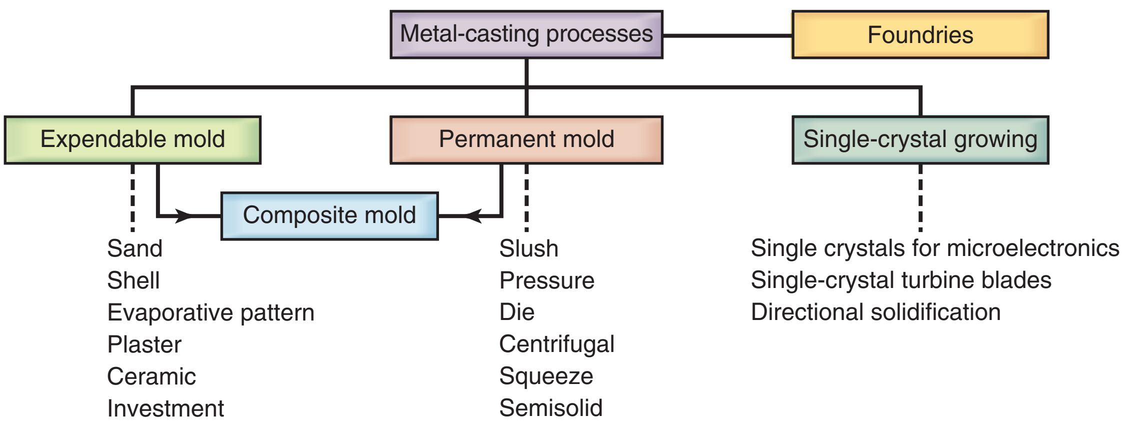

Figure II.3: Outline of metal-casting processes described in Part II.

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

Chapter 10

Fundamentals of Metal Casting

- First used about 6000 years ago, casting continues to be an important manufacturing process for producing very small, very large, and complex parts.
- The first topic described is solidification of molten metals, including the differences between solidification of pure metals and alloys.
- Fluid flow in casting is then described, with Bernoulli's and the continuity equations being applied to establish a framework for analyzing molten metal flow into the cavities of a mold.
- The importance of turbulent versus laminar flow is introduced.
- Heat transfer and shrinkage of castings are also described, including Chvorinov's rule for solidification time.
- The chapter ends with a description of the causes of porosity in castings and common methods of reducing them to improve the properties of castings.

10.1 Introduction

The **casting** process basically involves (a) pouring molten metal into a mold containing a cavity that produces the desired part shape, (b) allowing it to solidify, and (c) removing the part from the mold. As with all other manufacturing processes, an understanding of the underlying science is essential for producing high quality, economical castings, and for establishing proper techniques for mold design and casting practice.

Important considerations in casting operations are:

- Flow of the molten metal into the mold cavity, and design of gating systems or pathways for molten metal to fill the cavity
- Solidification and cooling of the metal in the mold
- Influence of the mold material.

This chapter describes relationships among various relevant factors involved in casting. The flow of molten metal into the mold cavity is first described in terms of mold design and fluid-flow characteristics. Solidification and cooling of metals in the mold are affected by several factors, including the metallurgical and thermal properties of the metal and the type of mold because it affects the rate of cooling. The chapter ends with a description of the factors influencing defect formation in castings.

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

10.2 Solidification of Metals

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

10.2.1 Pure Metals

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

As shown in Fig. 10.1b and described in greater detail in Section 10.5.2, metals generally shrink when they solidify (Table 10.1) and shrink further while cooling. This behavior is an important consideration, because shrinkage can lead to microcracking and associated porosity, which can adversely affect the mechanical properties of the casting.

As an example of the grain structure that develops in a casting, Fig. 10.2a shows a cross section of a box-shaped mold. At the mold walls, which are at ambient temperature at first or typically are much cooler than the molten metal, the metal cools rapidly, producing a solidified **skin**, or *shell*, of fine equiaxed grains. The grains generally grow in a direction opposite to that of the heat transfer out through the mold. Those grains that have favorable orientation grow preferentially, and are called **columnar grains** (Fig. 10.3). Those grains that have substantially different orientations are blocked from further growing. As the driving force of the heat transfer decreases away from the mold walls, the grains become equiaxed and coarse. This sequence

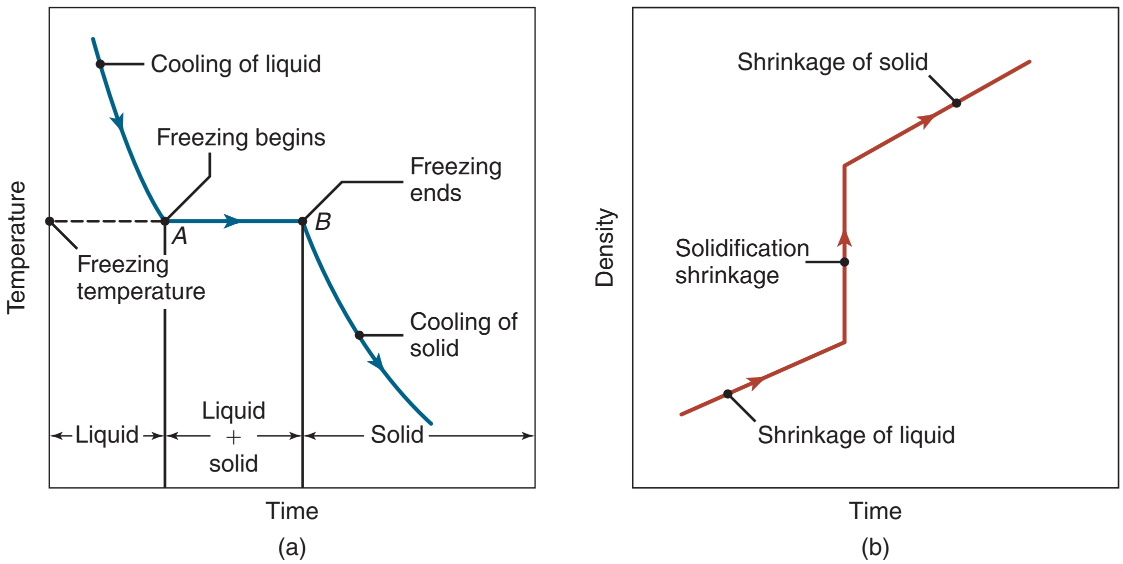

Figure 10.1: (a) Temperature as a function of time for the solidification of pure metals; note that freezing takes place at a constant temperature. (b) Density as a function of time.

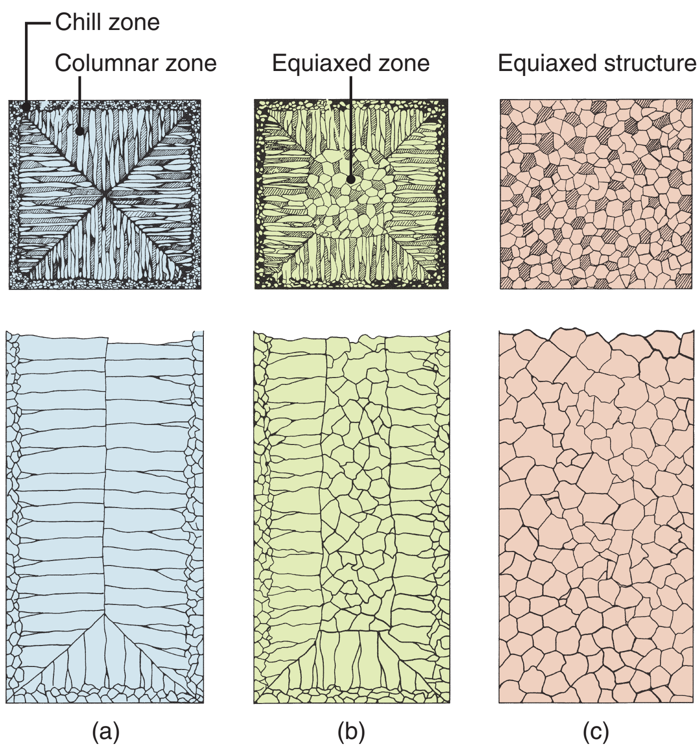

Figure 10.2: Schematic illustration of three cast structures of metals solidified in a square mold: (a) pure metals; (b) solid–solution alloys; and (c) structure obtained by using nucleating agents. *Source:* After G.W. Form, J.F. Wallace, J.L. Walker, and A. Cibula.

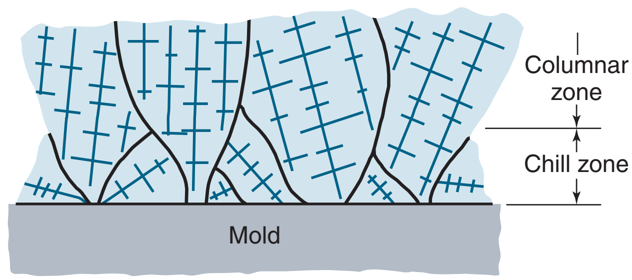

Figure 10.3: Development of a preferred texture at a cool mold wall; note that only favorably oriented grains grow away from the surface of the mold.

of grain development is known as **homogenous nucleation**, meaning that the grains (crystals) grow upon themselves, starting at the mold wall.

10.2.2 Alloys

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

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

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

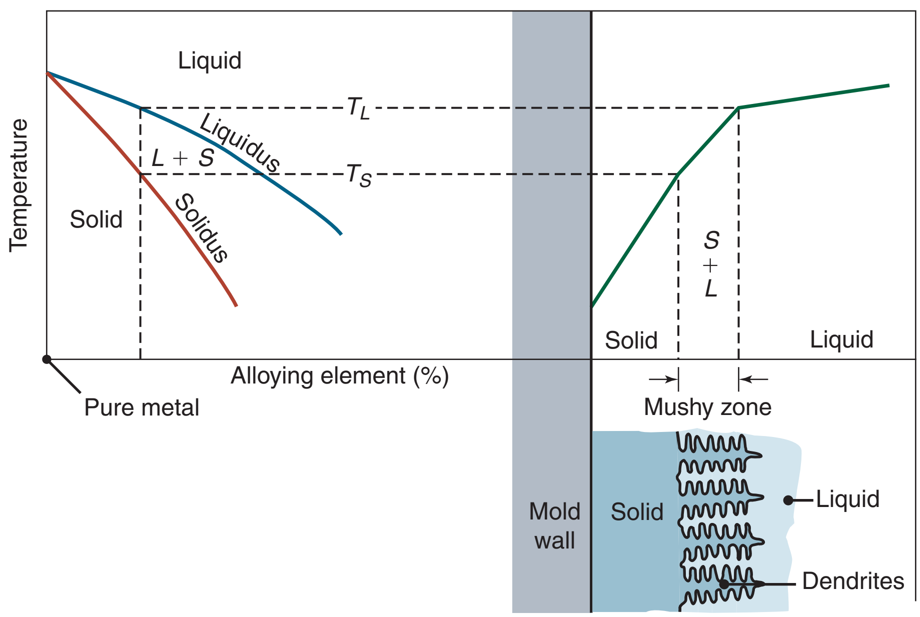

Figure 10.4: Schematic illustration of alloy solidification and temperature distribution in the solidifying metal. Note the formation of dendrites in the mushy zone.

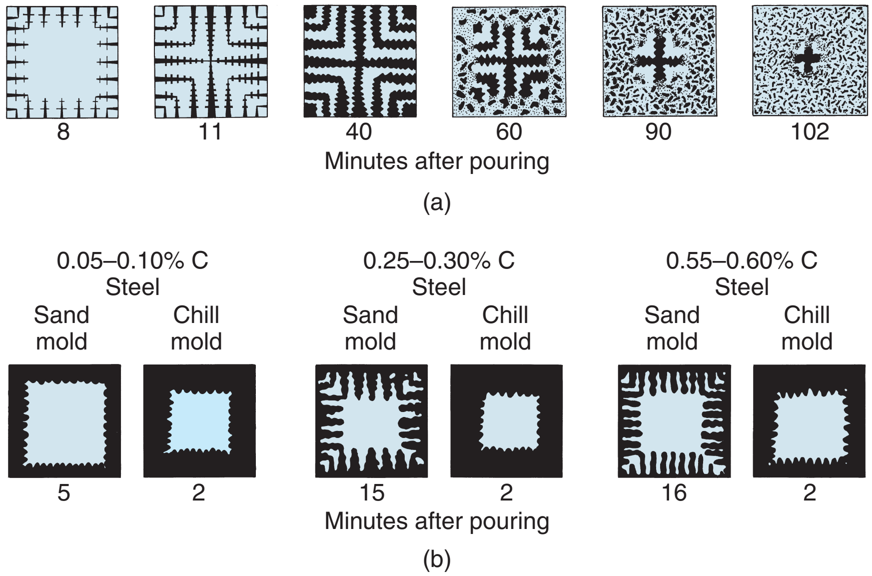

Figure 10.5: (a) Solidification patterns for gray cast iron in a 180-mm square casting. Note that after 11 minutes of cooling, dendrites begin to reach each other, but the casting is still mushy throughout. It takes about 2 hours more for this casting to solidify completely. (b) Solidification of carbon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

It can be noted in Fig. 10.4 that pure metals have a freezing range that approaches zero and that the solidification front moves as a plane without developing a mushy zone. Eutectics (Section 4.3) solidify in a similar manner, with an essentially plane front; the structure developed upon solidification depends on the composition of the eutectic. In alloys with a nearly symmetrical phase diagram (see Fig. 4.4), the structure is generally lamellar, with two or more solid phases present, depending on the alloy system. When the volume fraction of the minor phase of the alloy is less than about 25%, the structure generally becomes fibrous. These conditions are particularly significant for cast irons.

For alloys, a *short freezing range* generally involves a temperature difference of less than 50°C, and a *long freezing range* more than 110°C. Ferrous castings typically have narrow mushy zones, whereas aluminum and magnesium alloys have wide mushy zones; consequently, these alloys are in a mushy state throughout most of their solidification cycle.

Effects of Cooling Rates. Slow cooling rates, on the order of 10^2 K/s, or long local solidification times result in *coarse* dendritic structures, with large spacing between dendrite arms. For higher cooling rates, on the order of 10^4 K/s, or short local solidification times, the structure becomes *finer*, with smaller dendrite arm spacing. For still higher cooling rates, on the order of from 10^6 to 10^8, the structures developed are *amorphous*, as described in Section 6.15.

The structures developed and the resulting grain sizes have an influence on the properties of the casting. As grain size decreases, the strength and ductility of the cast alloy increase, microporosity (*interdendritic shrinkage voids*) in the casting decreases, and the tendency for the casting to crack (*hot tearing*, see Fig. 10.14) during solidification decreases. Lack of uniformity in grain size and grain distribution produce castings that have *anisotropic properties*.

10.2.3 Structure–Property Relationships

Because all castings are expected to meet design and service requirements, the relationships between properties and the structures developed during solidification are important. This section describes these

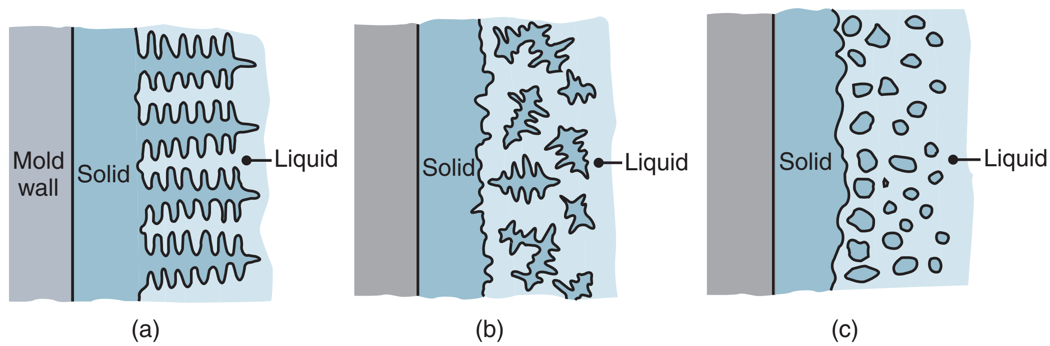

Figure 10.6: Schematic illustration of three basic types of cast structures: (a) columnar dendritic; (b) equiaxed dendritic; and (c) equiaxed nondendritic. *Source:* Courtesy of D. Apelian.

relationships in terms of dendrite morphology and the concentration of alloying elements in various regions within a casting.

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

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

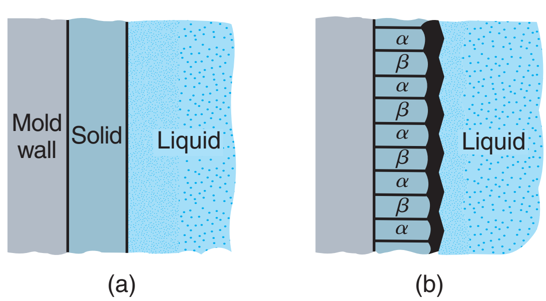

Figure 10.7: Schematic illustration of cast structures in (a) plane front, single phase, and (b) plane front, two phase. *Source:* Courtesy of D. Apelian.

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

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

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

10.2.4 Freeze Casting

Dendrite formation can be used to produce porous metals, ceramics, or polymers through the **freeze casting** process. In this approach, a slurry (suspension or mixture of particles in a liquid, usually water) is frozen. As the liquid solidifies, the particles are not soluble in the solid and therefore segregate at the solidification front. Eventually, the fluid freezes fully, with the carrier fluid and particles as separate phases.

The fluid can then be removed by lowering the pressure (in a vacuum), as shown in Fig. 10.8, and then raising the temperature. The result is a porous metal with a microstructure that is derived from the dendritic structure of the carrier fluid (Fig. 10.9). This structure generally has to be sintered to develop strength (Section 17.4).

10.3 Fluid Flow

To emphasize the importance of fluid flow in casting, consider a basic gravity casting system, as shown in Fig. 10.10. The molten metal is poured through a **pouring basin** or **cup**; it then flows through the **gating system** (consisting of sprue, runners, and gates) into the mold cavity. As also illustrated in Fig. 11.3, the **sprue** is a tapered vertical channel through which the molten metal flows downward in the mold. **Runners** are the channels that carry the molten metal from the sprue into the mold cavity or they connect the sprue to the **gate** (that portion of the runner through which the molten metal enters the mold cavity). **Risers**, also called **feeders**, serve as reservoirs of molten metal; they supply sufficient molten metal necessary to prevent porosity due to shrinkage during solidification.

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

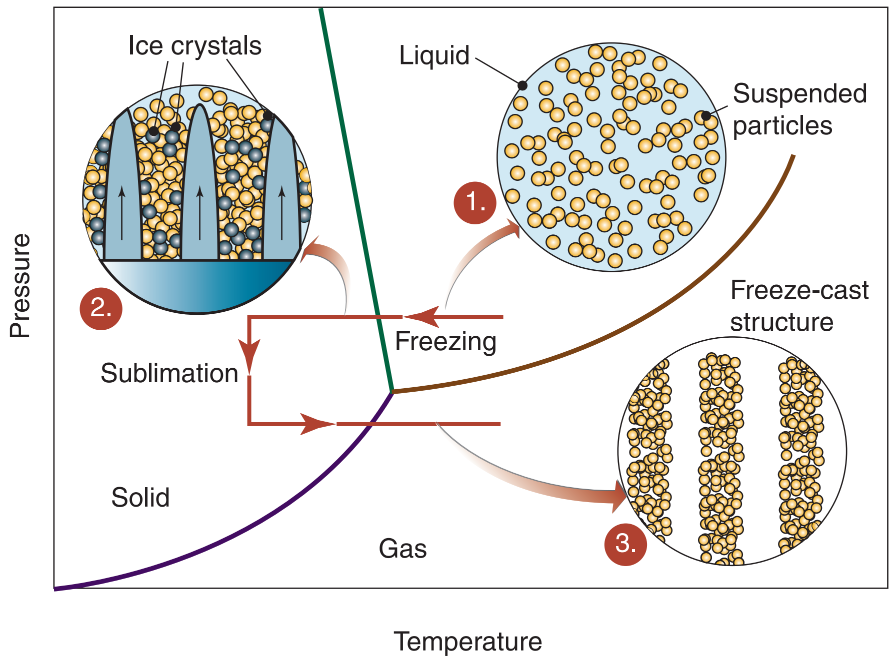

Figure 10.8: Freeze casting. (1) A slurry of a carrier liquid (commonly water) and insoluble particles is first reduced in temperature. (2) The liquid freezes in directional or dendritic fashion, forcing the particles away from the solidified volume where the particles are insoluble. (3) Decreasing pressure and increasing temperature evaporates the carrier fluid (*freeze drying*), leaving behind the particles that can be fused through sintering operations.

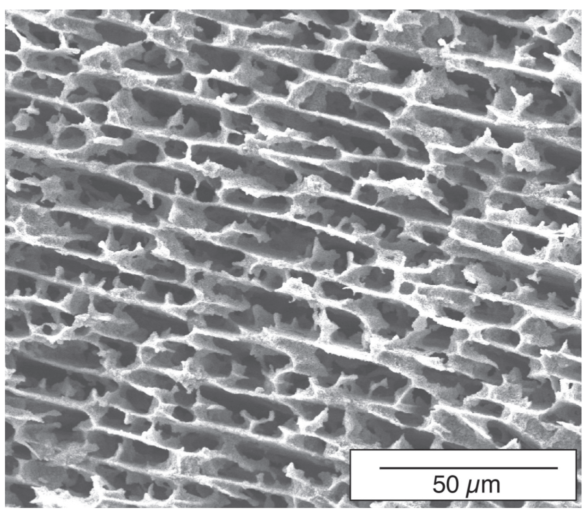

Figure 10.9: Microstructure after freeze casting. The specimen shown is titanium oxide (TiO_2) with pure water as a freezing agent. *Source:* Courtesy S. Naleway and T. Ogden, University of Utah.

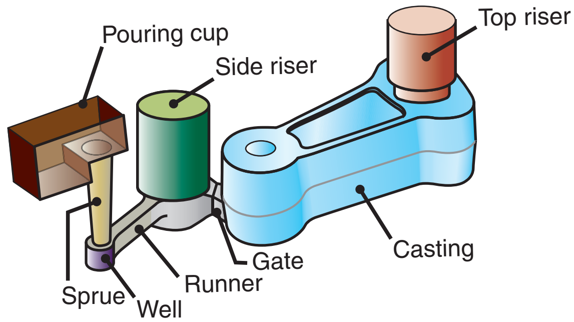

Figure 10.10: Schematic illustration of a typical riser-gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification.

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

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

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

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

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

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

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

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

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

Sprue Design. An application of the two principles just described is the traditional *tapered* design of sprues (shown in Fig. 10.10). Note that in a free-falling liquid (such as water from a faucet), the cross-sectional area of the stream decreases as the liquid gains velocity. Thus, if a sprue has a constant cross-sectional area and molten metal is poured into it, regions may develop where the liquid loses contact with the sprue walls. As a result, **aspiration** (a process whereby air is entrapped in the liquid) may take place. One of two basic alternatives is used to prevent aspiration: a tapered sprue is used to prevent molten metal separation from the sprue wall, or straight-sided sprues are supplied with a **choking** mechanism at the bottom, consisting of either a choke core or a runner choke, as shown in Fig. 11.3. The choke slows the flow sufficiently to prevent aspiration in the sprue.

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

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

where, for example, the subscript 1 denotes the top of the sprue and 2 denotes the bottom. The distances h_1 and h_2 are measured from the liquid level in the pouring cup or basin (Fig. 10.10), so that h_2 is larger than h_1. Moving downward from the top, the cross-sectional area of the sprue must therefore decrease. The area at the bottom of the sprue, A_2, is selected to allow for desired flow rates, as described below, and the profile is produced according to Eq. (10.5).

Depending on the assumptions made, expressions other than Eq. (10.5) can also be obtained. For example, assume a certain molten-metal velocity, V_1, at the top of the sprue. Then, using Eqs. (10.3) and (10.4), an expression can be obtained for the ratio A_1/A_2 as a function of h_1, h_2, and V_1.

Modeling. Another application of the foregoing equations is in the *modeling of mold filling* in casting. For example, consider the situation shown in Fig. 10.10, where molten metal is poured into a pouring cup or basin; it flows through a sprue to a runner and a gate and fills the mold cavity. If the pouring basin has a much larger cross-sectional area than the sprue bottom, then the velocity of the molten metal at the top of the pouring basin is very low, and it can be taken to be zero. If frictional losses are due to a viscous dissipation of energy, then f in Eq. (10.3) can be taken to be a function of the vertical distance, and is often approximated as a linear function. Therefore, the velocity of the molten metal leaving the gate is obtained from Eq. (10.3) as

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

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

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

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

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

Simulation of mold filling assists designers in the specification of the runner diameter, as well as the size and number of sprues and pouring basins. To ensure that the runners remain open, the *fill time* must be a small fraction of the solidification time, but the velocity should not be so high as to erode the mold (referred to as mold wash) or to result in too high of a Reynolds number (see below). Otherwise, turbulence and associated air entrainment will result. Several computational tools are now available to evaluate gating designs and to assist in the sizing of components, such as Magmasoft, Flow 3D Cast, Wincast, ProCast, Quikcast, SolidCast, SUTCast, and PASSAGE/PowerCAST.

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

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

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

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

Dross or slag can be eliminated only by *vacuum casting* (see Section 11.4.2). Conventional atmospheric casting relieves the problem of dross or slag by (a) skimming, (b) using properly designed pouring basins and runner systems, (c) tapping the molten metal from below the surface, such as in pressure casting (Fig. 11.18), or (d) using filters, which also can eliminate turbulent flow in the runner system. Filters are typically made of ceramics, mica, or fiberglass; their proper location and placement are important for effective filtering of dross and slag.

10.4 Fluidity of Molten Metal

The capability of molten metal to fill mold cavities is called *fluidity*; it consists of two basic factors: (a) the molten metal and (b) casting parameters. The characteristics of the molten metal that influence fluidity are:

Viscosity. As viscosity and its sensitivity to temperature increase, fluidity decreases.

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

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

Solidification Pattern of the Alloy. The manner in which solidification takes place (Section 10.2) can influence fluidity. Fluidity is inversely proportional to the freezing range (see Eq. 10.1): The shorter the range, as in pure metals and eutectics, the higher the fluidity. Conversely, alloys with long freezing ranges, such as solid–solution alloys, have lower fluidity.

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

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

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

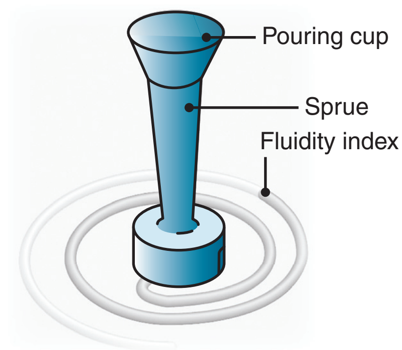

Figure 10.11: A test method for fluidity using a spiral mold. The fluidity index is the length of the solidified metal in the spiral passage. The greater the length of the solidified metal, the greater is the metal's fluidity.

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

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

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

Castability. Although complex, this term is generally used to describe the ease with which a metal can be cast to produce a part with good quality. It includes not only fluidity, but is also affected by casting practices.

10.4.1 Tests for Fluidity

Several tests have been developed to quantify fluidity, although none has been accepted universally. In one common test, the molten metal is made to flow along a channel that is at room temperature (Fig. 10.11); the distance the metal flows before it solidifies and stops flowing is a measure of its fluidity. Obviously, the length is a function of the thermal properties of the metal and the mold, as well as of the design of the channel.

10.5 Heat Transfer

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

A typical temperature distribution at the mold-liquid metal interface is shown in Fig. 10.12. Heat from the liquid metal is given off through the mold wall and to the surrounding air. The temperature drop at the air–mold and mold–metal interfaces is caused by the presence of boundary layers and imperfect contact at these interfaces. The shape of the curve depends on the thermal properties of the molten metal and the mold.

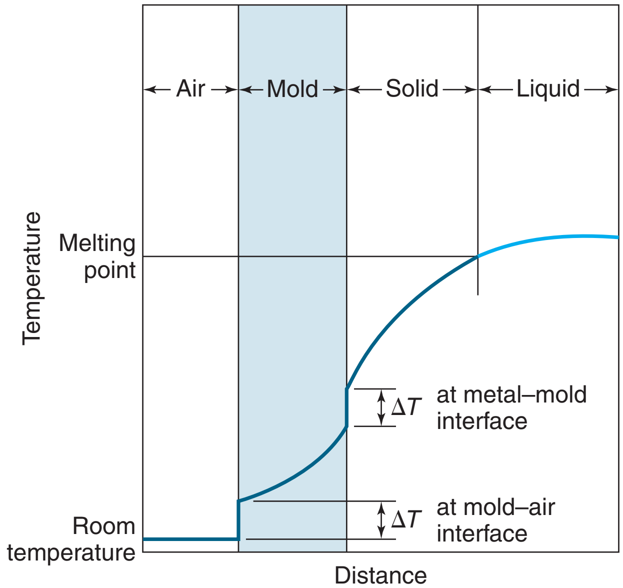

Figure 10.12: Temperature distribution at the interface of the mold wall and the liquid metal during the solidification of metals in casting.

10.5.1 Solidification Time

During the early stages of solidification of the metal, a thin skin begins to form at the relatively cool mold walls; as time passes, the thickness of the skin increases (Fig. 10.13). With flat mold walls, the thickness is proportional to the square root of time; thus, doubling the time will make the skin $\sqrt{2} = 1.41$ times or 41% thicker.

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

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

where C is a constant reflecting (a) the mold material, (b) the metal properties, including latent heat, and (c) the temperature. The parameter n has a value between 1.5 and 2, but usually taken as 2. Thus, for example, a large solid sphere will solidify and cool to ambient temperature at a much slower rate than will a smaller solid sphere. Note that the volume of a sphere is proportional to the cube of its diameter, and its surface area

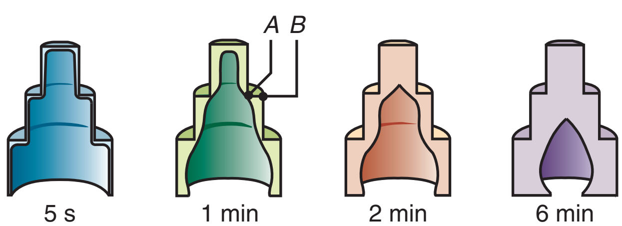

Figure 10.13: Solidified skin on a steel casting. The remaining molten metal is poured out at the times indicated in the figure. Hollow ornamental and decorative objects are made by a process called *slush casting*, which is based on this principle. *Source:* After H.F. Taylor, J. Wulff, and M.C. Flemings.

is proportional to the square of its diameter. Similarly, it can be shown that molten metal in a cube-shaped mold will solidify faster than in a spherical mold of the same volume (see Example 10.1).

The effects of mold geometry and elapsed time on skin thickness and shape are shown in Fig. 10.13. As illustrated, the unsolidified molten metal has been poured from the mold at different time intervals ranging from 5 seconds to 6 minutes. As expected, the skin thickness increases with elapsed time, and the skin is thinner at internal angles (location A in the figure) than at external angles (location B). The latter condition is caused by slower cooling at internal angles than at external angles.

Example 10.1 Solidification Times for Various Shapes

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

Find: Which piece will solidify the fastest, and which one the slowest?

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

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

The respective surface areas are as follows:

Sphere:

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

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

Cube:

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

Cylinder:

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

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

The respective solidification times are therefore

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

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

10.5.2 Shrinkage

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

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

Table 10.1: Volumetric Solidification Contraction or Expansion for Various Cast Metals.

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

The largest amount of shrinkage occurs during the phase change of the material from liquid to solid; detrimental effects of this shrinkage can be reduced through the use of risers or by pressure-feeding of molten metal. The amount of contraction during solidification of various metals is shown in Table 10.1. Note that some metals, such as gray cast iron, expand. The reason for this expansion is that graphite has a relatively high specific volume, and when it precipitates as graphite flakes during solidification of the gray cast iron, it causes a net expansion of the metal. Shrinkage, especially that due to thermal contraction, is further described in Section 12.2.1 in connection with design considerations in casting.

10.6 Defects

Depending on factors such as the quality of raw materials, product design, and control of processing parameters, several defects can develop in castings, as illustrated in Figs. 10.14 and 10.15. While some defects affect only the appearance of the parts made, others can have major adverse effects on their structural

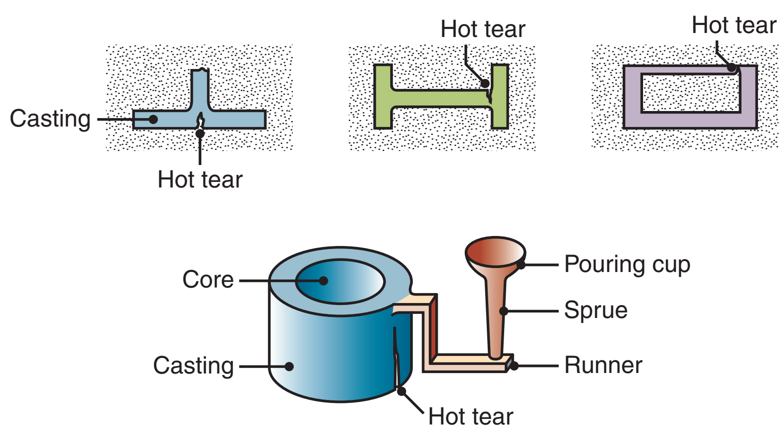

Figure 10.14: Examples of hot tears in castings. These defects occur because the casting cannot shrink freely during cooling, owing to constraints in various portions of the molds and cores. Exothermic (heat producing) compounds may be used as *exothermic padding* to control cooling at critical regions to avoid hot tearing.

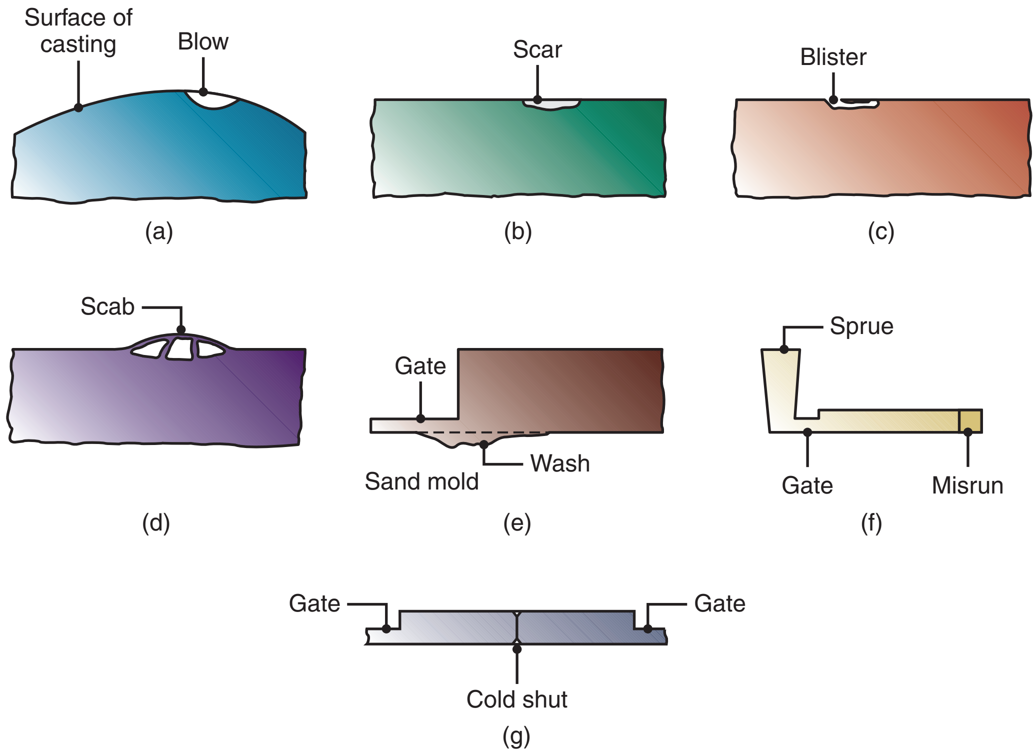

Figure 10.15: Examples of common defects in castings. These defects can be minimized or eliminated by proper design and preparation of molds and control of pouring procedures. *Source:* After J. Datsko.

integrity. The International Committee of Foundry Technical Associations has developed a standardized nomenclature, consisting of seven basic categories of casting defects, identified with boldface capital letters:

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

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

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

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

E—Incomplete casting, such as *misruns* (due to premature solidification), insufficient volume of the metal poured, and *runout* (due to loss of metal from the mold after pouring). Incomplete castings also can result from the molten metal being at too low a temperature or from pouring the metal too slowly.

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

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

10.6.1 Porosity

Porosity in a casting may be caused by *shrinkage*, entrained or dissolved *gases*, or both. Porous regions can develop in castings because of **shrinkage** of the solidified metal. Thin sections in a casting solidify sooner than thicker regions; consequently, molten metal flows into the thicker regions that have not yet solidified. Porous regions may develop at their centers because of contraction as the surfaces of the thicker regions begin to solidify first. *Microporosity* can develop when the liquid metal solidifies and shrinks between dendrites and between dendrite branches. Porosity is detrimental to the strength and ductility of a casting and its surface finish, potentially making the casting permeable, thus affecting the pressure tightness of a cast pressure vessel.

Porosity caused by shrinkage can be reduced or eliminated by various means:

- Adequate liquid metal should be provided to prevent cavities caused by shrinkage.
- Internal or external **chills**, as those used in sand casting (Fig. 10.16), are an effective means of reducing shrinkage porosity. The function of chills is to increase the rate of solidification in critical regions. Internal chills are usually made from the same material as the casting itself, and are left within the casting. Problems may arise that involve proper fusion of the internal chills with the casting; thus,

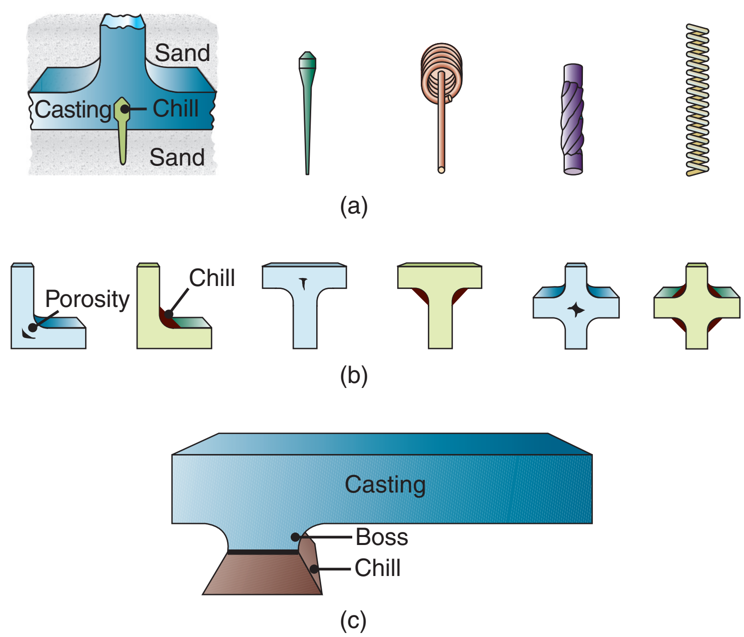

Figure 10.16: Various types of (a) internal and (b) external chills (dark areas at corners) used in castings to eliminate porosity caused by shrinkage. Chills are placed in regions where there is a larger volume of metal, as shown in (c).

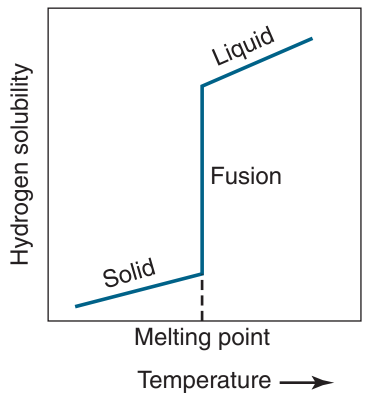

Figure 10.17: Solubility of hydrogen in aluminum. Note the sharp decrease in solubility as the molten metal begins to solidify.

foundries generally avoid using internal chills. External chills may be made from the same material as the casting or may be made of iron, copper, or graphite.

- Porosity in alloys can be reduced or eliminated by using high temperature gradients, that is, by increasing the cooling rate. For example, mold materials with higher thermal conductivity may be used.

- Subjecting the casting to hot isostatic pressing is another method of reducing porosity (see Section 17.3.2).

Gases are more soluble in liquid metals than in solid metals (Fig. 10.17); thus, when a metal begins to solidify, the dissolved gases are expelled. Gases also may be due to reactions of the molten metal with the mold materials. Gases either accumulate in regions of existing porosity (such as in interdendritic regions; see Section 10.2.3) or cause microporosity in the casting, particularly in cast iron, aluminum, and copper. Dissolved gases may be removed from the molten metal by *flushing* or *purging* with an inert gas or by melting and pouring the metal in a vacuum. If the dissolved gas is oxygen, the molten metal can be *deoxidized*.

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

Summary

- Casting is a solidification process in which molten metal is poured into a mold and allowed to cool. The metal may flow through a variety of passages (pouring basins, sprues, runners, risers, and gating systems) before reaching the final mold cavity. Bernoulli's theorem, the continuity law, and the Reynolds number are the analytical tools used in designing castings, with the goals of achieving an appropriate flow rate and eliminating defects associated with fluid flow.

- Solidification of pure metals takes place at a constant temperature, whereas solidification of alloys occurs over a range of temperatures. Phase diagrams are important tools for identifying the solidification point or points for technologically important metals.

- The composition and cooling rates of the molten metal both affect the size and shape of the grains and the dendrites in the solidifying alloy. In turn, the size and structure of grains and dendrites influence properties of the solidified casting. Solidification time is a function of the volume and surface area of a casting (Chvorinov's rule).
- The grain structure of castings can be controlled by various means to obtain desired properties. Because most metals contract during solidification and cooling, cavities can form in the casting. Porosity caused by gases evolved during solidification can be a significant problem, particularly because of its adverse effect on the mechanical properties of castings. Various defects also can develop in castings from lack of control of material and process variables.
- Dimensional changes and cracking (hot tearing) are difficulties that can arise during solidification and cooling. Several basic categories of casting defects have been identified.
- Melting practices have a direct effect on the quality of castings, as do foundry operations such as pattern and mold making, pouring the molten metal, removing the cast parts from molds, cleaning, heat treatment, and inspection.

Key Terms

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

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Review Questions

10.1. Explain why casting is an important manufacturing process.

10.2. Why do most metals shrink when they are cast?

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

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

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

10.6. What is superheat? Is it important? What are the consequences of excessive superheat?

10.7. Define shrinkage and porosity. How can you tell whether cavities in a casting are due to porosity or to shrinkage?

10.8. What is the function of chills? What are they made of?

10.9. Why is the Reynolds number important in casting?

10.10. What is a sprue? What shape should a sprue have if a mold has no other choking means?

10.11. How is fluidity defined? Why is it important?

10.12. Explain the reasons for hot tearing in castings.

10.13. Why is it important to remove dross or slag during the pouring of molten metal into the mold? What methods are used to remove them?

10.14. Why is Bernoulli's equation important in casting?

10.15. Describe thixocasting and rheocasting.

10.16. What is Chvorinov's Rule?

10.17. How is a blister related to a scab?

Qualitative Problems

10.18. Is there porosity in a chocolate bar? In an ice cube? Explain.

10.19. Describe the stages involved in the contraction of metals during casting.

10.20. Explain the effects of mold materials on fluid flow and heat transfer in casting operations.

10.21. It is known that pouring metal at a high rate into a mold can have certain disadvantages. Are there any disadvantages to pouring it very slowly?

10.22. Describe the events depicted in Fig. 10.5.

10.23. Would you be concerned about the fact that portions of internal chills are left within the casting? Explain.

10.24. Review Fig. 10.10 and make a summary, explaining the purpose of each feature in shown and the consequences of omitting the feature from the mold design.

10.25. Make a sketch of volume vs. temperature for a metal that shrinks when it cools from the liquid state to room temperature. On the graph, mark the area where shrinkage is compensated by risers.

10.26. What practical demonstrations can you suggest to indicate the relationship of the solidification time to the volume and surface area of a casting?

10.27. Explain why a casting may have to be subjected to various heat treatments.

10.28. List and explain the reasons that porosity can develop in a casting.

10.29. Why does porosity have detrimental effects on the mechanical properties of castings? Would physical properties, such as thermal and electrical conductivity, also be adversely affected by porosity? Explain.

10.30. A spoked handwheel is to be cast in gray iron. In order to prevent hot tearing of the spokes, would you insulate the spokes or chill them? Explain.

10.31. Which of the following considerations are important for a riser to function properly? Must it: (a) have a surface area larger than the part being cast, (b) be kept open to atmospheric pressure, and/or (c) solidify first? Explain.

10.32. Explain why the constant C in Eq. (10.7) depends on mold material, metal properties, and temperature.

10.33. Are external chills as effective as internal chills? Explain.

10.34. Explain why, as shown in Table 10.1, gray cast iron undergoes expansion rather than contraction during solidification.

10.35. Referring to Fig. 10.13, explain why internal corners, such as A, develop a thinner skin than external corners, such as B, during solidification.

10.36. Note the shape of the two risers shown in Fig. 10.10, and discuss your observations with respect to Eq. (10.7).

10.37. Is there any difference in the tendency for shrinkage void formation in metals with short and long freezing ranges, respectively? Explain.

10.38. What is the influence of the cross-sectional area of the spiral channel shown in Fig. 10.11 on fluidity test results? What is the effect of sprue height? If this test is run with the entire test setup heated to elevated temperatures, would the results be more useful? Explain.

10.39. It has long been observed that (a) low pouring temperatures (*i.e.*, low superheat) promote the formation of equiaxed grains over columnar grains and (b) equiaxed grains become finer as the pouring temperature decreases. Explain these two phenomena.

10.40. In casting metal alloys, what would you expect to occur if the mold were agitated (vibrated) aggressively after the molten metal had been in the mold for a sufficient amount of time to form a skin?

10.41. If you inspect a typical cube of ice, you are likely to see air pockets and cracks in the cube. Some ice cubes, however, are tubular in shape and do not have noticeable air pockets or cracks in their structure. Explain this phenomenon.

10.42. How can you tell whether cavities in a casting are due to shrinkage or entrained air bubbles?

10.43. Describe the drawbacks to having a riser that is (a) too large and (b) too small.

10.44. Reproduce Fig. 10.2 for a casting that is spherical in shape.

10.45. List the process variables that affect the fluidity index as shown in Fig. 10.11.

10.46. Assume that you have a method of measuring porosity in a casting. Could you use this information to accurately predict the strength of the casting? Explain.

Quantitative Problems

10.47. Derive Eq. (10.5).

10.48. Sketch a plot of specific volume versus temperature for a metal that shrinks as it cools from the liquid state to room temperature. On the graph, mark the area where shrinkage is compensated for by risers.

10.49. A round casting is 0.3 m in diameter and 1 m in length. Another casting of the same metal is elliptical in cross section, with a major-to-minor axis ratio of 2, and has the same length and cross sectional area as the round casting. Both pieces are cast under the same conditions. What is the difference in the solidification times of the two castings?

10.50. A 75-mm thick square plate and a right circular cylinder with a radius of 100 mm and a height of 25 mm have the same volume. If each is to be cast with the use of a cylindrical riser, will each part require the same-size riser to ensure proper feeding? Explain.

10.51. Assume that the top of a round sprue has a diameter of 75 mm and is at a height of 150 mm from the runner. Based on Eq. (10.5), plot the profile of the sprue diameter as a function of its height. Assume that the sprue has a diameter of 5 mm at the bottom.

10.52. Pure aluminum is poured into a sand mold. The metal level in the pouring basin is 250 mm above the metal level in the mold, and the runner is circular with a 7.5 mm diameter. What is the velocity and rate of the flow of the metal into the mold? Is the flow turbulent or laminar?

10.53. A cylinder with a diameter of 50 mm and height of 75 mm solidifies in 3 minutes in a sand casting operation. What is the solidification time if the cylinder height is doubled? What is the time if the diameter is doubled?

10.54. The volume flow rate of metal into a mold is 0.05 m^3/s. The top of the sprue has a diameter of 30 mm, and its length is 200 mm. What diameter should be specified at the bottom of the sprue to prevent aspiration? What is the resultant velocity and Reynolds number at the bottom of the sprue if the metal being cast is aluminum with a viscosity of 0.004 Ns/m^2?

10.55. A rectangular mold with dimensions 120 mm $\times$ 240 mm $\times$ 480 mm is filled with aluminum with no superheat. Determine the final dimensions of the part as it cools to room temperature. Repeat the analysis for gray cast iron.

10.56. The constant C in Chvorinov's rule is given as 2.5 s/mm^2 and is used to produce a cylindrical casting with a diameter of 60 mm and height of 130 mm. Estimate the time for the casting to fully solidify. The mold can be broken safely when the solidified shell is at least 20 mm. Assuming that the cylinder cools evenly, how much time must transpire after pouring the molten metal before the mold can be broken?

10.57. A sprue is 300 mm long and has a diameter of 75 mm at the top. The molten metal level in the pouring basing (which is much larger than the top of the sprue) is taken to be 75 mm from the top of the sprue for design purposes. If a flow rate of 500 cm^3/s is to be achieved, what should be the diameter at the bottom of the sprue? Will the sprue aspirate? Explain.

10.58. Pure copper is poured into a sand mold. The metal level in the pouring basin is 250 mm above the metal level in the mold, and the runner is circular with a 10 mm diameter. What are the velocity and rate of the flow of the metal into the mold? Is the flow turbulent or laminar?

10.59. For the sprue described in Problem 10.58, what runner diameter is needed to ensure a Reynolds number of 2000? How long will a 250 cm^3 casting take to fill with such a runner?

10.60. How long would it take for the sprue in Problem 10.58 to feed a casting with a square cross section of 50 mm per side and a height of 100 mm? Assume that the sprue is frictionless.

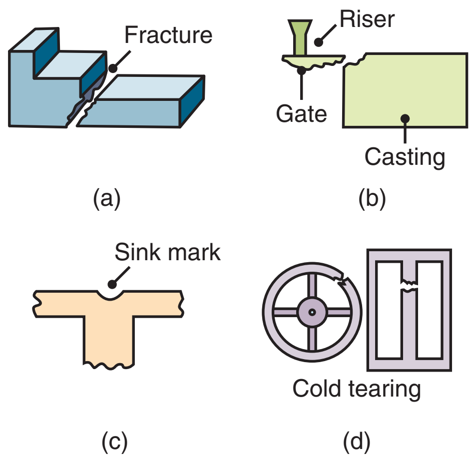
10.61. Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers to them.

10.62. When designing patterns for casting, pattern makers use special rulers that automatically incorporate solid shrinkage allowances into their designs. Therefore, a 100-mm patternmaker's ruler is longer than 100 mm. How long should a patternmaker's ruler be for (1) aluminum castings, (2) malleable cast iron, and (3) high manganese steel?

Synthesis, Design, and Projects

10.63. Can you devise fluidity tests other than that shown in Fig. 10.11? Explain the features of your test methods.

10.64. The illustration indicates various defects and discontinuities in cast products. Review each defect and offer solutions to avoid it.



10.65. The fluidity test shown in Fig. 10.11 illustrates only the principle of this test. Design a setup for such a test, showing the type of materials and the equipment to be used. Explain the method by which you would determine the length of the solidified metal in the spiral passage.

10.66. Utilizing the equipment and materials available in a typical kitchen, design an experiment to reproduce results similar to those shown in Fig. 10.13. Comment on your observations.

10.67. One method of relieving stress concentrations in a part is to apply a small, uniform plastic deformation to it. Make a list of your concerns and recommendations if such an approach is suggested for a casting.

10.68. Describe the effects on mold design, including the required change in the size of the risers, runners, chokes, and sprues, for a casting of a given shape that is to be doubled in volume.

10.69. Small amounts of slag often persist after skimming and are introduced into the molten-metal flow in casting. Recognizing that the slag is much less dense than the metal, design mold features that will remove small amounts of slag before the metal reaches the mold cavity.

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

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

Chapter 11

Metal-casting Processes and Equipment

Case Studies:

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

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

Alternative processes: Forging, powder metallurgy, additive manufacturing, machining, and fabrication.

11.1 Introduction

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

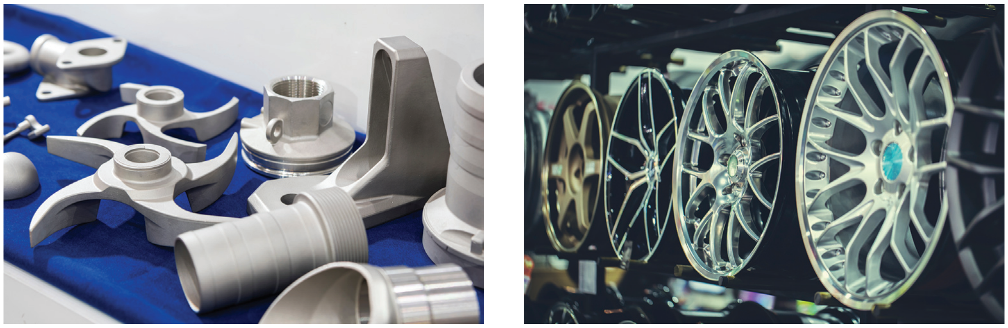
Four trends have had a major impact on the casting industry. (a) Mechanization and automation of the casting process, which has led to significant changes in the use of equipment and labor; advanced machinery and automated process-control systems have replaced or enhanced traditional methods of casting. (b) Increasing demand for high-quality castings with close dimensional tolerances. (c) Development of powerful modeling software, allowing predictive evaluation of dies and potential defects that result from poor design, as well as estimating a cast material's mechanical properties and its microstructure. This **Integrated Computer Materials Engineering** (ICME) trend has positively affected most manufacturing processes. (d) Additive manufacturing (Chapter 20) is still evolving, but has greatly aided mold manufacturing.

This chapter is organized around the major classifications of casting practices (see Fig. II.3 outlined in the Introduction to Part II), as they relate to mold materials, pattern production, molding processes, and methods of feeding the mold with molten metal. The major categories are:

1. **Expendable molds**, typically made of sand, plaster, ceramics, and similar materials, and generally mixed with various binders (*bonding agents*) for improved properties. A typical sand mold consists

Table 11.1: Summary of Casting Processes.

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



(a) (b)

Figure 11.1: (a) Examples of stainless steel castings. Note the intricate part shapes. (b) Die-cast magnesium automobile wheels. *Source:* (a) Shutterstock/Mr.1 (b) Shutterstock/socrates471.

of 90% sand, 7% clay, and 3% water. As described in Section 8.2, these materials are *refractories*, that is, they are capable of withstanding the high temperatures of molten metals. After the casting has solidified, the mold is broken up to remove the casting, hence the word *expendable*.

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

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

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

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

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

11.2 Expendable-mold, Permanent-pattern Casting Processes

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

Table 11.2: General Characteristics of Casting Processes.

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

Notes: 1. Relative rating, from 1 (best) to 5 (worst). Note that, for example, a die casting has relatively low porosity, mid-to-low shape complexity, high dimensional accuracy, high equipment and die costs, and low labor costs. These ratings are general, as significant variations can occur, depending on the particular production method.

2. Approximate values, without using rapid prototyping technologies. Minimum quantity is 1 when applying rapid prototyping.

Source: Data taken from J.A. Schey, *Introduction to Manufacturing Processes*, 3rd ed., McGraw-Hill, 2000.

11.2.1 Sand Casting

The traditional method of casting metals is using sand molds, and has been done for millennia. Sand casting is still the most prevalent form of casting, led by China (about 45 million metric tons per year), followed by India and the U.S. Typical applications of sand casting include machine bases, large turbine impellers, propellers, and plumbing fixtures. The capabilities of sand casting are given in Table 11.2.

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

Alternatively, a pattern can be machined directly into a sand preform. Since the strength of sand arises from its binders, machining can take place at high removal rates and can produce molds of high quality. An important and more recent development in mold and pattern making is the application of **additive manufacturing** (see Chapter 20) to directly produce molds. In sand casting, for example, a pattern can be binder-jet printed with complex shapes and self-supported cores to produce hollow sections, greatly easing mold assembly. There are several rapid prototyping techniques applicable to casting, and can produce molds or patterns; they are best suited for small production runs.

Sands. Most sand-casting operations use silica sand (SiO_2) as the mold material, although alternative sands and binders are under development, because of challenging health concerns associated with silica exposure in foundries. Sand is inexpensive and is suitable as a mold material because of its high-temperature characteristics and high melting point. There are two general types of sand: **naturally bonded** (*bank sand*) and **synthetic** (*lake sand*). Because its composition can be controlled more accurately, synthetic sand is preferred by most foundries.

Several factors are important in the selection of sand for molds, and certain tradeoffs with respect to properties have to be considered. Sand having fine, round grains can be packed closely, forming a smooth mold surface. Although fine-grained sand enhances mold strength, the fine grains also lower mold *permeability*. Good permeability of molds and cores allows gases and steam evolved during the casting process to escape easily. The mold also should have good *collapsibility*, in order to allow the casting to shrink while it is cooling, and thus prevent defects in the casting, such as hot tearing and cracking, shown in Fig. 10.14.

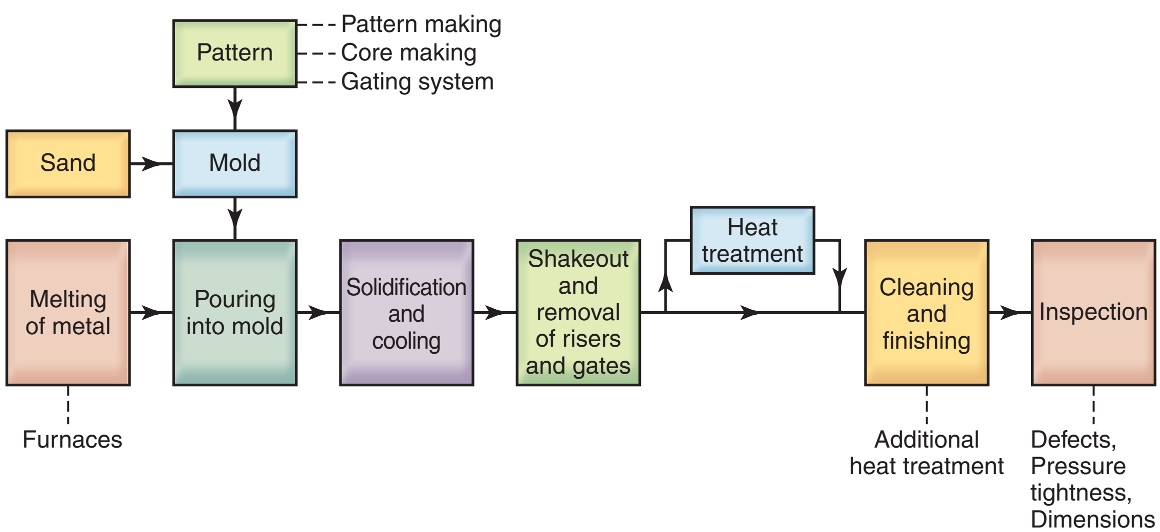


Figure 11.2: Outline of production steps in a typical sand-casting operation.

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

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

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

The major features of molds in sand casting are:

1. The **flask**, which supports the mold itself. Two-piece molds consist of a **cope** on top and a **drag** on the bottom; the seam between them is the *parting line*. When more than two pieces are used in a sand mold, the additional parts are called *cheeks*.

2. A **pouring basin** or **pouring cup**, into which the molten metal is poured.

3. A **sprue**, through which the molten metal flows downward by gravity.

4. The **runner system**, which has channels that carry the molten metal from the sprue to the mold cavity. **Gates** are the inlets into the mold cavity.

5. **Risers**, which supply additional molten metal to the casting as it shrinks during solidification. Two types of risers, a *blind riser* and an *open riser*, are shown in Fig. 11.3.

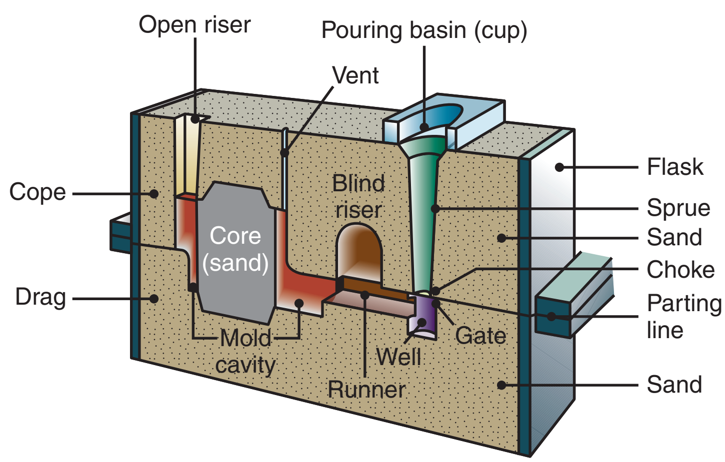


Figure 11.3: Schematic illustration of a sand mold, showing various features.

6. **Cores**, which are inserts made from sand and placed in the mold to form hollow regions or otherwise define the interior surface of the casting. Cores also are used on the outside of the casting to shape features, such as lettering and numbering.

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

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

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

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

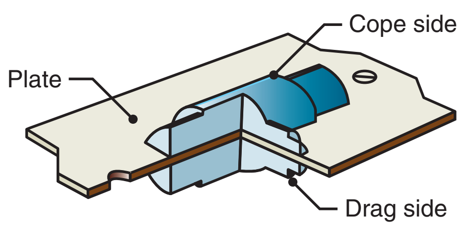


Figure 11.4: A typical metal match-plate pattern used in sand casting.

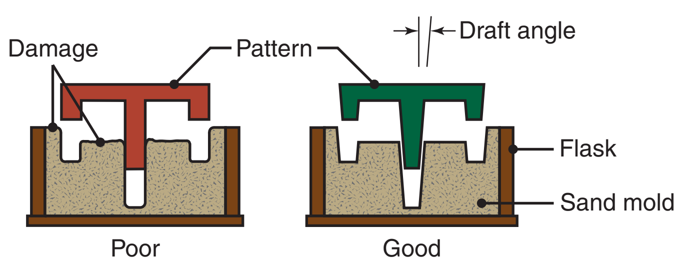


Figure 11.5: Taper on patterns for ease of removal from the sand mold.

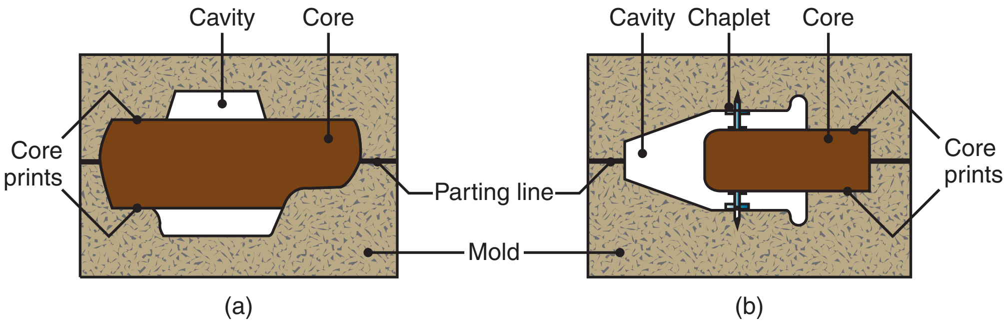


Figure 11.6: Examples of sand cores, showing core prints and chaplets to support the cores.

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

Cores are generally made in a manner similar to that used in sand mold making; most are made using shell (see Section 11.2.2), no-bake, or cold-box processes. Cores are shaped in *core boxes* and used in much the same way that patterns are used to form sand molds.

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

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

Sandslingers fill the flask uniformly with sand under a high-pressure stream; often automated, they are used to fill large flasks. An impeller in the machine throws sand from its blades or cups at such high speeds that the machine not only places the sand but also rams it sufficiently for proper packing.

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

In **vacuum molding** (also known as the *V process*), shown in Fig. 11.8, the pattern is covered tightly with a thin sheet of plastic. A flask is placed over the covered pattern and is then filled with dry, binderless sand. A second sheet of plastic is then placed on top of the sand, and a vacuum action compacts the sand. Both halves of the mold are made in this manner and are subsequently assembled. During pouring of the molten metal, the mold remains under a vacuum, but not the casting cavity. When the hot metal has solidified, the vacuum is turned off and the sand falls away, releasing the casting.

As shown in Fig. 11.8, vacuum molding does not require a draft in the part, and can be very economical because of the low tooling costs, long pattern life, and absence of binders in the sand (also simplifying sand recovery and reuse). Vacuum molding produces castings with high surface detail and dimensional accuracy; it is suited especially well for large, relatively flat (plane) castings.

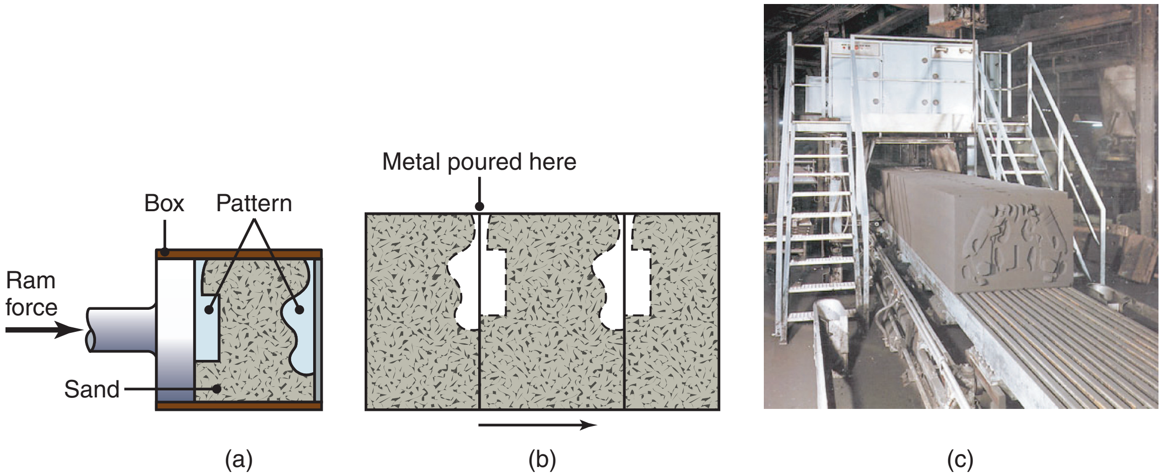


Figure 11.7: Vertical flaskless molding. (a) Sand is squeezed between two halves of the pattern. (b) Assembled molds pass along an assembly line for pouring. (c) A photograph of a vertical flaskless molding line. *Source:* Courtesy of American Foundry Society.

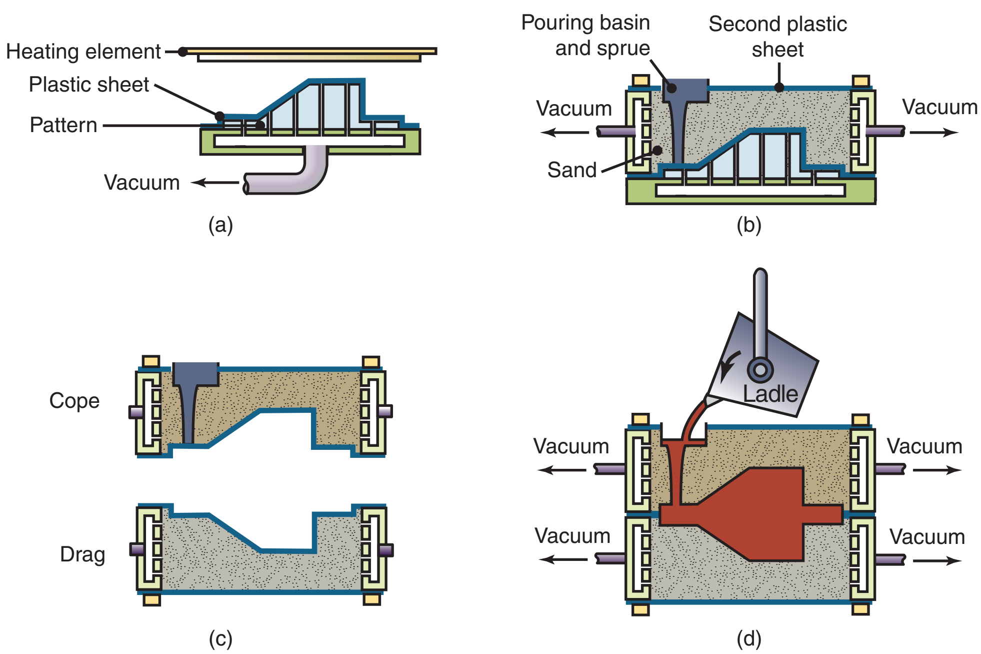


Figure 11.8: The vacuum molding process. (a) A plastic sheet is first thermoformed (see Section 19.6) over a pattern; (b) a vacuum flask is then placed over the pattern, a pouring basin/sprue insert is located, and the flask is filled with sand. A second sheet is located on the top of the sand mold, and a vacuum is applied to tightly compact the sand against the pattern. (c) A drag is also produced, along with cheeks, cores, etc., as in conventional sand casting. The cope and drag can be carefully transported without vacuum being applied. (d) After the mold halves are joined, a vacuum is applied to ensure mold strength, and molten metal is poured into the mold.

The Sand-casting Operation. After the mold has been shaped and the cores have been placed in their positions, the two mold halves (cope and drag) are closed, clamped, and weighted down, to prevent the separation of the mold sections under the pressure exerted when the molten metal is poured into the mold cavity. A complete sequence of operations in sand casting is shown in Fig. 11.9.

After solidification, the casting is shaken out of its mold, and the sand and oxide layers adhering to the casting are removed (by means of vibration, using a shaker, or by sand blasting). Castings are also cleaned

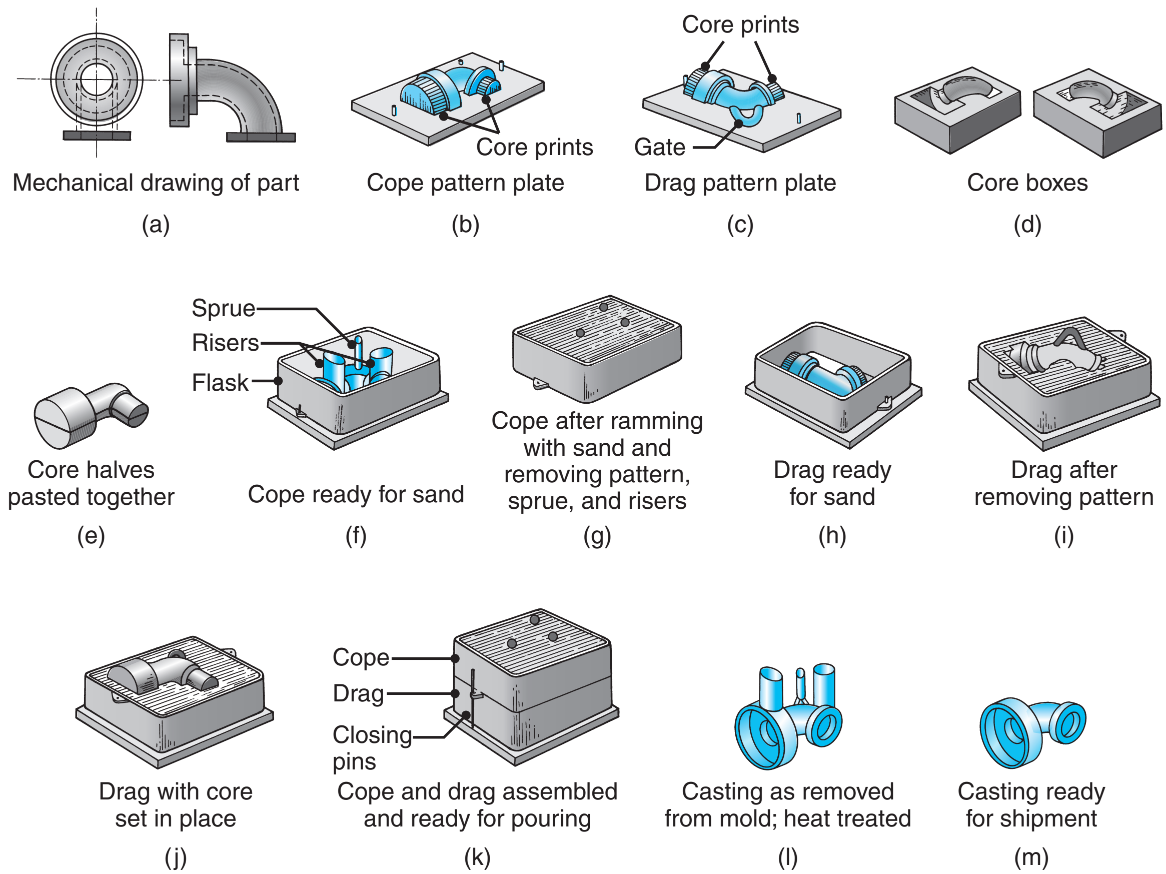


Figure 11.9: Schematic illustration of the sequence of operations for sand casting. (a) A mechanical drawing or CAD representation of the part is used to generate a design for the pattern. Considerations such as part shrinkage and draft must be included into the drawing. (b–c) Patterns have been mounted on plates equipped with pins for alignment. Note also the presence of core prints designed to hold the core in place. (d–e) Core boxes produce core halves, which are pasted together. The cores will be used to produce the hollow area of the part shown in (a). (f) The cope half of the mold is assembled by securing the cope pattern plate to the flask with aligning pins and attaching inserts to form the sprue and risers. (g) The flask is rammed with sand, and the plate and inserts are removed. (h) The drag half is produced in a similar manner, with the pattern inserted. A bottom board is placed below the drag and is aligned with pins. (i) The pattern, flask, and bottom board are inverted, and the pattern is withdrawn, leaving the appropriate imprint. (j) The core is set in place within the drag cavity. (k) The mold is closed by placing the cope on top of the drag and securing the assembly with pins. The flasks are then subjected to pressure to counteract buoyant forces in the molten metal, which might lift the cope. (l) After the metal solidifies, the casting is removed from the mold. (m) The sprue and risers are cut off and recycled, and the casting is cleaned, inspected, and heat treated (if necessary). *Source:* Courtesy of Steel Founders' Society of America.

by blasting with steel shot or grit (*shot blasting*; Section 26.8). The risers and gates are cut off either by oxyfuel-gas cutting, sawing, shearing, or abrasive wheels; they may also be trimmed in appropriate dies. Gates and risers on steel castings may also be removed with air carbon-arc cutting (Section 30.8) or torches. Castings may be further cleaned by electrochemical means or by pickling with chemicals to remove surface oxides (see Section 34.16).

The casting may subsequently be *heat treated* (Chapter 4) to improve certain properties required for its intended use; heat-treatment is particularly important for steel castings. *Finishing operations* may involve machining, straightening, or forging with dies (sizing) to obtain final dimensions. *Inspection* is an important final step, and is carried out to ensure that the casting meets all design and quality-control requirements.

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

Mold Ablation. Ablation can be used to improve the mechanical properties and production rates in sand casting. In this process, a sand mold is filled with molten metal, and the mold is then immediately sprayed with a liquid and/or gas solvent to progressively erode the sand. As the mold is exposed, the liquid stream causes rapid and directional solidification of the metal. With properly designed risers, mold ablation results in significantly lower porosity than conventional sand casting, leading to higher strength and ductility; it has therefore been applied to normally difficult-to-cast materials or for metal-matrix composites. Since ablation speeds up solidification and also removes cores, significant productivity improvements can also be achieved.

11.2.2 Shell Molding

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

The capabilities of **shell-mold casting** are given in Table 11.2. In this process, a mounted pattern, made of a ferrous metal or aluminum, is (a) heated to a range of 175°–370°C, (b) coated with a parting agent (such as silicone), and (c) clamped to a box or chamber. The box contains fine sand, mixed with 2.5–4% of a thermosetting resin binder (such as phenol-formaldehyde), which coats the sand particles. Either the box is rotated upside down (Fig. 11.10) or the sand mixture is blown over the pattern, allowing it to form a coating.

The assembly is then placed in an oven for a short period of time to complete curing of the resin. In most shell-molding machines, the oven consists of a metal box, with gas-fired burners that swing over the shell mold and cure it. The shell hardens around the pattern and is removed by means of built-in ejector pins. Two half-shells are made in this manner and are bonded or clamped together to form a mold.

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

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

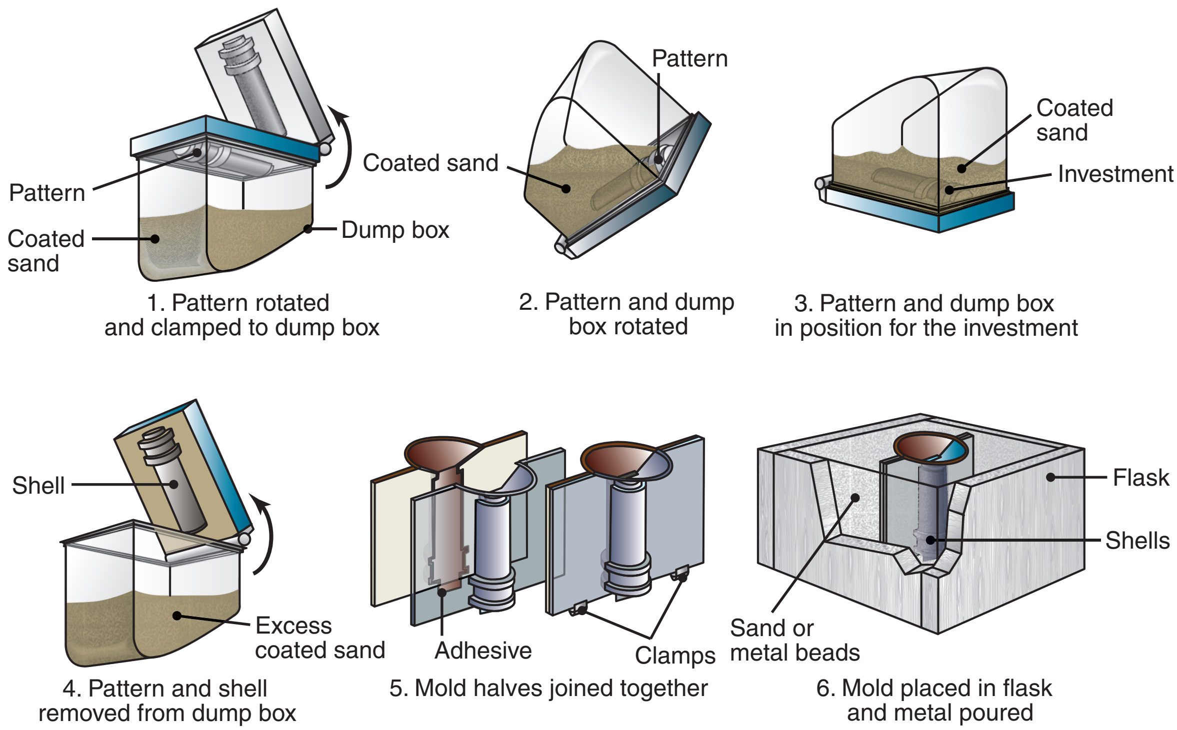


Figure 11.10: The shell-molding process, also called the dump-box technique.

11.2.3 Plaster-mold Casting

This process, and the ceramic-mold and investment casting processes (described in Sections 11.2.4 and 11.3.2) are known as **precision casting**, because of the high dimensional accuracy and good surface finish obtained. Typical parts made are lock components, gears, valves, fittings, tooling, and ornaments. They weigh in the range of 125–250 g, although parts as light as 1 g have been made. The capabilities of plaster-mold casting are given in Table 11.2.

In the *plaster-molding process*, the mold is made of plaster of paris (gypsum or calcium sulfate), with the addition of talc and silica powder to improve strength and to control the time required for the plaster to set. The three components are mixed with water and the slurry is poured over the pattern. After the plaster sets, usually within 15 minutes, it is removed and the mold is dried, at a typical temperature range of 120° to 260°C. The mold halves are then assembled to form the mold cavity and are preheated to about 120°C. The molten metal is then poured into the mold.

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

Patterns for plaster molding are generally made of aluminum alloys or thermosetting plastics, but brass or zinc alloys are also used. Since there is a limit to the maximum temperature that the plaster mold can withstand (generally about 1200°C), plaster-mold casting is used only for aluminum, magnesium, zinc, and some copper-based alloys. The castings have a good surface finish with fine details. Also, because plaster molds have lower thermal conductivity than other mold materials, the castings cool slowly; a more uniform grain structure is obtained and with less warpage. The wall thickness of the parts made can be as thin as 1 to 2.5 mm.

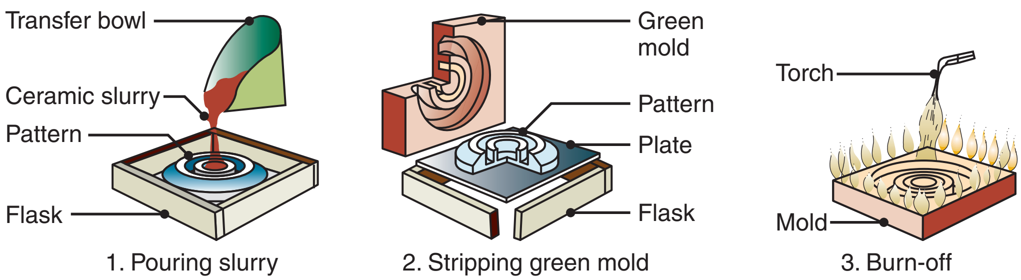


Figure 11.11: Sequence of operations in making a ceramic mold. *Source: Metals Handbook*, Vol. 5, 8th ed, ASM International, 1970.

11.2.4 Ceramic-mold Casting

This process, also called *cope-and-drag investment casting*, is similar to the plaster-mold process, except that it uses refractory mold materials suitable for high-temperature applications. A slurry is first produced from a mixture of fine-grained zircon ($ZrSiO_4$), aluminum oxide, fused silica, and bonding agents; this slurry is then poured over the pattern (Fig. 11.11) which has been placed in a flask. Typical parts made are impellers, cutters for machining operations, dies for metalworking operations, and molds for casting plastic and rubber components. Parts weighing as much as 700 kg have been cast by this process.

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

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

11.3 Expendable-mold, Expendable-pattern Casting Processes

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

11.3.1 Evaporative-pattern Casting (Lost-foam Process)

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

In this process, polystyrene beads, containing 5–8% pentane (a volatile hydrocarbon), are placed in a preheated die that is usually made of aluminum. Complex patterns may be made by bonding various individual pattern sections, using a hot-melt adhesive (Section 32.4.1). Polymethylmethacrylate (PMMA) and polyalkylene carbonate also may be used as pattern materials for ferrous castings.

The polystyrene expands and takes the shape of the die cavity; additional heat is applied to fuse and bond the beads together. The die is cooled and opened, and the polystyrene pattern is removed. The pattern is then coated with water-based refractory slurry, dried, and placed in a flask. The flask is filled with loose,

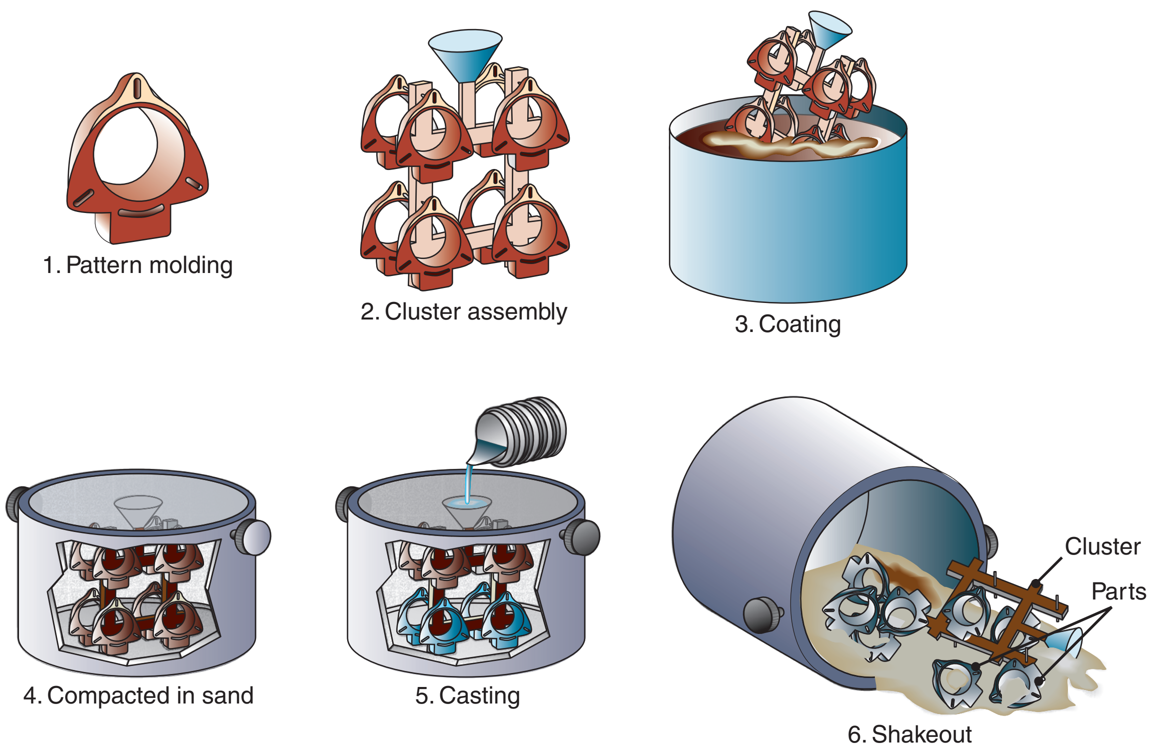


Figure 11.12: Schematic illustration of the expendable-pattern casting process, also known as lost-foam or evaporative-pattern casting.

fine sand, which surrounds and supports the pattern (Fig. 11.12), and may be dried or mixed with bonding agents to give it additional strength. The sand is compacted periodically, without removing the polystyrene pattern; then the molten metal is poured into the mold. The molten metal vaporizes the pattern and fills the mold cavity, completely replacing the space previously occupied by the polystyrene. Any degradation by-products from the polystyrene are vented into the surrounding sand.

Because the polymer requires considerable energy to degrade, large thermal gradients are present at the metal–polymer interfaces. In other words, the molten metal cools faster than it would if it were poured directly into an empty cavity; consequently, fluidity is less than in sand casting. This has important effects on the microstructure throughout the casting, and also leads to directional (columnar) solidification of the metal (see Section 10.2.3).

The evaporative-pattern process has several advantages over other casting methods:

- The process is relatively simple, because there are no parting lines, cores, or riser systems.
- The flasks used for the process are inexpensive.
- Polystyrene is inexpensive, and can be processed easily into patterns having complex shapes, various sizes, and fine surface detail.
- The casting requires minimal finishing and cleaning operations.
- The process can be automated and is economical for long production runs; however, the cost of producing the die and the need for two sets of tooling are significant factors to consider.

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

Case Study 11.1 Lost-foam Casting of Engine Blocks

One of the most important components in an internal combustion engine is the engine block. Industry trends have focused upon high-quality, low-cost and lightweight designs. Economic benefits can be gained through casting more complex geometries and by incorporating multiple components into one part. Recognizing that EPC can simultaneously satisfy all of these requirements, Mercury Castings built a lost-foam casting line to produce aluminum engine blocks and cylinder heads.

One example of a part produced through lost-foam casting is a 45-kW, three-cylinder engine block used for marine applications, such as an outboard motor on a small boat, and illustrated in Fig. 11.13c. Previously manufactured as eight separate die castings, the block was converted to a single 10-kg casting, with a weight and cost savings of 1 kg and $25, respectively, on each block. The casting chosen also allowed consolidation of the engine's cylinder head and the exhaust and cooling systems into the block, thus eliminating the associated machining operations and fasteners required in sand-cast or die-cast designs. Moreover, since the pattern contained holes, which could be cast without the need for cores, numerous drilling operations were eliminated.

Mercury Marine also was in the midst of developing a new V6 engine, utilizing a new corrosion-resistant aluminum alloy with increased wear resistance. This engine design also required the integration of the cylinder block and the engine head, featuring hollow sections for water jacket cooling that could not be cored out in die casting or semipermanent mold processes (which were used for other V6 blocks). Based on the success that the foundry had with the three-cylinder lost-foam block, engineers applied this process for casting the V6 die block (Fig. 11.13b). The new engine block involves only one casting, that is lighter and less expensive than the previous designs. Produced with an integrated cylinder head and exhaust and cooling system, this component is cast hollow to develop more efficient water jacket cooling of the engine during its operation.

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

Source: Courtesy of Mercury Marine.

11.3.2 Investment Casting

The *investment-casting* process, also called the **lost-wax process**, was first used during the period from 4000 to 3000 B.C. Typical parts made are components for office equipment and mechanical components, such as gears, cams, valves, and ratchets. Parts up to 1.5 m in diameter and weighing as much as 1140 kg have been cast successfully. The capabilities of investment casting are given in Table 11.3.

The sequence of operations involved in investment casting is shown in Fig. 11.14. The pattern is made of wax or of a plastic, such as polystyrene, by molding or rapid-prototyping techniques (Chapter 20). It

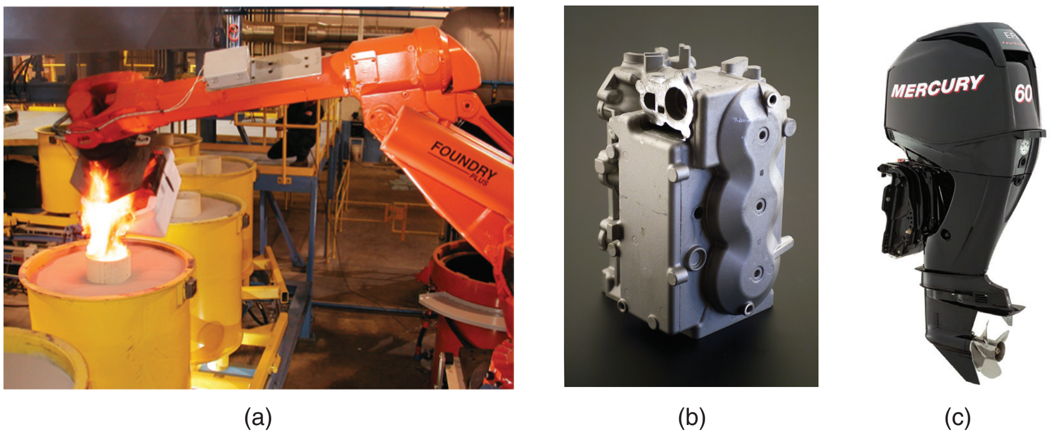


Figure 11.13: (a) Metal is poured into a mold for lost-foam casting of a 45-kW, three-cylinder marine engine; (b) finished engine block; (c) completed outboard motor. *Source:* Mercury Marine, a division of Brunswick Corporation.

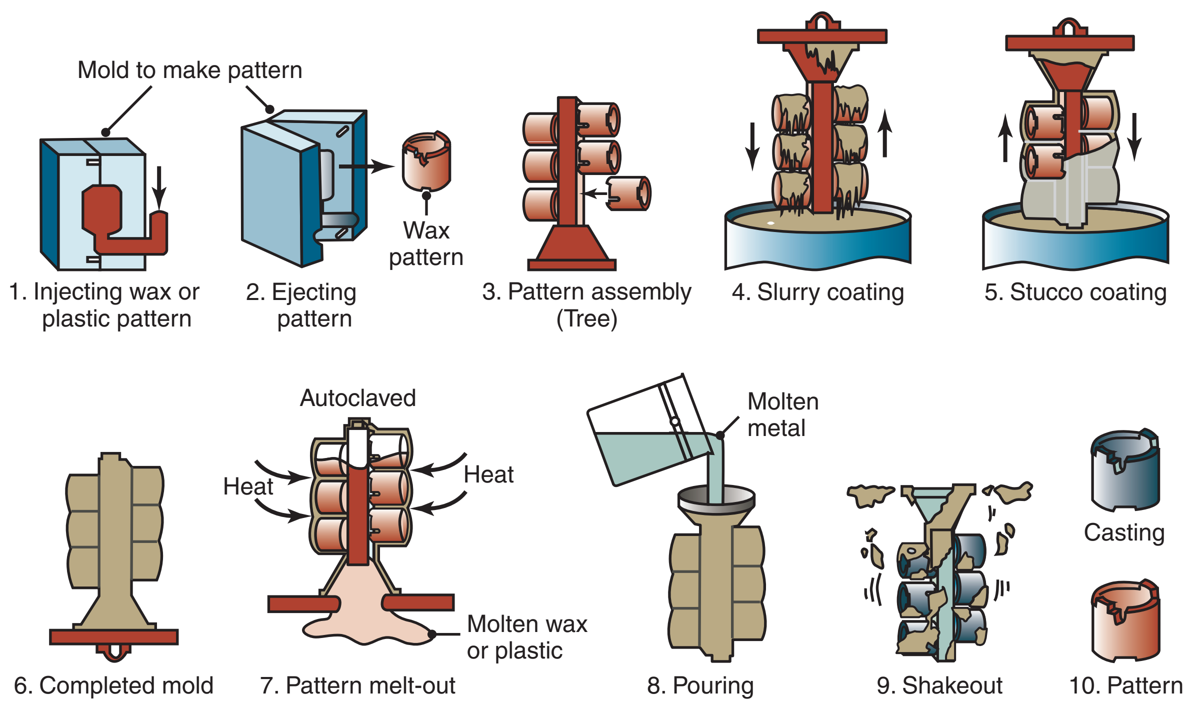


Figure 11.14: Schematic illustration of the investment-casting (lost-wax) process. Castings produced by this method can be made with very fine detail and from a variety of metals. *Source:* Courtesy of Steel Founders' Society of America.

is then dipped into a slurry of refractory material, such as very fine silica and binders, including water, ethyl silicate, and acids. After this initial coating has dried, the pattern is coated repeatedly to increase its thickness, for higher strength. Note that smaller particles can be used for the initial coating to develop a better surface finish in the casting; subsequent layers use larger particles and are intended to increase the coating thickness quickly.

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

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

A number of patterns can be joined together to make one mold, called a **tree** (Fig. 11.14), significantly increasing the production rate. For small parts, the tree can be inserted into a permeable flask and filled with a liquid slurry. The investment is then placed into a chamber and evacuated (to remove any air bubbles) until the mold solidifies. The flask is usually placed in a vacuum-casting machine, so that the molten metal is drawn into the permeable mold and onto the part, thus producing fine detail.

Although the mold materials and the labor involved make the lost-wax process costly, it is suitable for casting high-melting-point alloys, with good surface finish and close dimensional tolerances. Few or no finishing operations are required, which otherwise would add significantly to cost of the casting. The process is capable of producing intricate shapes from a wide variety of ferrous and nonferrous metals and alloys, with parts weighing from 1 g to 35 kg. Advances include the casting of titanium aircraft-engine and structural airframe components, with wall thicknesses on the order of 1.5 mm, thus competing with previously used sheet-metal structures (see Chapter 40).

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

The sequence of operations involved in making a turbine disk by this method is shown in Fig. 11.25. If the cores are made of ceramics, they are later removed by leaching with caustic solutions under high pressure and temperature. The molten metal may also be poured in a vacuum, to extract evolved gases and reduce oxidation, thus improving the casting quality. To further reduce microporosity, the castings made by this, as well as other processes, are subjected to hot isostatic pressing.

Case Study 11.2 Investment Casting of Total Knee Replacements

With major advances in medical care, life expectancies have increased significantly, so the expectations for the quality of life in the later years of a person's life remain high. One of the reasons for improvement has been the great success of orthopedic implants. Hip, knee, shoulder, spine, and other implants have resulted in greatly increased activity and reduced pain for millions worldwide.

An example of an orthopedic implant that has greatly improved quality of life is total knee replacement (TKR), as shown in Fig. 11.15a. TKRs are very popular and reliable for the relief of osteoarthritis, a chronic and painful degenerative condition of the knee joint that typically sets in after middle age. TKRs consist of multiple parts, including femoral, tibial, and patellar components. Typical materials used include cobalt alloys, titanium alloys, and ultrahigh-molecular-weight polyethylene (UHMWPE). Each material is chosen for specific properties important in the application of the implant.

This case study describes the investment casting of femoral components of TKRs, which are produced from cobalt–chrome alloy (Section 6.6). The manufacturing process begins with injection molding of the patterns, which are then hand assembled onto *trees*, as shown in Fig. 11.15b. The patterns are spaced properly on a central wax sprue; they are then welded in place by dipping them into molten wax and pressing them against the sprue until the patterns are held in place. The final assembled tree, shown in Fig. 11.16a, contains 12 knee implants arranged in four rows.

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

Figure 11.16 shows the progression of investment casting, from tree, to investment, to casting. A mold, ready for investment casting, is placed into a casting machine. The mold is placed upside down on the machine, directly over a measured volume of molten cobalt chrome alloy. The machine then rotates so that the metal flows into the mold, as shown in Fig. 11.15d. The tree is allowed to cool and the mold is removed; the cast parts are machined from the tree and are further machined and polished to the required surface finish and dimensional tolerance.

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

11.4 Permanent-mold Casting Processes

Permanent-mold casting processes have certain advantages over other casting processes, as described below.

11.4.1 Permanent-mold Casting

In *permanent-mold casting* (also called *hard-mold casting*), two halves of a mold are made from such materials as cast iron, steel, bronze, graphite, or refractory metal alloys, with high resistance to erosion and thermal fatigue. Typical parts made are automobile pistons, cylinder heads, connecting rods, gear blanks for appliances, and kitchenware. Parts that can be made economically typically weigh less than 25 kg, although special castings, weighing a few hundred kilograms, have been made using this process. The capabilities of permanent-mold casting are given in Table 11.3.

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

In order to increase the life of permanent molds, the surfaces of the mold cavity are usually coated with a refractory slurry, such as sodium silicate and clay, or are sprayed with graphite every few castings. These coatings also serve as parting agents and as thermal barriers, thus controlling the rate of cooling of the casting. Mechanical ejectors, such as pins located in various parts of the mold, may be required for the removal of complex castings. Ejectors usually leave small round impressions, which generally are not significant.

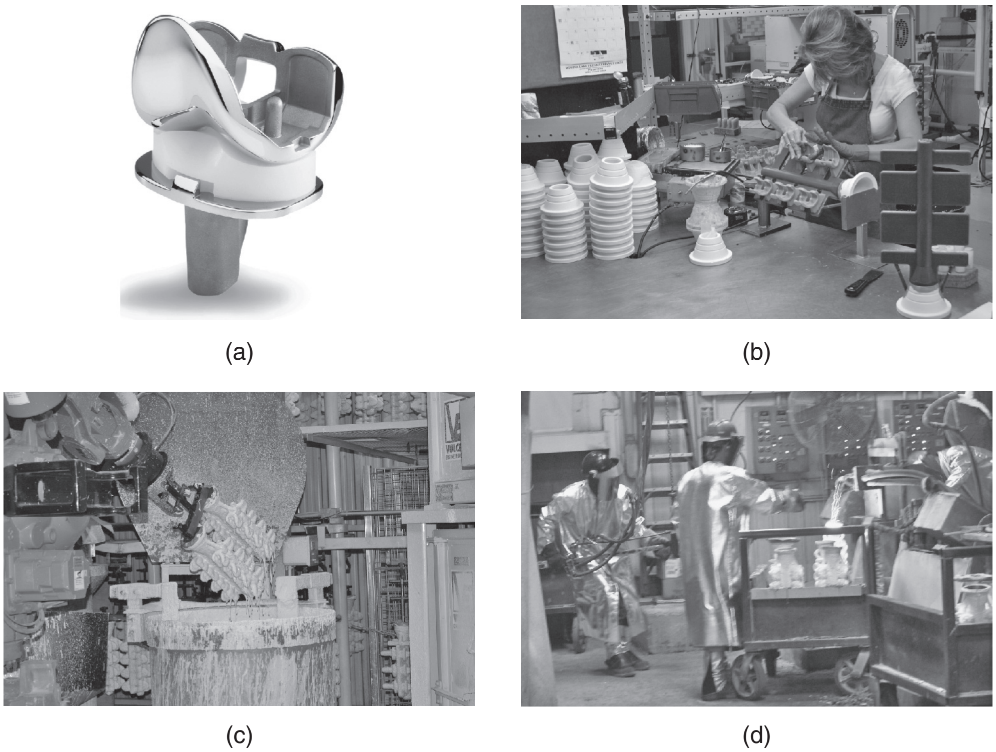


Figure 11.15: Manufacture of total knee replacements. (a) The Zimmer NexGen mobile-bearing knee (MBK); the femoral portion (top component) of the total knee replacement is the subject of Case Study 11.2. (b) Assembly of patterns onto a central tree. (c) Dipping of the tree into slurry to develop a mold from investment. (d) Pouring of metal into a mold. *Source:* Courtesy of M. Hawkins, Zimmer, Inc.

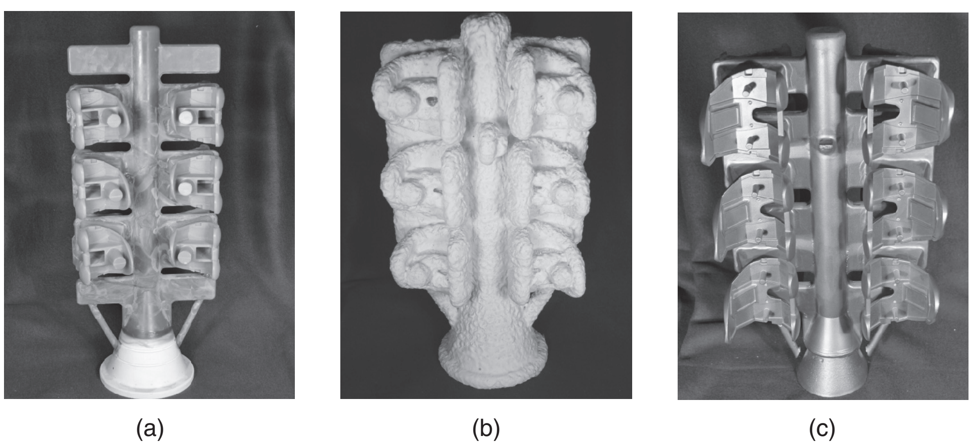


Figure 11.16: Progression of the tree. (a) After assembly of blanks onto the tree; (b) after coating with investment; (c) after removal from the mold. *Source:* Courtesy of M. Hawkins, Zimmer Biomet, Inc.

Table 11.3: Properties and Typical Applications of Some Common Die-casting Alloys. *Source:* American Die Casting Institute.

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

The two molds are clamped together by mechanical means, and heated to about 150° to 200°C to facilitate metal flow and reduce thermal damage to the dies. Molten metal is then poured through the gating system; after solidification, the molds are opened and the casting is removed. The mold often incorporates special cooling features, such as a means for pumping cooling water through the channels located in the mold and the use of cooling fins. Although the permanent-mold casting operation can be performed manually, it is often automated for large production runs.

This process is used mostly for aluminum, magnesium, and copper alloys, as well as for gray iron because of their generally lower melting points; however, steels also can be cast using graphite or heat-resistant metal molds. Permanent-mold casting produces castings with a good surface finish, close dimensional tolerances, uniform and good mechanical properties, and at high production rates.

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

11.4.2 Vacuum Casting

A schematic illustration of the *vacuum-casting* process, also called *countergravity low-pressure* (CL) *process* (not to be confused with the vacuum molding process described in Section 11.2.1) is shown in Fig. 11.17. Vacuum casting is an alternative to investment, shell-mold, and green-sand casting, and is suitable particularly for thin-walled complex shapes. With uniform properties, typical parts made are superalloy gas-turbine components with walls as thin as 0.5 mm.

In this process, a mixture of fine sand and urethane is molded over metal dies, and cured with amine vapor. The mold is then held with a robot arm and immersed partially into molten metal held in an induction furnace. The metal may be melted in air (*CLA process*) or in a vacuum (*CLV process*). The vacuum reduces the air pressure inside the mold to about two-thirds of the atmospheric pressure, thus drawing the molten metal into the mold cavities through a gate in the bottom of the mold. The metal in the furnace is

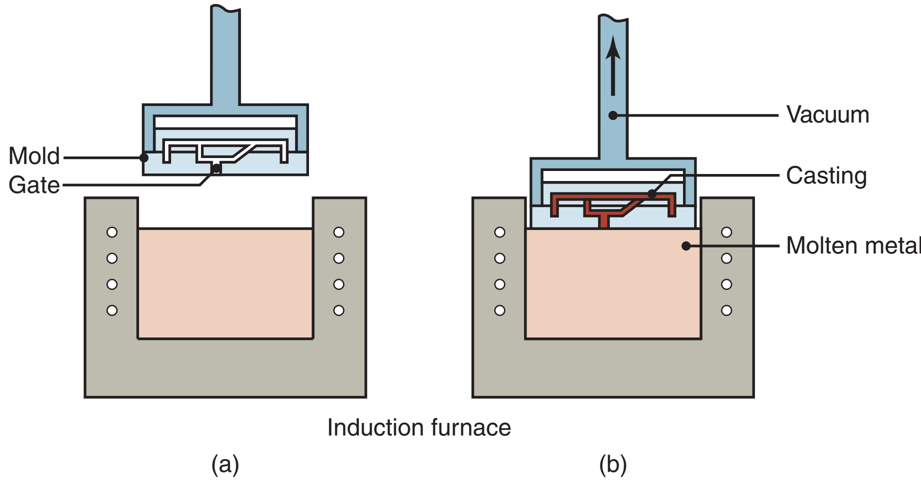


Figure 11.17: Schematic illustration of the vacuum-casting process. Note that the mold has a bottom gate. (a) Before and (b) after immersion of the mold into the molten metal. *Source:* After R. Blackburn.

usually at a temperature of 55°C above the liquidus temperature of the alloy; consequently, it begins to solidify within a very short time.

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

11.4.3 Slush Casting

Note in Fig. 10.13 that a solidified skin develops in a casting, which becomes thicker with time. Thin-walled hollow castings can be made by permanent-mold casting using this principle, in a process called *slush casting*. The molten metal is poured into the metal mold; after the desired thickness of solidified skin is obtained, the mold is inverted (or *slung*) and the remaining liquid metal is poured out. The mold halves are then opened and the casting is removed. Note that this operation is similar to making hollow chocolate shapes and other confectionaries. Slush casting is suitable for small production runs, and is generally used for making ornamental and decorative objects, such as lamp bases and stems, and toys from low-melting-point metals, such as zinc, tin, and lead alloys.

11.4.4 Pressure Casting

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

11.4.5 Die Casting

The *die-casting* process, developed in the early 1900s, is a further example of permanent-mold casting. The European term for this process is *pressure die casting*, and should not be confused with pressure casting, described in Section 11.4.4. Typical parts made by die casting are housings for transmissions, business-machine and appliance components, hand-tool components, and toys. The weight of most castings typically ranges from less than 90 g to about 25 kg. Equipment costs, particularly the cost of dies, are somewhat high, but labor costs are generally low when the process is semi- or fully automated. The capabilities of die casting are given in Table 11.3.

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

The **hot-chamber process** (Fig. 11.18) involves the use of a piston, which forces a specific volume of metal into the die cavity through a gooseneck and nozzle; pressures range up to 35 MPa, with an average of about 15 MPa. The metal is held under pressure until it solidifies in the die. To improve die life and to aid in rapid metal cooling (thereby reducing cycle time), dies are usually cooled by circulating water or oil through various passageways in the die block. Low-melting-point alloys, such as zinc, magnesium, tin, and lead, are commonly cast using this process. Cycle times usually range from 200 to 300 shots (individual injections) per hour for zinc, although very small components, such as zipper teeth, can be cast at rates of 18,000 shots per hour.

In the **cold-chamber process** (Fig. 11.19), molten metal is poured into the injection cylinder (*shot chamber*). The chamber is not heated, hence the term *cold chamber*. The metal is forced into the die cavity at pressures usually ranging from 20 to 70 MPa, although they may be as high as 150 MPa.

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

Freeze casting. Die casting can be used for *freeze casting* (see Section 10.2.4) to produce porous metals. In this case, the die is maintained at room temperature, thereby freezing a carrier fluid and separating a suspended powder; the cast part is then sintered (see Section 17.4).

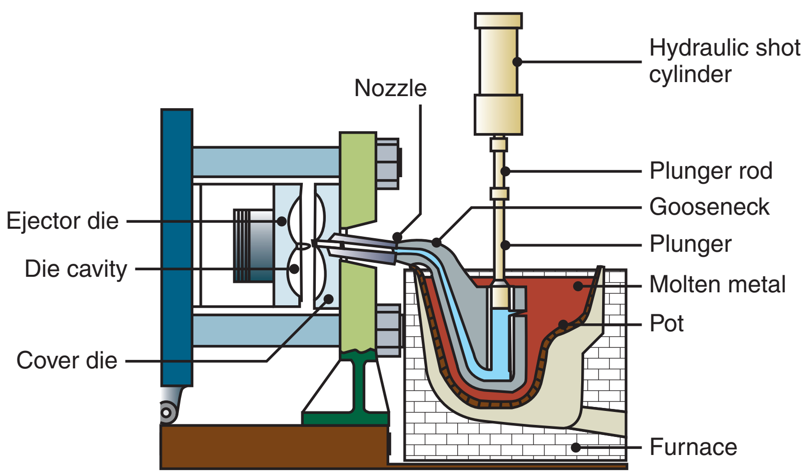


Figure 11.18: Schematic illustration of the hot-chamber die-casting process.

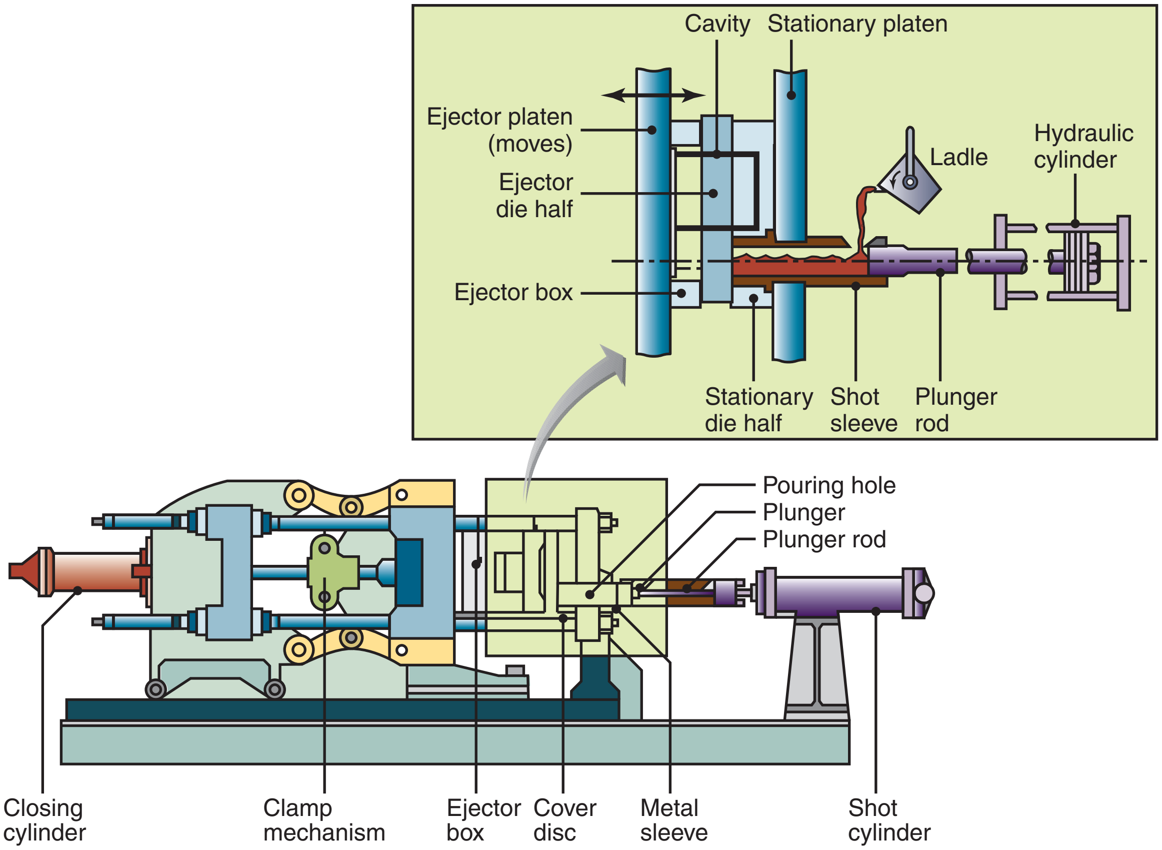


Figure 11.19: Schematic illustration of the cold-chamber die-casting process. These machines are large as compared to the size of the casting, because high forces are required to keep the two halves of the dies closed under pressure.

Process Capabilities and Machine Selection. Die casting has the capability for rapid production of high-quality parts with complex shapes, especially with aluminum, brass, magnesium, and zinc (Table 11.3). It also produces good dimensional accuracy and surface details, so that parts require little or no subsequent finishing operations (net-shape forming; Section 1.6). Because of the high pressures involved, walls as thin as 0.38 mm are produced, which are thinner than those obtained by other casting methods. However, ejector marks remain on part surfaces, as may small amounts of flash (thin material squeezed out between the dies at the die parting line).

Cycle time greatly depends on the ability of a die to extract heat from the molten metal. It is a common practice to incorporate cooling channels in the die, and to pump coolant through the cooling channels; the forced heat transfer keeps the die cool and allows continuous operation. **Conformal** or **contoured cooling** can be performed with dies produced in additive manufacturing; in this case, the cooling channels closely follow the contour of the mold to most efficiently extract heat from the desired location. Conformal cooling is described in greater detail in Section 20.10.

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

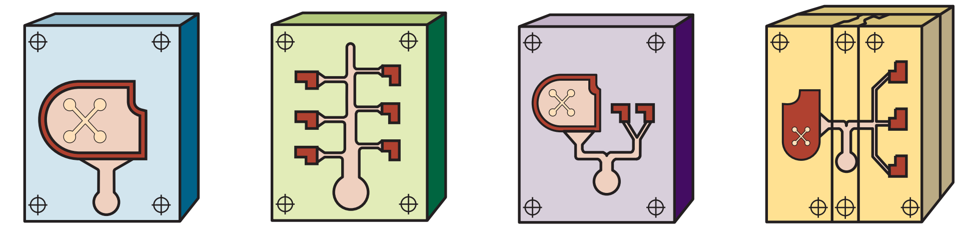


Figure 11.20: Various types of cavities in a die-casting die. *Source:* Courtesy of American Die Casting Institute.

surface finish and dimensional accuracy, die casting can produce smooth surfaces, such as for bearings, that otherwise would normally have to be machined.

Multimaterial components, such as pins, shafts, and certain threaded fasteners, can be die cast integrally. Called **insert casting**, this process is similar to placing wooden sticks in popsicles prior to freezing (see also Section 19.3). For high interfacial strength, insert surfaces may be knurled (see Fig. 23.11), grooved, or splined. Steel, brass, and bronze inserts are commonly used with die-casting alloys. In selecting insert materials, the possibility of *galvanic corrosion* should be taken into account. To avoid this potential problem, the insert can be insulated, plated, or surface treated.

Because of the high pressures involved, dies for die casting have a tendency to separate unless they are clamped together tightly (see Fig. 11.19). Die-casting machines are hence rated according to the clamping force that can be exerted to keep the dies closed during casting. The capacities of commercially available machines range from about 22.5 to 2700 metric tons. Other factors involved in the selection of die-casting machines are die size, piston stroke, shot pressure, various features, and cost.

Die-casting dies (Fig. 11.20) may be *single cavity, multiple cavity* (several identical cavities), *combination cavity* (several different cavities), or *unit dies* (simple, small dies that can be combined in two or more units in a master holding die). Typically, the ratio of die weight to part weight is 1000 to 1. Thus, for example, the die for a casting weighing 2 kg would weigh about 2000 kg. The dies are usually made of hot-work die steels or mold steels (see Section 5.7). **Heat checking** of dies (surface cracking from cyclic heating and cooling of the die, described in Section 3.6) can be a problem. When the die materials are selected and maintained properly, however, dies can last more than a half million shots before any significant die wear takes place.

Case Study 11.3 Die Casting of a Headlight Mount

Figure 11.22 shows a die-cast aluminum component of a daytime running lamp and turn signal for an automobile. Aluminum was preferable to plastic because of its higher heat-sink characteristics and rigidity, and also because tight tolerances were required for mounting and providing wiring access to LED bulbs. The fin size, thickness, and spacing were determined from a heat transfer analysis. The fins were tapered to allow for easy removal from a die, and the corner radii were designed to prevent distortion during ejection. The part was then oriented so that mounting holes and pockets were coplanar to the die parting line to simplify die fabrication. Heating channels were incorporated into the die near the thin sections to slow cooling, while cooling channels were incorporated near the thick sections. The resulting thermal balance led to lower distortion in the final product. The final product was cast from 380 aluminum; it measures $100 \times 75 \times 100$ mm for the turn signal and $250 \times 100 \times 50$ mm for the daytime running light sub-assembly.

Case Study 11.4 Die Cast Magnesium Liftgate

Figure 11.21 shows a complex high-pressure die-casting produced from a 2017 Chrysler Pacifica, and represents the first high-volume magnesium application of its kind in the automotive industry. The casting forms part of a four-piece assembly, with aluminum sheet upper and lower outer panels and a wiper reinforcement. The AM60B magnesium alloy part reduced the weight of the liftgate by more than 10 kg, representing a 50% reduction over the previous generation design. However, the liftgate affected the designs of the motor, strut, hinge, and other mechanical components, so that the weight savings was actually much greater.

Lightweighting strategies such as design optimization and exploitation of materials with high strength-to-weight ratios are common in automotive and aerospace applications so as to achieve ever increasing fuel economy goals. The original design was a weldment of seven steel stampings; the redesigned liftgate was combined into a single magnesium casting, with 10 spot welds and rivets compared to 84 in the original design. The thin-walled casting takes special care to extract the heat from the magnesium slowly, in order to prevent solidification in the mold and resulting underfills.

11.4.6 Centrifugal Casting

As its name implies, the *centrifugal-casting* process utilizes *inertia* (caused by rotation) to force the molten metal into the mold cavities, a method that was first suggested in the early 1800s. The capabilities of centrifugal casting are given in Table 11.3. There are three types of centrifugal casting: true centrifugal casting, semicentrifugal casting, and centrifuging.

Figure 11.21: A magnesium liftgate for a 2017 Chrysler Pacifica, saving more than 10 kg in weight over the previous generation steel stamping, and with reduction of welds from 84 to 10. Magnesium is increasingly used for vehicle lightweighting, and high-pressure die castings such as this one can be produced with thin walls and intricate part details. *Source:* Courtesy of American Foundry Society.

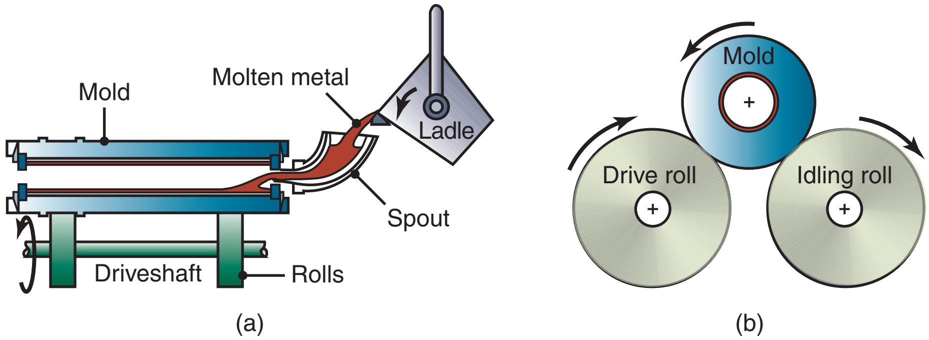


Figure 11.22: (a) Schematic illustration of the centrifugal-casting process. Pipes, cylinder liners, and similarly shaped parts can be cast with this process. (b) Side view of the machine.

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

Cylindrical parts ranging from 13 mm to 3 m in diameter and 16 m long can be cast centrifugally, with wall thicknesses ranging from 6 to 125 mm. The pressure generated by the centrifugal force is high (the angular acceleration can be as much as 150 times gravity); such high pressure is necessary for casting thick-walled parts. Castings with good quality, dimensional accuracy, and external surface detail are produced by this process.

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

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

11.4.7 Squeeze Casting and Semisolid-metal Forming

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

Squeeze Casting. The *squeeze-casting* or *liquid-metal forging* process was invented in the 1930s, but developed for industrial applications in the 1960s, and involves the solidification of molten metal under high pressure (Fig. 11.24). Typical products made are automotive components and mortar bodies (a cannon with a short body). The machinery includes a die, punch, and ejector pin. The pressure applied by the punch keeps the entrapped gases in solution, while the contact under high pressure at the die–metal interface

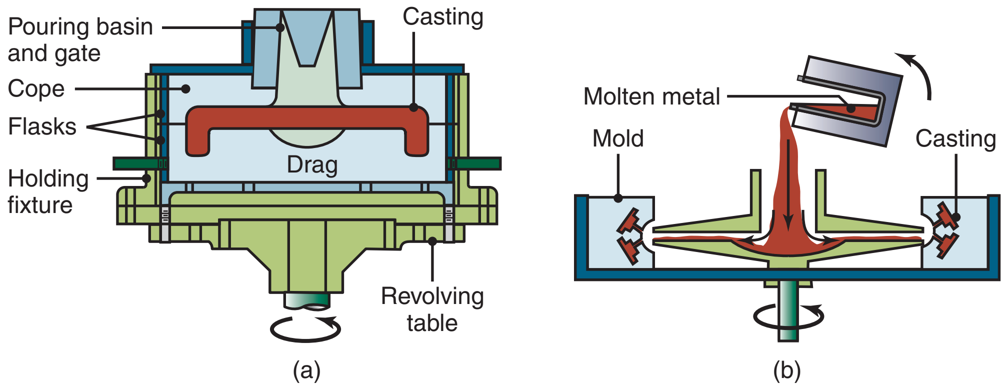


Figure 11.23: (a) Schematic illustration of the semicentrifugal casting process. Wheels with spokes can be cast by this process. (b) Schematic illustration of casting by centrifuging. The molds are placed at the periphery of the machine, and the molten metal is forced into the molds by centrifugal force.

promotes rapid heat transfer, thus resulting in a casting with a fine microstructure and good mechanical properties.

The application of pressure also overcomes hot-metal feeding difficulties that may arise when casting metals with a long freezing range (Section 10.2.2). Complex parts can be made to near-net shape, with fine surface detail from both nonferrous and ferrous alloys.

Semisolid-metal Forming. *Semisolid-metal forming*, also called *mushy-state processing* (see Fig. 10.4) was developed in the 1970s. When it enters the die, the metal (consisting of liquid and solid components) is stirred so that all of the dendrites are broken into fine solids. When cooled in the die, a fine-grained structure is developed. The alloy exhibits *thixotropic behavior*, described in Section 10.2.3, hence the process is also called **thixoforming** or **thixomolding**, meaning its viscosity decreases when agitated. Thus, at rest and above its solidus temperature, the molten alloy has the consistency of butter at room temperature, but when agitated vigorously, its consistency becomes more like that of motor oil.

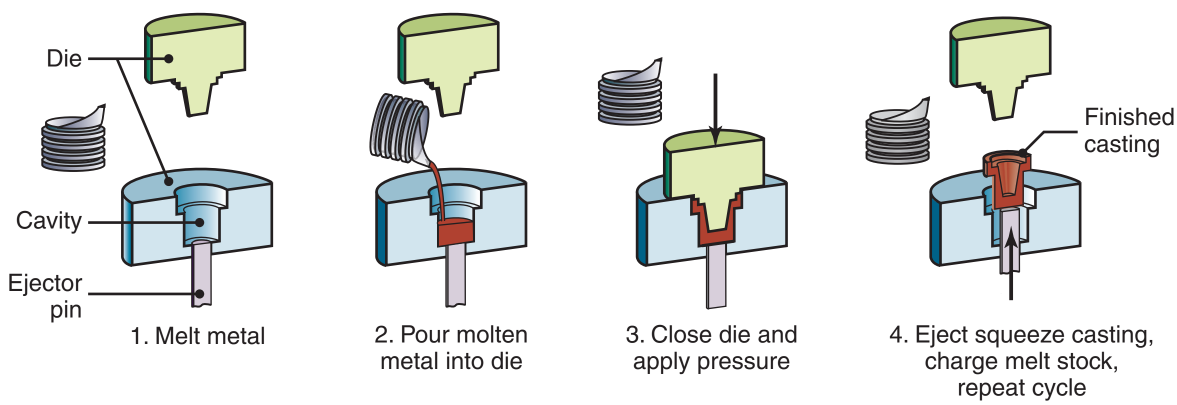


Figure 11.24: Sequence of operations in the squeeze-casting process. This process combines the advantages of casting and forging.

Processing metals in their mushy state also has led to developments in *mushy-state extrusion*, similar to injection molding (described in Section 19.3), *forging*, and *rolling* processes, hence the term *semisolid metalworking*. These processes are also used in making parts with specially designed casting alloys, wrought alloys, and metal-matrix composites (Section 9.5). They also have the capability for blending granules of different alloys, called *thixoblending*, for specific applications.

Thixotropic behavior has also been utilized in developing technologies that combine casting and forging, using cast billets that are then forged when the metal is 30–40% liquid. Parts made include automotive control arms, brackets, and steering components. Processing steels by thixoforming has not yet reached the same stage as with aluminum and magnesium, largely because of the high temperatures involved (which adversely affect die life) and the difficulty in making complex shapes.

The advantages of semisolid metal forming over die casting are: (a) the structures developed are homogeneous, with uniform properties, lower porosity, and high strength; (b) both thin and thick parts can be made; (c) casting alloys as well as wrought alloys can be used; (d) parts can subsequently be heat treated; and (e) the lower superheat results in shorter cycle times. However, material and overall costs are higher than those for die casting.

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

11.4.8 Composite-mold Casting Operations

Composite molds are made of two or more different materials and are used in shell molding and various other casting processes. They are generally employed in casting complex shapes, such as impellers for turbines. Composite molds increase the strength of the mold, improve the dimensional accuracy and surface finish of the castings, and can help reduce overall costs and processing time. Molding materials commonly used are shells (made as described in Section 11.2.2), plaster, sand with binder, metal, and graphite. These molds may include cores and chills to control the rate of solidification in critical areas of castings.

11.5 Casting Techniques for Single-crystal Components

This section describes the techniques used to cast single-crystal components, such as gas turbine blades which generally are made of nickel-based superalloys, and used in the hot stages of the engine.

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

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

Single-crystal Blades. In *crystal growing*, developed in the late 1960s, the mold has a constriction in the shape of a corkscrew or helix (Figs. 11.25b and c); its cross section is so small that it allows only one crystal

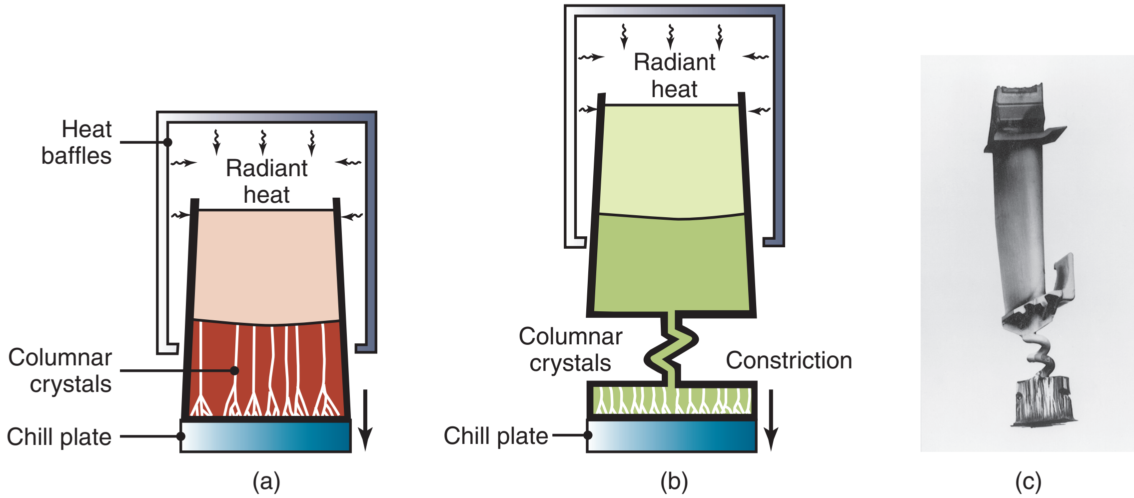


Figure 11.25: Methods of casting turbine blades: (a) directional solidification; (b) method to produce a single-crystal blade; (c) a single-crystal blade with the constriction portion still attached (see also Fig. 1.1). *Source:* (a) and (b) After B.H. Kear, (c) Courtesy of ASM International.

to fit through. The mechanism of crystal growth is such that only the most favorably oriented crystals are able to grow through the helix (a situation similar to that shown in Fig. 10.3), because all other crystals are intercepted by the walls of the helical passage.

As the assembly is slowly lowered, a single crystal grows upward through the constriction and begins to grow in the mold; strict control of the rate of movement is essential. Although single-crystal blades are more expensive than other types, the lack of grain boundaries makes them resistant to creep and thermal shock, hence they have a longer and more reliable service life.

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

- In the **crystal-pulling method**, also known as the **Czochralski** (CZ) **process** (Fig. 11.26), a seed crystal is dipped into the molten metal and then pulled out slowly, at a rate of about 10 μm/s, while being rotated. The liquid metal begins to solidify on the seed, and the crystal structure of the seed continues throughout. *Dopants* (Section 28.3) may be added to the liquid metal to impart specific electrical properties. Single crystals of silicon, germanium, and various other elements are grown using this process. Single-crystal ingots up to 400 mm in diameter and over 2 m in length have been produced by this technique, although 200- and 300-mm ingots are common in the production of silicon wafers for integrated circuit manufacture (Part V).

- The **floating-zone method** (Fig. 11.26b) starts with a rod of polycrystalline silicon resting on a single crystal; an induction coil then heats these two pieces while the coil moves slowly upward. The single crystal grows upward, while maintaining its orientation. Thin wafers are then cut from the rod (see Section 28.4), cleaned, and polished for use in microelectronic device fabrication. This process is suitable for producing diameters under 150 mm, with very low levels of impurities.

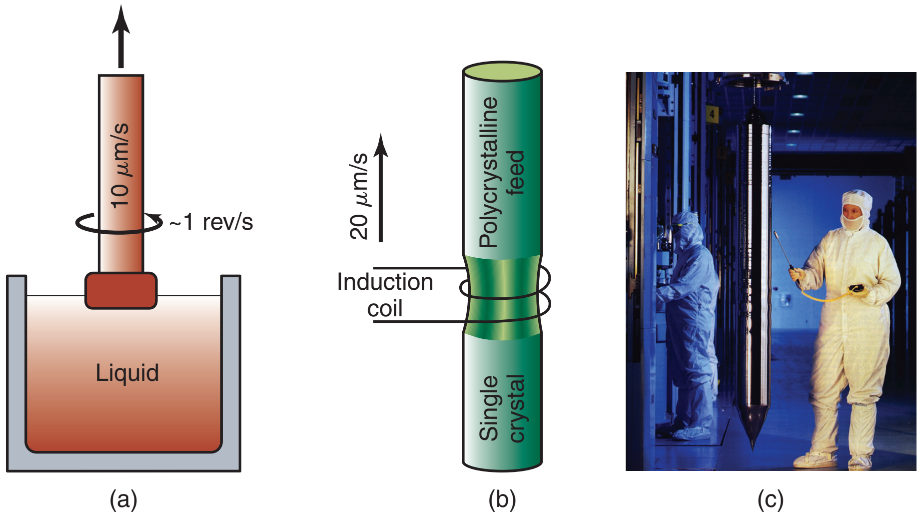


Figure 11.26: Two methods of crystal growing: (a) crystal pulling (Czochralski process) and (b) the floating-zone method. (c) A single-crystal ingot produced by the Czochralski process. *Source:* Courtesy of Intel Corp.

11.6 Rapid Solidification

The properties of *amorphous alloys*, also known as *metallic glasses*, are described in Section 6.15. The technique for making these alloys, called *rapid solidification*, involves cooling the molten metal at rates as high as 10^6 K/s so that it does not have sufficient time to crystallize (see also Fig. 1.11). Rapid solidification results in a significant extension of solid solubility (Section 4.2), grain refinement, and reduced microsegregation (see Section 10.2.3). Metallic glasses have very high strength but limited ductility; this behavior can be thought of as an extension of the Hall–Petch effect (see Section 1.5.1), where the grain size is on the order of one atom.

In a method called **melt spinning** (Fig. 19.6), the alloy is melted by induction in a ceramic crucible. It is then propelled, under high gas pressure, against a rotating copper disk (chill block), which rapidly chills the alloy (**splat cooling**), forming a metallic glass strip. Significant research is taking place to produce bulk forms of metallic glass.

11.7 Inspection of Castings

Several methods can be used to inspect castings to determine their quality and the presence and types of any defects. Castings can be inspected *visually*, or *optically*, for surface defects. Subsurface and internal defects are investigated using various *nondestructive* techniques, described in Section 36.10. In *destructive testing* (Section 36.11), specimens are removed from various locations in a casting, and tested for strength, ductility, and various other mechanical properties, and to determine the presence, location, and distribution of porosity and other defects.

Pressure tightness of cast components, such as valves, pumps, and pipes, is usually determined by sealing the openings in the casting, then pressurizing it with water, oil, or air. For leak tightness requirements in critical applications, pressurized helium or specially scented gases, with detectors (sniffers), are used. The casting is then inspected for leaks while the pressure is maintained; unacceptable or defective castings are remelted for reprocessing.

11.8 Melting Practice and Furnaces

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

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

1. **Electric arc** furnaces, described in Section 5.2.3 and illustrated in Fig. 5.2, are used extensively in foundries, because of their high rate of melting (thus high-production rate), much less pollution than other types, and their ability to hold the molten metal (keeping it at a constant temperature for a period of time) for alloying purposes.

2. **Induction** furnaces (Fig. 5.2c) are especially useful in smaller foundries, and produce composition-controlled melts. There are two basic types. (a) The *coreless induction furnace* consists of a crucible, surrounded with a water-cooled copper coil through which high-frequency current passes. Because there is a strong electromagnetic stirring action during induction heating, this type of furnace has excellent mixing characteristics and is used for alloying and adding a new charge of metal into the furnace. (b) A core or channel furnace, uses low-frequency current (as low as 60 Hz), and has a coil that surrounds only a small portion of the unit. These furnaces are commonly used in nonferrous foundries, and are particularly suitable for *superheating* (heating above normal casting temperature to improve fluidity), for *holding*, which makes it suitable for die-casting applications, and for *duplexing* (using two furnaces: melting the metal in one furnace and then transferring it to another).

3. **Crucible** furnaces (Fig. 11.27a), which have been used extensively throughout history, are heated using various fuels, such as commercial gases, fuel oil, and fossil fuel, and with electricity. Crucible furnaces may be stationary, tilting, or movable.

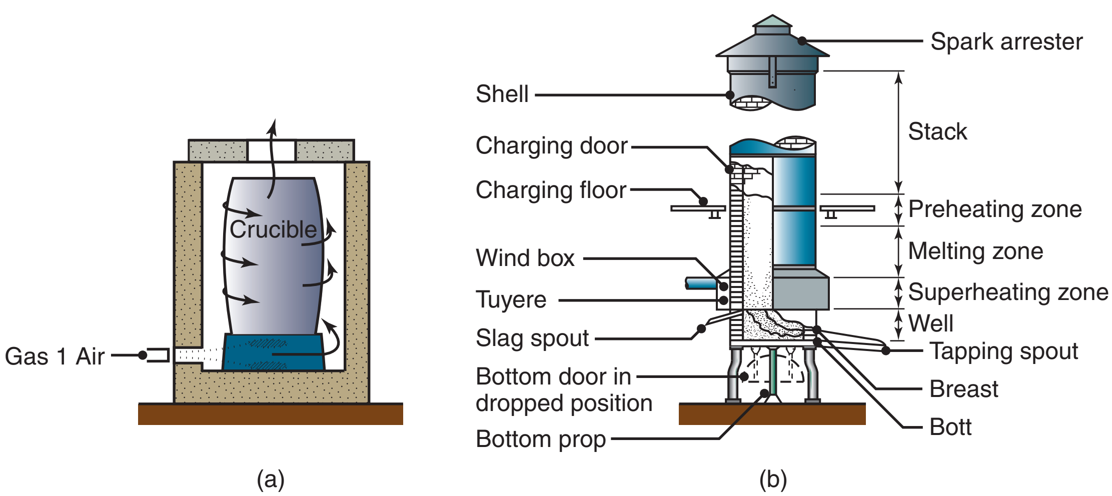


Figure 11.27: Two types of melting furnaces used in foundries: (a) crucible and (b) cupola.

4. **Cupolas** are basically vertical refractory-lined steel vessels, charged with alternating layers of metal, coke, and flux (Fig. 11.27b). Although they require major investments and are increasingly replaced by induction furnaces, cupolas operate continuously, have high melting rates, and produce large amounts of molten metal.

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

11.9 Foundries and Foundry Automation

Casting operations are carried out in **foundries** (from the Latin *fundere*, meaning melting and pouring). Although these operations traditionally have involved much manual labor, modern foundries have efficient automated and computer-integrated facilities for all aspects of their operations.

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

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

Summary

- Expendable-mold, permanent-pattern processes include sand, shell-mold, plaster-mold, and ceramic-mold casting. These processes require the destruction of the mold for each casting produced, but mold production is facilitated by a reusable pattern.

- Expendable-mold, expendable-pattern processes include lost-foam and investment casting. In these processes, a pattern is consumed for each mold produced, and the mold is destroyed after each casting.

- Permanent-mold processes have molds or dies that can be used to produce castings at high production rates. Common permanent-mold processes include slush casting, pressure casting, die casting, and centrifugal casting.

- The molds used in permanent-mold casting are made of metal or graphite, and are used repeatedly to produce a large number of parts. Because metals are good heat conductors but do not allow gases to escape, permanent molds have fundamentally different effects on castings than sand or other aggregate mold materials.

- In permanent-mold casting, die and equipment costs are relatively high, but the processes are economical for large production runs. Scrap loss is low, dimensional accuracy is relatively high, and good surface details can be achieved.

- Casting processes include squeeze casting (a combination of casting and forging), semisolid-metal forming, rapid solidification (for the production of amorphous alloys), and the casting of single-crystal components (such as turbine blades and silicon ingots for making wafers in integrated-circuit manufacture).
- Melting processes and their control are important factors in casting operations. They include proper melting of the metals, preparation for alloying and removal of slag and dross, and pouring the molten metal into the molds. Inspection of castings for possible internal or external defects also is essential.
- Castings are generally subjected to subsequent processing, such as heat treatment and machining operations, to produce the final desired shapes, surface characteristics, and the required surface finish and dimensional accuracy.

Key Terms

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

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Review Questions

11.1. Describe the differences between expendable and permanent molds.

11.2. Name the important factors in selecting sand for molds.

11.3. What are the major types of sand molds? What are their characteristics?

11.4. List important considerations when selecting pattern materials.

11.5. What is the function of a core?

11.6. What is the difference between sand-mold and shell-mold casting?

11.7. What are composite molds? Why are they used?

11.8. Describe the features of plaster-mold casting.

11.9. Name the type of materials typically used for permanent-mold casting processes.

11.10. What are the advantages of pressure casting over other processes?

11.11. List the advantages and limitations of die casting.

11.12. What is the purpose of a riser? What is a blind riser?

11.13. Explain the purpose of a vent and a runner in a casting mold.

11.14. How are shell molds produced?

11.15. What keeps the mold together in vacuum casting?

11.16. What is squeeze casting? What are its advantages?

11.17. What are the advantages of the lost-foam casting process?

11.18. How are single-crystal turbine blades produced?

Qualitative Problems

11.19. What are the reasons for the large variety of casting processes that have been developed over the years? Explain with specific examples.

11.20. Why are risers not as useful in die casting as they are in sand casting?

11.21. Describe the drawbacks to having a riser that is (a) too large and (b) too small.

11.22. Why can blind risers be smaller than open-top risers?

11.23. Why does die casting produce the smallest cast parts?

11.24. Why is the investment-casting process capable of producing fine surface detail on castings?

11.25. What differences, if any, would you expect in the properties of castings made by permanent-mold versus sand-casting processes?

11.26. Recently, cores for sand casting have been produced from salt. What advantages and disadvantages would you expect from using salt cores?

11.27. Would you recommend preheating the molds used in permanent-mold casting? Would you remove the casting soon after it has solidified? Explain your reasons.

11.28. Give reasons for, and examples of, using die inserts.

11.29. Referring to Fig. 11.3, do you think it is necessary to weigh down or clamp the two halves of the mold? Explain your reasons. Do you think that the kind of metal cast, such as gray cast iron versus aluminum, should make a difference in the clamping force? Explain.

11.30. Explain why squeeze casting produces parts with better mechanical properties, dimensional accuracy, and surface finish than do expendable-mold processes.

11.31. How are the individual wax patterns attached on a "tree" in investment casting?

11.32. Describe the measures that you would take to reduce core shifting in sand casting.

11.33. You have seen that, even though die casting produces thin parts, there is a limit to how thin they can be. Why can't even thinner parts be made by this process?

11.34. How are hollow parts with various cavities made by die casting? Are cores used? If so, how? Explain.

11.35. It was stated that the strength-to-weight ratio of die-cast parts increases with decreasing wall thickness. Explain why.

11.36. How are risers and sprues placed in sand molds? Explain, with appropriate sketches.

11.37. In shell-mold casting, the curing process is critical to the quality of the finished mold. In this stage of the process, the shell-mold assembly and cores are placed in an oven for a short period of time to complete the curing of the resin binder. List probable causes of unevenly cured cores or of uneven core thicknesses.

11.38. Why does the die-casting machine shown in Fig. 11.19 have such a large mechanism to close the dies? Explain.

11.39. Chocolate forms are available in hollow shapes. What process should be used to make these chocolates?

11.40. What are the benefits to heating the mold in investment casting before pouring in the molten metal? Are there any drawbacks? Explain.

11.41. The "slushy" state of alloys refers to that state between the solidus and liquidus temperatures, as described in Section 10.2.2. Pure metals do not have such a slushy state. Does this mean that pure metals cannot be slush cast? Explain.

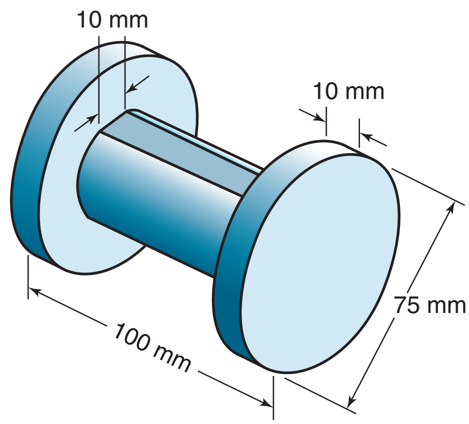
11.42. Can a chaplet also act as a chill? Explain.

11.43. Rank the casting processes described in this chapter in terms of their solidification rate. (That is, which processes extract heat the fastest from a given volume of metal?)

Quantitative Problems

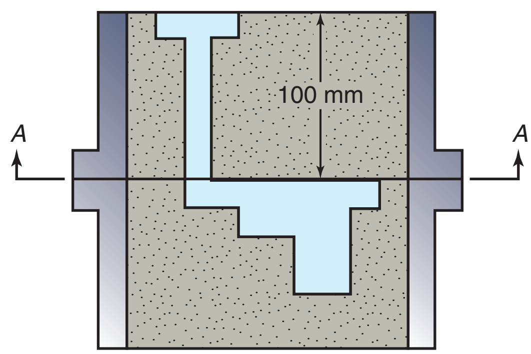
11.44. Estimate the clamping force for a die-casting machine in which the casting is rectangular with projected dimensions of 125 mm $\times$ 175 mm. Would your answer depend on whether it is a hot-chamber or cold-chamber process? Explain.

11.45. The blank for the spool shown below is to be sand cast out of A-319, an aluminum casting alloy. Make a sketch of the wooden pattern for this part, and include all necessary allowances for shrinkage and machining.

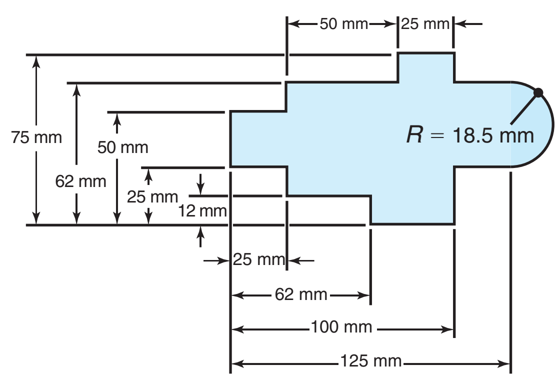


11.46. Repeat Problem 11.45, but assume that the aluminum spool is to be cast by expendable-pattern casting. Explain the important differences between the two patterns.

11.47. In sand casting, it is important that the cope-mold half be weighted down with sufficient force to keep it from floating when the molten metal is poured in. For the casting shown below, calculate the minimum amount of weight necessary to keep the cope from floating up as the molten metal is poured in. (*Hint:* The buoyancy force exerted by the molten metal on the cope is dependent on the effective height of the metal head above the cope.)



Section *A–A*



Material: Low-carbon steel
Density: 7196 kg/m^3
All dimensions in inches

11.48. If an acceleration of 125 g is necessary to produce a part in true centrifugal casting and the part has an inner diameter of 300 mm, a mean outer diameter of 400 mm, and a length of 8 m, what rotational speed is needed?

11.49. A jeweler wishes to produce 20 gold rings in one investment-casting operation. The wax parts are attached to a wax central sprue with a 20-mm diameter. The rings are located in four rows, each 15 mm from the other on the sprue. The rings require a 3-mm diameter, 12-mm long runner to the sprue. Estimate the weight of gold needed to completely fill the rings, runners, and sprues. Assume a typical ring has a 25-mm outer diameter, 19-mm inner diameter, and 5-mm width. The specific gravity of gold is 19.3.

11.50. Assume that you are an instructor covering the topics described in this chapter, and you are giving a quiz on the numerical aspects of casting processes to test the understanding of the students. Prepare two quantitative problems and supply the answers.

Synthesis, Design, and Projects

11.51. Describe the procedures that would be involved in making a large outdoor bronze statue. Which casting process(es) would be suitable? Why?

11.52. The optimum shape of a riser is spherical to ensure that it cools more slowly than the casting it feeds. However, spherically shaped risers are difficult to cast. (a) Sketch the shape of a blind riser that is easy to mold, but also has the smallest possible surface-area-to-volume ratio. (b) Compare the solidification time of the riser in part (a) with that of a riser shaped like a right circular cylinder. Assume that the volume of each riser is the same and the height of each is equal to the diameter. (See Example 10.1.)

11.53. Sketch and describe a casting line consisting of machinery, conveyors, robots, sensors, etc., that automatically could perform the expendable-pattern casting process.

11.54. Outline the casting processes that would be most suitable for making small toys. Explain your choices.

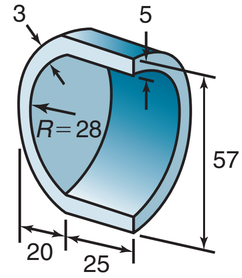
11.55. Make a list of the mold and die materials used in the casting processes described in this chapter. Under each type of material, list the casting processes that are employed and explain why these processes are suitable for that particular mold or die material.

11.56. Write a brief report on the permeability of molds and the techniques that are used to determine permeability.

11.57. Light metals commonly are cast in vulcanized rubber molds. Conduct a literature search and describe the mechanics of this process.

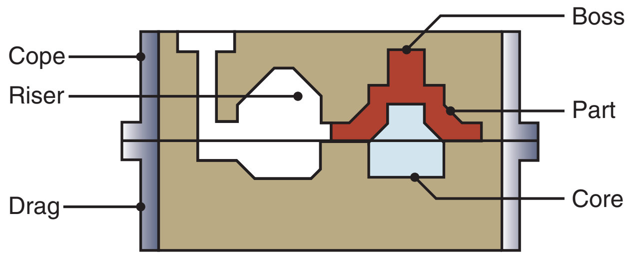
11.58. It sometimes is desirable to cool metals more slowly than they would be if the molds were maintained at room temperature. List and explain the methods you would use to slow down the cooling process.

11.59. The part shown below is a hemispherical shell used as an acetabular (mushroom-shaped) cup in a total hip replacement. Select a casting process for making this part, and provide a sketch of all the patterns or tooling needed if it is to be produced from a cobalt–chrome alloy.



Dimensions in mm

11.60. Porosity that has developed in the boss of a casting is illustrated below. Show that the porosity can be eliminated simply by repositioning the parting line of this casting.



11.61. Review Fig. II.1b, and note that the gemstones have been cast in place. Design a ring with a means of securing a gemstone in the wax pattern, such that it will remain in the mold as the wax is being melted. Could such an approach be used in lost foam casting?