Part III Solidification Processes

10 Fundamentals of Metal Casting

Chapter Contents

This part of the book covers those manufacturing processes in which the starting work material is either a liquid or is in a highly plastic condition, and a part is created through solidification of the material. Casting and molding processes dominate this category of shaping operations. With reference to Figure 10.1, the solidification processes can be classified according to the engineering material that is processed: (1) metals, (2) ceramics, specifically glasses,[1] and (3) polymers and polymer matrix composites (PMCs). Casting of metals is covered in this and the following chapter. Glassworking is covered in Chapter 12, and the processing of polymers and PMCs is treated in Chapters 13 and 14.

Casting is a process in which molten metal flows by gravity or other force into a mold where it solidifies in the shape of the mold cavity. The term *casting* is also applied to the part that is made by this process. It is one of the oldest shaping processes, dating back 6000 years (Historical Note 10.1). The principle of casting seems simple: melt the metal, pour it into a mold, and let it cool and solidify; yet there are many factors and variables that must be considered in order to accomplish a successful casting operation.

Casting includes both the casting of ingots and the casting of shapes. The term *ingot* is usually associated with the primary metals industries; it describes a large casting that is simple in shape and intended for

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[1]Among the ceramics, only glass is processed by solidification; traditional and new ceramics are shaped using particulate processes (Chapter 16).
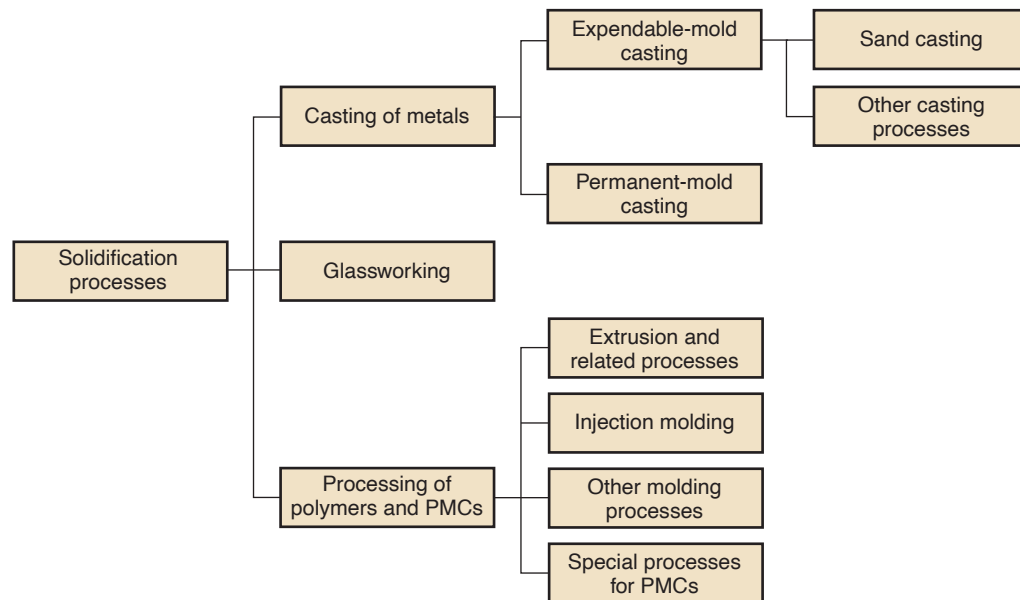
FIGURE 10.1   Classification of solidification processes.

Historical Note 10.1   *Origins of casting*

Casting of metals can be traced back to around 4000 B.C.E. Gold was the first metal to be discovered and used by the early civilizations; it was malleable and could be readily hammered into shape at room temperature. There seemed to be no need for other ways to shape gold. It was the subsequent discovery of copper that gave rise to the need for casting. Although copper could be forged to shape, the process was more difficult (due to strain hardening) and limited to relatively simple forms. Historians believe that hundreds of years elapsed before the process of casting copper was first performed, probably by accident during the reduction of copper ore in preparation for hammering the metal into some useful form. Thus, through serendipity, the art of casting was born. It is likely that the discovery occurred in Mesopotamia, and the "technology" quickly spread throughout the rest of the ancient world.

It was an innovation of significant importance in the history of mankind. Shapes much more intricate could be formed by casting than by hammering. More sophisticated tools and weapons could be fabricated. More detailed implements and ornaments could be fashioned. Fine gold jewelry could be made more beautiful and valuable than by previous methods. Alloys were first used for casting when it was

discovered that mixtures of copper and tin (the alloy thus formed was bronze) yielded much better castings than copper alone. Casting permitted the creation of wealth to those nations that could perform it best. Egypt ruled the Western civilized world during the Bronze Age (nearly 2000 years) largely due to its ability to perform the casting process.

Religion provided an important influence during the Dark Ages (circa 400–1400) for perpetuating the foundryman's skills. Construction of cathedrals and churches required the casting of bells that were used in these structures. Indeed, the time and effort needed to cast the large bronze bells of the period helped to move the casting process from the realm of art toward the regimen of technology. Advances in melting and moldmaking techniques were made. Pit molding, in which the molds were formed in a deep pit located in front of the furnace to simplify the pouring process, was improved as a casting procedure. In addition, the bell founder learned the relationships between the tone of the bell, which was the important measure of product quality, and its size, shape, thickness, and metal composition.

Another important product associated with the development of casting was the cannon. Chronologically, it followed the bell, and therefore many of the casting

techniques developed for bell founding were applied to cannon making. The first cast cannon was made in Ghent, Belgium, in the year 1313—by a religious monk, of all people. It was made of bronze, and the bore was formed by means of a core during casting. Because of the rough bore surface created by the casting process, these early guns were not accurate and had to be fired at relatively close range to be effective. It was soon realized that accuracy and range could be improved if the bore were made smooth by machining the surface. Quite appropriately, this machining process was called ***boring*** (Section 21.2.5).

subsequent reshaping by processes such as rolling or forging. Ingot casting is discussed in Chapter 6. ***Shape casting*** involves the production of more complex geometries that are much closer to the final desired shape of the part or product. It is with the casting of shapes rather than ingots that this chapter and the next are concerned.

A variety of shape casting methods are available, thus making it one of the most versatile of all manufacturing processes. Among its capabilities and advantages are the following:

➢ Casting can be used to create complex part geometries, including both external and internal shapes.
➢ Some casting processes are capable of producing parts to ***net shape***. No further manufacturing operations are required to achieve the required geometry and dimensions of the parts. Other casting processes are ***near net shape***, for which some additional shape processing is required (usually machining) in order to achieve accurate dimensions and details.
➢ Casting can be used to produce very large parts. Castings weighing more than 100 tons have been made.
➢ The casting process can be performed on any metal that can be heated to the liquid state.
➢ Some casting methods are quite suited to mass production.

There are also disadvantages associated with casting—different disadvantages for different casting methods. These include limitations on mechanical properties, porosity, poor dimensional accuracy and surface finish for some casting processes, safety hazards to humans when processing hot molten metals, and environmental problems.

Parts made by casting processes range in size from small components weighing only a few ounces up to very large products weighing tons. The list of parts includes dental crowns, jewelry, statues, wood-burning stoves, engine blocks and heads for automotive vehicles, machine frames, railway wheels, frying pans, pipes, and pump housings. All varieties of metals can be cast, ferrous and nonferrous.

Casting can also be used on other materials such as polymers and ceramics; however, the details are sufficiently different that discussion of the casting processes for these materials is postponed until later chapters. This chapter and the next deal exclusively with metal casting. Here the fundamentals that apply to virtually all casting operations are discussed. In the following chapter, the individual casting processes are described, along with some of the product design issues that must be considered when making parts out of castings.

0.1 Overview of Casting Technology

As a production process, casting is usually carried out in a foundry. A *foundry* is a factory equipped for making molds, melting and handling metal in molten form, performing the casting process, and cleaning the finished casting. The workers who perform the casting operations in these factories are called *foundrymen*.

10.1.1 CASTING PROCESSES

Discussion of casting logically begins with the mold. The *mold* contains a cavity whose geometry determines the shape of the cast part. The actual size and shape of the cavity must be slightly oversized to allow for shrinkage that occurs in the metal during solidification and cooling. Different metals undergo different amounts of shrinkage, so the mold cavity must be designed for the particular metal to be cast if dimensional accuracy is critical. Molds are made of a variety of materials, including sand, plaster, ceramic, and metal. The various casting processes are often classified according to these different types of molds.

To accomplish a casting operation, the metal is first heated to a temperature high enough to completely transform it into a liquid state. It is then poured, or otherwise directed, into the cavity of the mold. In an *open mold*, Figure 10.2(a), the liquid metal is simply poured until it fills the open cavity. In a *closed mold*, Figure 10.2(b), a passageway, called the gating system, is provided to permit the molten metal to flow from outside the mold into the cavity. The closed mold is by far the more important category in production casting operations.

As soon as the molten metal is in the mold, it begins to cool. When the temperature drops sufficiently (e.g., to the freezing point for a pure metal), solidification begins. Solidification involves a change of phase of the metal. Time is required to complete the phase change, and considerable heat is given up in the process. It is during this step in the process that the metal assumes the solid shape of the mold cavity and many of the properties and characteristics of the casting are established.

Once the casting has cooled sufficiently, it is removed from the mold. Depending on the casting method and metal used, further processing may be required. This
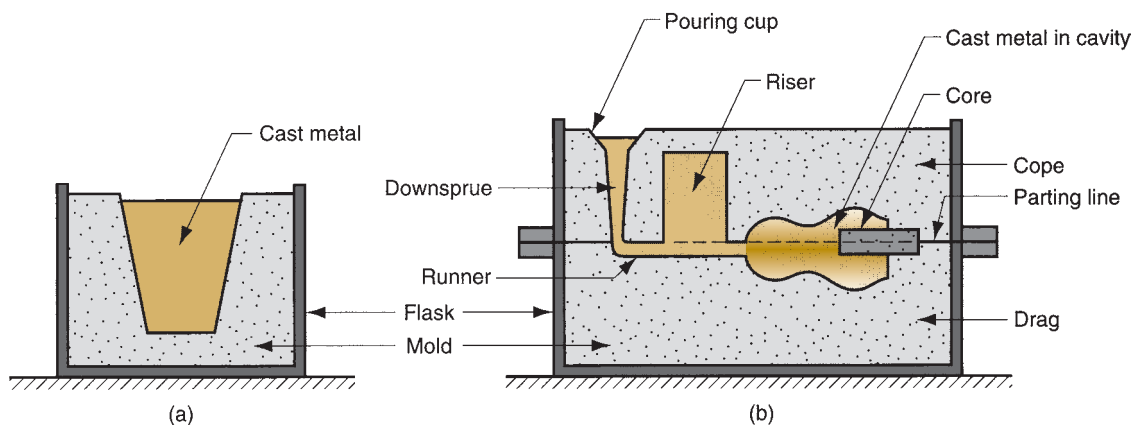

FIGURE 10.2 Two forms of mold: (a) open mold, simply a container in the shape of the desired part; and (b) closed mold, in which the mold geometry is more complex and requires a gating system (passageway) leading into the cavity.

may include trimming any excess metal from the actual cast part, cleaning the surface, inspecting the product, and heat treatment to enhance properties. In addition, machining may be required to achieve closer tolerances on certain part features and to remove the cast surface.

Casting processes divide into two broad categories, according to type of mold used: expendable mold casting and permanent mold casting. An ***expendable mold*** means that the mold in which the molten metal solidifies must be destroyed in order to remove the casting. These molds are made out of sand, plaster, or similar materials, whose form is maintained by using binders of various kinds. Sand casting is the most prominent example of the expendable mold processes. In sand casting, the liquid metal is poured into a mold made of sand. After the metal hardens, the mold must be sacrificed in order to recover the casting.

A ***permanent mold*** is one that can be used over and over to produce many castings. It is made of metal (or, less commonly, a ceramic refractory material) that can withstand the high temperatures of the casting operation. In permanent mold casting, the mold consists of two (or more) sections that can be opened to permit removal of the finished part. Die casting is the most familiar process in this group.

More intricate casting geometries are generally possible with the expendable mold processes. Part shapes in the permanent mold processes are limited by the need to open the mold. On the other hand, some of the permanent mold processes have certain economic advantages in high production operations. The expendable mold and permanent mold casting processes are described in Chapter 11.

10.1.2 SAND-CASTING MOLDS

Sand casting is by far the most important casting process. A sand-casting mold will be used to describe the basic features of a mold. Many of these features and terms are common to the molds used in other casting processes. Figure 10.2(b) shows the cross-sectional view of a typical sand-casting mold, indicating some of the terminology. The mold consists of two halves: cope and drag. The ***cope*** is the upper half of the mold, and the ***drag*** is the bottom half. These two mold parts are contained in a box, called a ***flask***, which is also divided into two halves, one for the cope and the other for the drag. The two halves of the mold separate at the ***parting line***.

In sand casting (and other expendable mold processes) the mold cavity is formed by means of a ***pattern***, which is made of wood, metal, plastic, or other material and has the shape of the part to be cast. The cavity is formed by packing sand around the pattern, about half each in the cope and drag, so that when the pattern is removed, the remaining void has the desired shape of the cast part. The pattern is usually made oversized to allow for shrinkage of the metal as it solidifies and cools. The sand for the mold is moist and contains a binder to maintain its shape.

The cavity in the mold provides the external surfaces of the cast part. In addition, a casting may have internal surfaces. These surfaces are determined by means of a ***core***, a form placed inside the mold cavity to define the interior geometry of the part. In sand casting, cores are generally made of sand, although other materials can be used, such as metals, plaster, and ceramics.

The ***gating system*** in a casting mold is the channel, or network of channels, by which molten metal flows into the cavity from outside the mold. As shown in the figure, the gating system typically consists of a ***downsprue*** (also called simply the ***sprue***), through which the metal enters a ***runner*** that leads into the main cavity. At the top of the downsprue, a ***pouring cup*** is often used to minimize splash and turbulence as the

metal flows into the downsprue. It is shown in the diagram as a simple cone-shaped funnel. Some pouring cups are designed in the shape of a bowl, with an open channel leading to the downsprue.

In addition to the gating system, any casting in which shrinkage is significant requires a riser connected to the main cavity. The *riser* is a reservoir in the mold that serves as a source of liquid metal for the casting to compensate for shrinkage during solidification. The riser must be designed to freeze after the main casting in order to satisfy its function.

As the metal flows into the mold, the air that previously occupied the cavity, as well as hot gases formed by reactions of the molten metal, must be evacuated so that the metal will completely fill the empty space. In sand casting, for example, the natural porosity of the sand mold permits the air and gases to escape through the walls of the cavity. In permanent metal molds, small vent holes are drilled into the mold or machined into the parting line to permit removal of air and gases.

0.2 Heating and Pouring

To perform a casting operation, the metal must be heated to a temperature somewhat above its melting point and then poured into the mold cavity to solidify. Several aspects of these two steps are discussed in this section.

10.2.1 HEATING THE METAL

Heating furnaces of various kinds (Section 11.4.1) are used to heat the metal to a molten temperature sufficient for casting. The heat energy required is the sum of (1) the heat to raise the temperature to the melting point, (2) the heat of fusion to convert it from solid to liquid, and (3) the heat to raise the molten metal to the desired temperature for pouring. This can be expressed:

$$H = \rho V\{C_s (T_m - T_o) + H_f + C_l (T_p - T_m)\} \tag{10.1}$$

where H = total heat required to raise the temperature of the metal to the pouring temperature, J (Btu); ρ = density, g/cm^3 (lbm/in^3); C_s = weight specific heat for the solid metal, J/g-C (Btu/lbm-F); T_m = melting temperature of the metal, C (F); T_o = starting temperature—usually ambient, C (F); H_f = heat of fusion, J/g (Btu/lbm); C_l = weight specific heat of the liquid metal, J/g-C (Btu/lbm-F); T_p = pouring temperature, C (F); and V = volume of metal being heated, cm^3 (in^3).

Example 10.1 Heating metal for casting	One cubic meter of a certain eutectic alloy is heated in a crucible from room temperature to 100°C above its melting point for casting. The alloy's density = 7.5 g/cm³, melting point = 800°C, specific heat = 0.33 J/g°C in the solid state and 0.29 J/g°C in the liquid state; and heat of fusion = 160 J/g. How much heat energy must be added to accomplish the heating, assuming no losses?

Solution: Assume ambient temperature in the foundry = 25°C and that the density of the liquid and solid states of the metal are the same. Noting that one m^3 = 10^6 cm^3, and substituting the property values into Equation (10.1),

$$H = (7.5)\,(10^6)\{0.33(800 - 25) + 160 + 0.29\,(100)\} = 3335(10^6)\ \text{J}$$

The above equation is of conceptual value, but its computational value is limited, notwithstanding the calculation in Example 10.1. Use of Equation (10.1) is complicated by the following factors: (1) Specific heat and other thermal properties of a solid metal vary with temperature, especially if the metal undergoes a change of phase during heating. (2) A metal's specific heat may be different in the solid and liquid states. (3) Most casting metals are alloys, and most alloys melt over a temperature range between a solidus and liquidus rather than at a single melting point; thus, the heat of fusion cannot be applied so simply as indicated above. (4) The property values required in the equation for a particular alloy are not readily available in most cases. (5) There are significant heat losses to the environment during heating.

10.2.2   POURING THE MOLTEN METAL

After heating, the metal is ready for pouring. Introduction of molten metal into the mold, including its flow through the gating system and into the cavity, is a critical step in the casting process. For this step to be successful, the metal must flow into all regions of the mold before solidifying. Factors affecting the pouring operation include pouring temperature, pouring rate, and turbulence.

The ***pouring temperature*** is the temperature of the molten metal as it is introduced into the mold. What is important here is the difference between the temperature at pouring and the temperature at which freezing begins (the melting point for a pure metal or the liquidus temperature for an alloy). This temperature difference is sometimes referred to as the ***superheat***. This term is also used for the amount of heat that must be removed from the molten metal between pouring and when solidification commences [7].

Pouring rate refers to the volumetric rate at which the molten metal is poured into the mold. If the rate is too slow, the metal will chill and freeze before filling the cavity. If the pouring rate is excessive, turbulence can become a serious problem. ***Turbulence*** in fluid flow is characterized by erratic variations in the magnitude and direction of the velocity throughout the fluid. The flow is agitated and irregular rather than smooth and streamlined, as in laminar flow. Turbulent flow should be avoided during pouring for several reasons. It tends to accelerate the formation of metal oxides that can become entrapped during solidification, thus degrading the quality of the casting. Turbulence also aggravates ***mold erosion***, the gradual wearing away of the mold surfaces due to impact of the flowing molten metal. The densities of most molten metals are much higher than water and other fluids normally encountered. These molten metals are also much more chemically reactive than at room temperature. Consequently, the wear caused by the flow of these metals in the mold is significant, especially under turbulent conditions. Erosion is especially serious when it occurs in the main cavity because the geometry of the cast part is affected.

10.2.3   ENGINEERING ANALYSIS OF POURING

There are several relationships that govern the flow of liquid metal through the gating system and into the mold. An important relationship is ***Bernoulli's theorem***, which states that the sum of the energies (head, pressure, kinetic, and

friction) at any two points in a flowing liquid are equal. This can be written in the following form:

$$h_1 + \frac{p_1}{\rho} + \frac{v_1^2}{2g} + F_1 = h_2 + \frac{p^2}{\rho} + \frac{v_2^2}{2g} + F_2 \tag{10.2}$$

where h = head, cm (in), p = pressure on the liquid, N/cm² (lb/in²); ρ = density, g/cm³ (lbm/in³); v = flow velocity, cm/s (in/sec); g = gravitational acceleration constant, 981 cm/s/s ($32.2 \times 12 = 386$ in/sec/sec); and F = head losses due to friction, cm (in). Subscripts 1 and 2 indicate any two locations in the liquid flow.

Bernoulli's equation can be simplified in several ways. If friction losses are ignored (to be sure, friction will affect the liquid flow through a sand mold), and the system is assumed to remain at atmospheric pressure throughout, then the equation can be reduced to

$$h_1 + \frac{v_1^2}{2g} = h_2 + \frac{v_2^2}{2g} \tag{10.3}$$

This can be used to determine the velocity of the molten metal at the base of the sprue. Let point 1 be defined at the top of the sprue and point 2 at its base. If point 2 is used as the reference plane, then the head at that point is zero ($h_2 = 0$) and h_1 is the height (length) of the sprue. When the metal is poured into the pouring cup and overflows down the sprue, its initial velocity at the top is zero ($v_1 = 0$). Hence, Equation (10.3) further simplifies to

$$h_1 = \frac{v_2^2}{2g}$$

which can be solved for the flow velocity:

$$v = \sqrt{2gh} \tag{10.4}$$

where v = the velocity of the liquid metal at the base of the sprue, cm/s (in/sec); g = 981 cm/s/s (386 in/sec/sec); and h = the height of the sprue, cm (in).

Another relationship of importance during pouring is the ***continuity law***, which states that the volume rate of flow remains constant throughout the liquid. The volume flow rate is equal to the velocity multiplied by the cross-sectional area of the flowing liquid. The continuity law can be expressed:

$$Q = v_1 A_1 = v_2 A_2 \tag{10.5}$$

where Q = volumetric flow rate, cm³/s (in³/sec); v = velocity as before; A = cross-sectional area of the liquid, cm² (in²); and the subscripts refer to any two points in the flow system. Thus, an increase in area results in a decrease in velocity, and vice versa.

Equations (10.4) and (10.5) indicate that the sprue should be tapered. As the metal accelerates during its descent into the sprue opening, the cross-sectional area of the channel must be reduced; otherwise, as the velocity of the flowing metal increases toward the base of the sprue, air can be aspirated into the liquid and conducted into the mold cavity. To prevent this condition, the sprue is designed with a taper, so that the volume flow rate vA is the same at the top and bottom of the sprue.

Assuming that the runner from the sprue base to the mold cavity is horizontal (and therefore the head h is the same as at the sprue base), then the volume rate

of flow through the gate and into the mold cavity remains equal to vA at the base. Accordingly, the time required to fill a mold cavity of volume V can be estimated as

$$T_{MF} = \frac{V}{Q} \qquad (10.6)$$

where T_{MF} = mold filling time, s (sec); V = volume of mold cavity, cm^3 (in^3); and Q = volume flow rate, as before. The mold filling time computed by Equation (10.6) must be considered a minimum time. This is because the analysis ignores friction losses and possible constriction of flow in the gating system; thus, the mold filling time will be longer than what is given by Equation (10.6).

Example 10.2 Pouring calculations	A mold sprue is 20 cm long, and the cross-sectional area at its base is 2.5 cm^2. The sprue feeds a horizontal runner leading into a mold cavity whose volume is 1560 cm^3. Determine: (a) velocity of the molten metal at the base of the sprue, (b) volume rate of flow, and (c) time to fill the mold.

Solution: (a) The velocity of the flowing metal at the base of the sprue is given by Equation (10.4):

$$v = \sqrt{2(981)(20)} = 198.1 \text{ cm/s}$$

(b) The volumetric flow rate is

$$Q = (2.5 \text{ cm}^2)(198.1 \text{ cm/s}) = 495 \text{ cm}^3/\text{s}$$

(c) Time required to fill a mold cavity of 1560 cm^3 at this flow rate is

$$T_{MF} = 1560/495 = 3.2 \text{ s}$$

10.2.4 FLUIDITY

The molten metal flow characteristics are often described by the term **fluidity**, a measure of the capability of a metal to flow into and fill the mold before freezing. Fluidity is the inverse of viscosity (Section 3.4); as viscosity increases, fluidity decreases. Standard testing methods are available to assess fluidity, including the spiral mold test shown in Figure 10.3, in which fluidity is indicated by the length of the solidified metal in the spiral channel. A longer cast spiral means greater fluidity of the molten metal.

Factors affecting fluidity include pouring temperature relative to melting point, metal composition, viscosity of the liquid metal, and heat transfer to the surroundings. A higher pouring temperature relative to the freezing point of the metal increases the time it remains in the liquid state, allowing it to flow further before freezing.

FIGURE 10.3 Spiral mold test for fluidity, in which fluidity is measured as the length of the spiral channel that is filled by the molten metal prior to solidification.
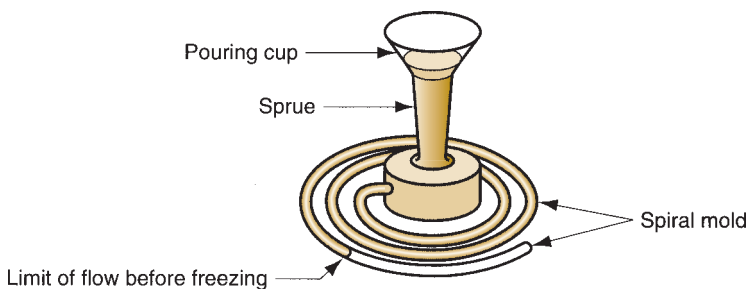
This tends to aggravate certain casting problems such as oxide formation, gas porosity, and penetration of liquid metal into the interstitial spaces between the grains of sand forming the mold. This last problem causes the surface of the casting to contain imbedded sand particles, thus making it rougher and more abrasive than normal.

Composition also affects fluidity, particularly with respect to the metal's solidification mechanism. The best fluidity is obtained by metals that freeze at a constant temperature (e.g., pure metals and eutectic alloys). When solidification occurs over a temperature range (most alloys are in this category), the partially solidified portion interferes with the flow of the liquid portion, thereby reducing fluidity. In addition to the freezing mechanism, metal composition also determines *heat of fusion*—the amount of heat required to solidify the metal from the liquid state. A higher heat of fusion tends to increase the measured fluidity in casting.

0.3 Solidification and Cooling

After pouring into the mold, the molten metal cools and solidifies. This section examines the physical mechanism of solidification that occurs during casting. Issues associated with solidification include the time for a metal to freeze, shrinkage, directional solidification, and riser design.

10.3.1 SOLIDIFICATION OF METALS

Solidification involves the transformation of the molten metal back into the solid state. The solidification process differs depending on whether the metal is a pure element or an alloy.

Pure Metals   A pure metal solidifies at a constant temperature equal to its freezing point, which is the same as its melting point. The melting points of pure metals are well known and documented (Table 4.1). The process occurs over time as shown in the plot of Figure 10.4, called a cooling curve. The actual freezing takes time,
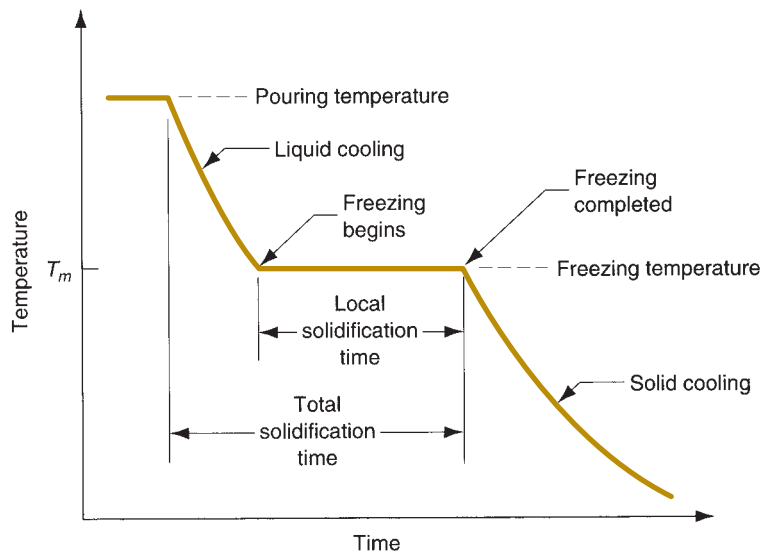
FIGURE 10.4   Cooling curve for a pure metal during casting.

called the ***local solidification time*** in casting, during which the metal's latent heat of fusion is released into the surrounding mold. The ***total solidification time*** is the time taken between pouring and complete solidification. After the casting has completely solidified, cooling continues at a rate indicated by the downward slope of the cooling curve.

Because of the chilling action of the mold wall, a thin skin of solid metal is initially formed at the interface immediately after pouring. Thickness of the skin increases to form a shell around the molten metal as solidification progresses inward toward the center of the cavity. The rate at which freezing proceeds depends on heat transfer into the mold, as well as the thermal properties of the metal.

It is of interest to examine the metallic grain formation and growth during this solidification process. The metal which forms the initial skin has been rapidly cooled by the extraction of heat through the mold wall. This cooling action causes the grains in the skin to be fine and randomly oriented. As cooling continues, further grain formation and growth occur in a direction away from the heat transfer. Since the heat transfer is through the skin and mold wall, the grains grow inwardly as needles or spines of solid metal. As these spines enlarge, lateral branches form, and as these branches grow, further branches form at right angles to the first branches. This type of grain growth is referred to as ***dendritic growth***, and it occurs not only in the freezing of pure metals but alloys as well. These treelike structures are gradually filled-in during freezing, as additional metal is continually deposited onto the dendrites until complete solidification has occurred. The grains resulting from this dendritic growth take on a preferred orientation, tending to be coarse, columnar grains aligned toward the center of the casting. The resulting grain formation is illustrated in Figure 10.5.

Most Alloys   Most alloys freeze over a temperature range rather than at a single temperature. The exact range depends on the alloy system and the particular composition. Solidification of an alloy can be explained with reference to Figure 10.6, which shows the phase diagram for a particular alloy system (Section 6.1.2) and the cooling curve for a given composition. As temperature drops, freezing begins at the temperature indicated by the ***liquidus*** and is completed when the ***solidus*** is reached. The start of freezing is similar to that of the pure metal. A thin skin is formed at the mold wall due to the large temperature gradient at this surface. Freezing then progresses as before through the formation of dendrites that grow away from the walls. However, owing to the temperature spread between the liquidus and solidus, the nature of the dendritic growth is such that an advancing zone is formed in which both liquid and solid metal coexist. The solid portions are the dendrite structures that have formed sufficiently to trap small islands of liquid metal in the matrix. This solid–liquid region has a soft consistency that has motivated its name as the ***mushy zone***. Depending on the conditions of freezing, the mushy zone can be relatively
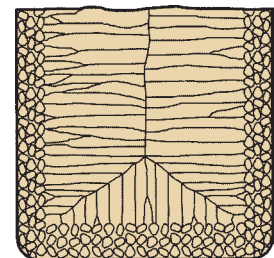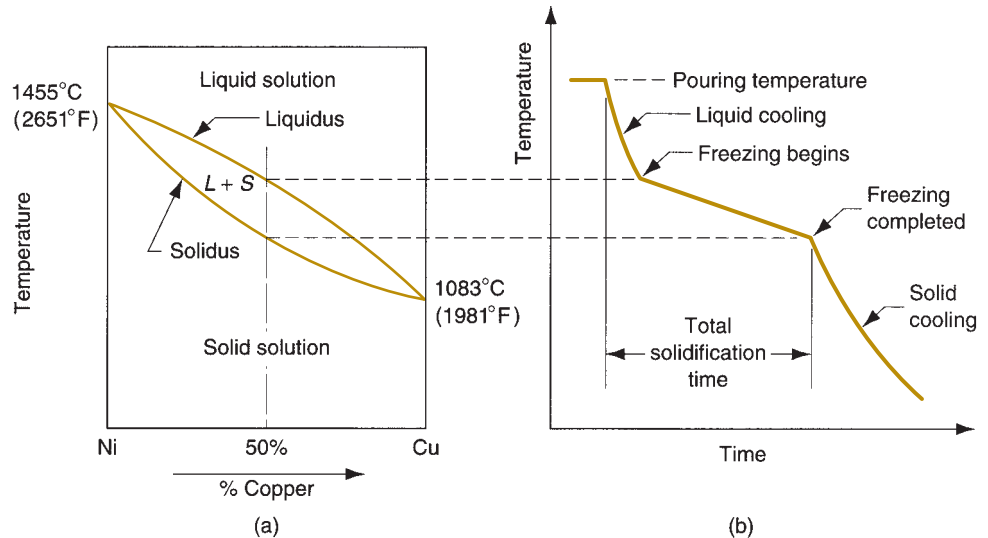

FIGURE 10.5   Characteristic grain structure in a casting of a pure metal, showing randomly oriented grains of small size near the mold wall, and large columnar grains oriented toward the center of the casting.

FIGURE 10.6
(a) Phase diagram for a copper–nickel alloy system and (b) associated cooling curve for a 50%Ni–50%Cu composition during casting.

narrow, or it can exist throughout most of the casting. The latter condition is promoted by factors such as slow heat transfer out of the hot metal and a wide difference between liquidus and solidus temperatures. Gradually, the liquid islands in the dendrite matrix solidify as the temperature of the casting drops to the solidus for the given alloy composition.

Another factor complicating solidification of alloys is that the composition of the dendrites as they start to form favors the metal with the higher melting point. As freezing continues and the dendrites grow, there develops an imbalance in composition between the metal that has solidified and the remaining molten metal. This composition imbalance is finally manifested in the completed casting in the form of segregation of the elements. The segregation is of two types, microscopic and macroscopic. At the microscopic level, the chemical composition varies throughout each individual grain. This is due to the fact that the beginning spine of each dendrite has a higher proportion of one of the elements in the alloy. As the dendrite grows in its local vicinity, it must expand using the remaining liquid metal that has been partially depleted of the first component. Finally, the last metal to freeze in each grain is that which has been trapped by the branches of the dendrite, and its composition is even further out of balance. Thus, there is a variation in chemical composition within single grains of the casting.

At the macroscopic level, the chemical composition varies throughout the entire casting. Since the regions of the casting that freeze first (at the outside near the mold walls) are richer in one component than the other, the remaining molten alloy is deprived of that component by the time freezing occurs at the interior. Thus, there is a general segregation through the cross section of the casting, sometimes called **ingot segregation**, as illustrated in Figure 10.7.

Eutectic Alloys   Eutectic alloys constitute an exception to the general process by which alloys solidify. A **eutectic alloy** is a particular composition in an alloy system for which the solidus and liquidus are at the same temperature. Hence, solidification occurs at a constant temperature rather than over a temperature range, as described above. The effect can be seen in the phase diagram of the lead–tin system shown in
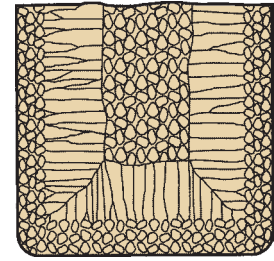
FIGURE 10.7   Characteristic grain structure in an alloy casting, showing segregation of alloying components in the center of casting.

Figure 6.3. Pure lead has a melting point of 327°C (621°F), while pure tin melts at 232°C (450°F). Although most lead–tin alloys exhibit the typical solidus–liquidus temperature range, the particular composition of 61.9% tin and 38.1% lead has a melting (freezing) point of 183°C (362°F). This composition is the ***eutectic composition*** of the lead–tin alloy system, and 183°C is its ***eutectic temperature***. Lead–tin alloys are not commonly used in casting, but Pb–Sn compositions near the eutectic are used for electrical soldering, where the low melting point is an advantage. Examples of eutectic alloys encountered in casting include aluminum–silicon (11.6% Si) and cast iron (4.3% C).

10.3.2   SOLIDIFICATION TIME

Whether the casting is pure metal or alloy, solidification takes time. The total solidification time is the time required for the casting to solidify after pouring. This time is dependent on the size and shape of the casting by an empirical relationship known as ***Chvorinov's rule***, which states:

$$T_{TS} = C_m \left(\frac{V}{A}\right)^n \tag{10.7}$$

where T_{TS} = total solidification time, min; V = volume of the casting, cm^3 (in^3); A = surface area of the casting, cm^2 (in^2); n is an exponent usually taken to have a value = 2; and C_m is the ***mold constant***. Given that $n = 2$, the units of C_m are min/cm^2 (min/in^2), and its value depends on the particular conditions of the casting operation, including mold material (e.g., specific heat, thermal conductivity), thermal properties of the cast metal (e.g., heat of fusion, specific heat, thermal conductivity), and pouring temperature relative to the melting point of the metal. The value of C_m for a given casting operation can be based on experimental data from previous operations carried out using the same mold material, metal, and pouring temperature, even though the shape of the part may be quite different.

Chvorinov's rule indicates that a casting with a higher volume-to-surface area ratio will cool and solidify more slowly than one with a lower ratio. This principle is put to good use in designing the riser in a mold. To perform its function of feeding molten metal to the main cavity, the metal in the riser must remain in the liquid phase longer than the casting. In other words, the T_{TS} for the riser must exceed the T_{TS} for the main casting. Since the mold conditions for both riser and casting are the same, their mold constants will be equal. By designing the riser to have a larger volume-to-area ratio, the main casting will most likely solidify first and the effects of shrinkage will be minimized. Before discussing how the riser might be designed based on Chvorinov's rule, consider the topic of shrinkage, which is the reason why risers are needed.

10.3.3 SHRINKAGE

The discussion of solidification has neglected the impact of shrinkage that occurs during cooling and freezing. Shrinkage occurs in three steps: (1) liquid contraction during cooling prior to solidification; (2) contraction during the phase change from liquid to solid, called *solidification shrinkage*; and (3) thermal contraction of the solidified casting during cooling to room temperature. The three steps can be explained with reference to a cylindrical casting made in an open mold, as shown in Figure 10.8. The molten metal immediately after pouring is shown in part (0) of the series. Contraction of the liquid metal during cooling from pouring temperature to freezing temperature causes the height of the liquid to be reduced from its starting level as in (1) of the figure. The amount of this liquid contraction is usually around 0.5%. Solidification shrinkage, seen in part (2), has two effects. First, contraction causes a further reduction in the height of the casting. Second, the amount of liquid metal available to feed the top center portion of the casting becomes restricted. This is usually the last region to freeze, and the absence of metal creates a void in the casting at this location. This shrinkage cavity is called a *pipe* by foundrymen. Once solidified, the casting experiences further contraction in height and diameter while cooling, as in (3). This shrinkage is determined by the solid metal's coefficient of thermal expansion, which in this case is applied in reverse to determine contraction.

FIGURE 10.8 Shrinkage of a cylindrical casting during solidification and cooling: (0) starting level of molten metal immediately after pouring; (1) reduction in level caused by liquid contraction during cooling; (2) reduction in height and formation of shrinkage cavity caused by solidification shrinkage; and (3) further reduction in height and diameter due to thermal contraction during cooling of the solid metal. For clarity, dimensional reductions are exaggerated in our sketches.
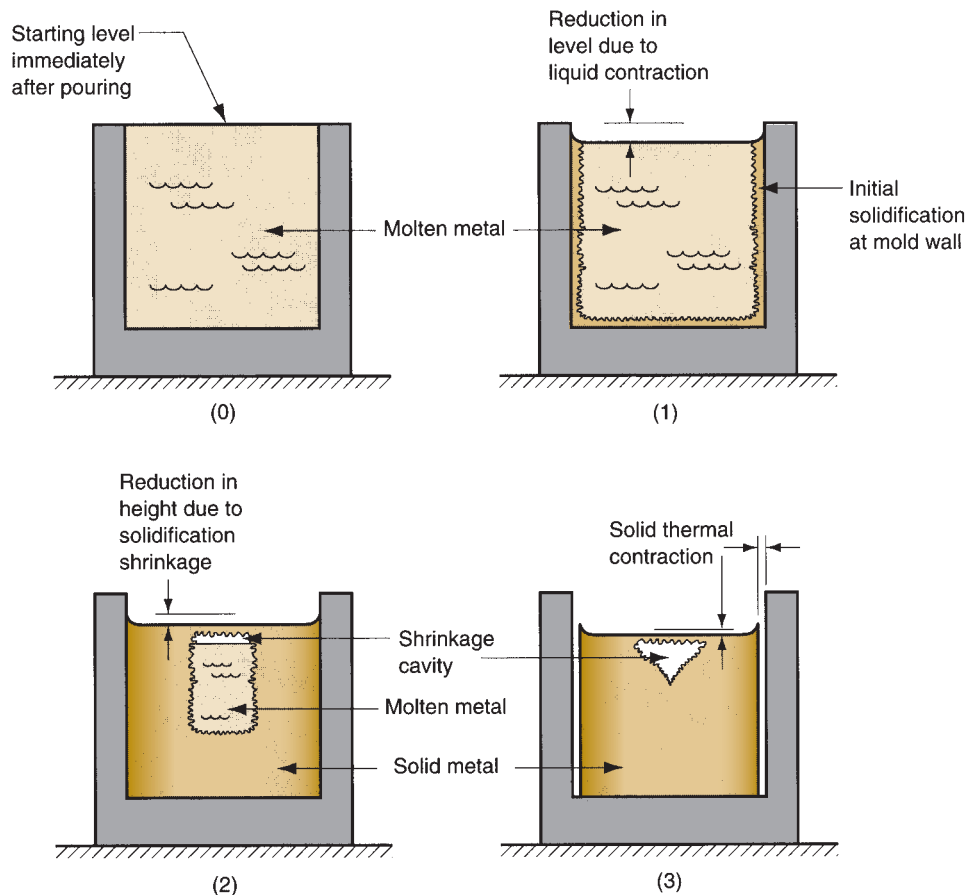
TABLE • 10.1 Typical linear shrinkage values for different casting metals due to solid thermal contraction.

Metal	Linear shrinkage	Metal	Linear shrinkage	Metal	Linear shrinkage
Aluminum alloys	1.3%	Magnesium	2.1%	Steel, chrome	2.1%
Brass, yellow	1.3%–1.6%	Magnesium alloy	1.6%	Tin	2.1%
Cast iron, gray	0.8%–1.3%	Nickel	2.1%	Zinc	2.6%
Cast iron, white	2.1%	Steel, carbon	1.6% – 2.1%		

Compiled from [10].

Solidification shrinkage occurs in nearly all metals because the solid phase has a higher density than the liquid phase. The phase transformation that accompanies solidification causes a reduction in the volume per unit weight of metal. The exception is cast iron containing high carbon content, whose solidification during the final stages of freezing is complicated by a period of graphitization, which results in expansion that tends to counteract the volumetric decrease associated with the phase change [7]. Compensation for solidification shrinkage is achieved in several ways depending on the casting operation. In sand casting, liquid metal is supplied to the cavity by means of risers (Section 10.3.5). In die casting (Section 11.3.3), the molten metal is applied under pressure.

Pattern-makers account for thermal contraction by making the mold cavities oversized. The amount by which the mold must be made larger relative to the final casting size is called the *pattern shrinkage allowance*. Although the shrinkage is volumetric, the dimensions of the casting are expressed linearly, so the allowances must be applied accordingly. Special "shrink rules" with slightly elongated scales are used to make the patterns and molds larger than the desired casting by the appropriate amount. Table 10.1 lists typical values of linear shrinkage for various cast metals; these values can be used to determine shrink rule scales.

10.3.4 DIRECTIONAL SOLIDIFICATION

In order to minimize the damaging effects of shrinkage, it is desirable for the regions of the casting most distant from the liquid metal supply to freeze first and for solidification to progress from these remote regions toward the riser(s). In this way, molten metal will continually be available from the risers to prevent shrinkage voids during freezing. The term *directional solidification* is used to describe this aspect of the freezing process and the methods by which it is controlled. The desired directional solidification is achieved by observing Chvorinov's rule in the design of the casting itself, its orientation within the mold, and the design of the riser system that feeds it. For example, by locating sections of the casting with lower V/A ratios away from the riser, freezing will occur first in these regions and the supply of liquid metal for the rest of the casting will remain open until these bulkier sections solidify.

Another way to encourage directional solidification is to use *chills*—internal or external heat sinks that cause rapid freezing in certain regions of the casting. *Internal chills* are small metal parts placed inside the cavity before pouring so that the molten metal will solidify first around these parts. The internal chill should have a chemical composition similar to the metal being poured, most readily achieved by making the chill out of the same metal as the casting itself.

FIGURE 10.9
(a) External chill to encourage rapid freezing of the molten metal in a thin section of the casting; and (b) the likely result if the external chill were not used.
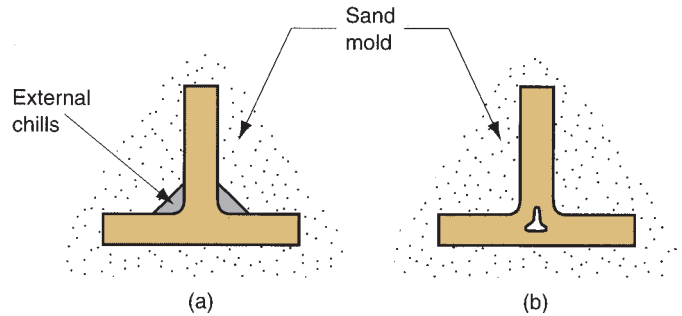
External chills are metal inserts in the walls of the mold cavity that can remove heat from the molten metal more rapidly than the surrounding sand in order to promote solidification. They are often used effectively in sections of the casting that are difficult to feed with liquid metal, thus encouraging rapid freezing in these sections while the connection to liquid metal is still open. Figure 10.9 illustrates a possible application of external chills and the likely result in the casting if the chill were not used.

As important as it is to initiate freezing in the appropriate regions of the cavity, it is also important to avoid premature solidification in sections of the mold nearest the riser. Of particular concern is the passageway between the riser and the main cavity. This connection must be designed in such a way that it does not freeze before the casting, which would isolate the casting from the molten metal in the riser. Although it is generally desirable to minimize the volume in the connection (to reduce wasted metal), the cross-sectional area must be sufficient to delay the onset of freezing. This goal is usually aided by making the passageway short in length, so that it absorbs heat from the molten metal in the riser and the casting.

10.3.5   RISER DESIGN

As described earlier, a riser, Figure 10.2(b), is used in a sand-casting mold to feed liquid metal to the casting during freezing in order to compensate for solidification shrinkage. To function, the riser must remain molten until after the casting solidifies. Chvorinov's rule can be used to compute the size of a riser that will satisfy this requirement. The following example illustrates the calculation.

Example 10.3 Riser design using Chvorinov's rule	A cylindrical riser must be designed for a sand-casting mold. The casting itself is a steel rectangular plate with dimensions 7.5 cm × 12.5 cm × 2.0 cm. Previous observations have indicated that the total solidification time (T_{TS}) for this casting = 1.6 min. The cylinder for the riser will have a diameter-to-height ratio = 1.0. Determine the dimensions of the riser so that its T_{TS} = 2.0 min.
	Solution: First determine the V/A ratio for the plate. Its volume $V = 7.5 \times 12.5 \times 2.0 = 187.5$ cm³, and its surface area $A = 2(7.5 \times 12.5 + 7.5 \times 2.0 + 12.5 \times 2.0) = 267.5$ cm². Given that $T_{TS} = 1.6$ min, the mold constant

C_m can be determined from Equation (10.7), using a value of $n = 2$ in the equation.

$$C_m = \frac{T_{TS}}{(V/A)^2} = \frac{1.6}{(187.5/267.5)^2} = 3.26 \text{ min/cm}^2$$

Next the riser must be designed so that its total solidification time is 2.0 min, using the same value of mold constant. The volume of the riser is given by

$$V = \frac{\pi D^2 h}{4}$$

and the surface area is given by $A = \pi Dh + \frac{2\pi D^2}{4}$

Since the D/H ratio $= 1.0$, then $D = H$. Substituting D for H in the volume and area formulas,

$$V = \pi D^3/4$$

and

$$A = \pi D^2 + 2\pi D^2/4 = 1.5\pi D^2$$

Thus the V/A ratio $= D/6$. Using this ratio in Chvorinov's equation,

$$T_{TS} = 2.0 = 3.26 \left(\frac{D}{6}\right)^2 = 0.09056 \, D^2$$

$$D^2 = 2.0/0.09056 = 22.086 \text{ cm}^2$$

$$D = 4.7 \text{ cm}$$

Since $H = D$, then $H = 4.7$ cm also.

The riser represents waste metal that will be separated from the cast part and remelted to make subsequent castings. It is desirable for the volume of metal in the riser to be a minimum. Since the geometry of the riser is normally selected to maximize the V/A ratio, this tends to reduce the riser volume as much as possible. Note that the volume of the riser in Example 10.3 is $V = \pi(4.7)^3/4 = 81.5 \text{ cm}^3$, only 44% of the volume of the plate (casting), even though its total solidification time is 25% longer.

Risers can be designed in different forms. The design shown in Figure 10.2(b) is a *side riser*. It is attached to the side of the casting by means of a small channel. A *top riser* is one that is connected to the top surface of the casting. Risers can be open or blind. An *open riser* is exposed to the outside at the top surface of the cope. This has the disadvantage of allowing more heat to escape, promoting faster solidification. A *blind riser* is entirely enclosed within the mold, as in Figure 10.2(b).