CHAPTER 13

Fundamentals of Casting

13.1 Introduction to Materials Processing

Almost every manufactured product (or component of a product) goes through a series of activities that include (1) design, defining what we want to produce; (2) material selection; (3) process selection; (4) manufacture; (5) inspection and evaluation; and (6) feedback. Previous chapters have presented the fundamentals of *materials engineering*, the study of the structure, properties, processing, and performance of engineering materials and the systems interactions between these aspects. Other chapters have addressed the use of heat treatment to achieve desired properties and various aspects of quality assurance. In this chapter, we begin a focus on **materials processing**, the science and technology through which a material is converted into a useful shape with structure and properties that are optimized for the proposed service environment. A less-technical definition of materials processing might be "whatever must be done to convert stuff into things."

A primary objective of materials processing is the production of a desired shape in the desired quantity. Shape-producing processes can be grouped into five basic "families," as indicated in **Figure 13.1**. **Casting** processes exploit the properties of a liquid as it flows into and assumes the shape of a prepared container and then solidifies on cooling. The **material removal** processes remove selected segments from an initially oversized piece. Traditionally, these processes have often been referred to as **machining**, a term used to describe the mechanical cutting of materials. The more general term, *material removal*, includes a wide variety of techniques, including those based on chemical, thermal, and physical processes. **Deformation processes** exploit the ductility or plasticity of certain materials, mostly metals, to produce the desired shape by mechanically moving or rearranging the solid. **Consolidation processes** build a desired shape by putting smaller pieces together. Included here are welding, brazing, soldering, adhesive bonding, and mechanical fasteners. **Powder metallurgy** is the manufacture of a desired shape from particulate material, a type of consolidation that can also involve aspects of casting and forming. The newest grouping or classification is **additive manufacturing** or **direct digital manufacturing**, which

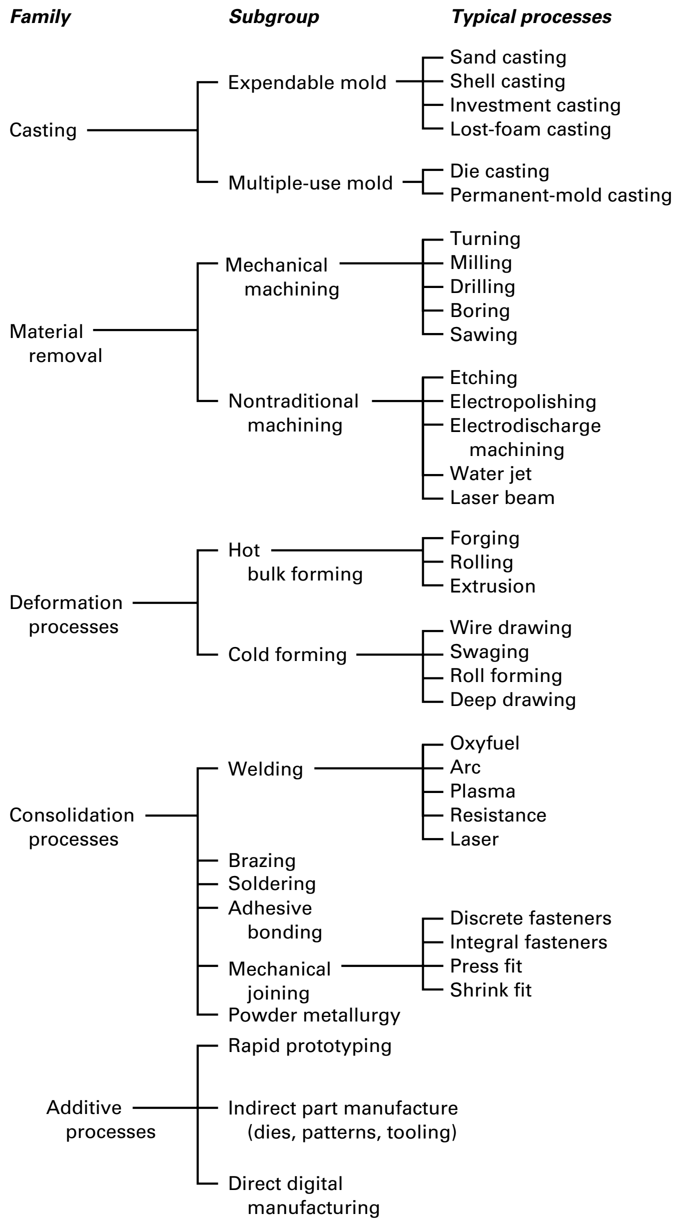


FIGURE 13.1 The five materials processing families with subgroups and typical processes.

includes a variety of processes developed to directly convert a computer-file “drawing” to a finished product by a layer-by-layer deposition of material. Products can be made without any intervening patterns, dies, or other tooling.

Each of the five basic families has distinct advantages and limitations, and the various processes within the families have their own unique characteristics. For example, cast products can have extremely complex shapes, but also possess structures that are produced by solidification and are therefore subject to such defects as shrinkage and porosity. Material removal processes are capable of outstanding dimensional precision, but produce scrap when material is cut away to produce the desired shape. Deformation processes can have high rates of production, but generally require powerful equipment and dedicated tools or dies. Complex products can often be assembled from simple shapes, but the joint areas are often affected by the joining process and may possess characteristics different from the original base material. Direct digital manufacturing can produce parts almost on-demand, but is limited in the time it takes to produce a part, the size of part that can be produced, and the range of materials and properties that are available.

When selecting the process or processes to be used in obtaining a desired shape and achieving the desired properties, decisions should be made with the knowledge of all available alternatives and their associated assets and limitations. A large portion of this book is dedicated to presenting the various processes that can be applied to engineering materials. They are grouped according to the basic categories of Figure 13.1. The emphasis is on process fundamentals, descriptions of the various alternatives, and an assessment of associated assets and limitations. We will begin with a survey of the casting processes.

13.2 Introduction to Casting

In the casting processes, a material is first melted, heated to proper temperature, and sometimes treated to modify its chemical composition. The molten material is then poured into a cavity or mold that holds it in the desired shape during cool-down and solidification. In a single step, simple or complex shapes can be made from any material that can be melted. By proper design and process control, the resistance to working stresses can be optimized, and a pleasing appearance can be produced.

An extremely high percentage of manufactured goods contain at least one metal casting. Cast parts range in size from a fraction of a centimeter and a fraction of a gram (such as the individual teeth on a zipper), to over 10 meters and many tons (as in the huge propellers and stern frames of ocean liners). Moreover, the casting processes have distinct advantages when the production involves complex shapes, parts having hollow sections or internal cavities, parts that contain irregular curved surfaces (except those that can be made from thin sheet metal), very large parts, or parts made from metals that are difficult to machine.

It is almost impossible to design a part that cannot be cast by one or more of the commercial casting processes. However, as with all manufacturing techniques, the best results and lowest cost are only achieved if the designer understands the various options and tailors the design to use the most appropriate process in the most efficient manner. The variety of casting processes uses different **mold materials** (sand, metal, or various ceramics) and pouring methods (gravity, vacuum, low pressure, or high pressure). All share the requirement that the material should solidify in a manner that would maximize the properties and avoid the formation of defects, such as shrinkage voids, gas porosity, and trapped inclusions.

Basic Requirements of Casting Processes

Six basic steps are present in most casting processes:

1. A container must be produced with a *cavity* having the desired shape and size (*mold cavity*), with due allowance for shrinkage of the solidifying material. Any geometrical feature desired in the finished casting must be present in the cavity. The mold material must provide the desired detail and also withstand the high temperatures and not contaminate the molten material. In some processes, a new mold is prepared for each casting (single-use molds), whereas in other processes, the mold is made from a material that can withstand repeated use, such as metal or graphite. The **multiple-use molds** tend to be quite costly and are generally employed with products where large quantities are desired. The more economical **single-use molds** are usually preferred for the production of smaller quantities, but may also be required when casting the higher melting-temperature materials.
2. A *melting process* must be capable of providing molten material at the proper temperature, in the desired quantity, with acceptable quality, and at a reasonable cost.
3. A *pouring technique* must be devised to introduce the molten metal into the mold. Provision should be made for the escape of all air or gases present in the cavity prior to pouring, as well as those generated by the introduction of the hot metal. The molten material must be free to fill the cavity, producing a high-quality casting that is fully dense and free of defects.
4. The *solidification process* should be properly designed and controlled. Castings should be designed so that solidification and solidification shrinkage can occur without producing internal porosity or voids. In addition, the molds should not provide excessive restraint to the shrinkage that accompanies cooling, a feature that may cause the casting to crack when it is still hot and its strength is low.
5. It must be possible to remove the casting from the mold. With single-use molds that are broken apart and destroyed after each casting, mold removal presents no serious difficulty. With multiple-use molds, however, the removal of a complex-shaped casting may be a major design problem.
6. Various *cleaning, finishing, and inspection* operations may be required after the casting is removed from the mold. Extraneous material is usually attached where the metal entered the cavity; excess material may be present along mold parting lines (segment separation interfaces); and mold material may adhere to the casting surface. All of these must be removed from the finished casting.

Each of these six steps will be considered in more detail as we move through the chapter. The fundamentals of solidification, pattern design, gating, and risering will all be developed. Various defects will also be considered, together with their causes and cures.

13.3 Casting Terminology

Before we proceed to the process fundamentals, it is helpful to first become familiar with a bit of casting vocabulary. **Figure 13.2** shows a two-part mold, its cross section, and a variety of features or components that are present in a typical casting process. To produce a casting, we begin by constructing a **pattern**—an approximate duplicate of the final casting. **Molding material** will then be packed around the pattern, and the pattern is removed to create all or part of the mold cavity. The rigid metal or wood frame that holds the molding aggregate is called a **flask**. In a horizontally parted two-part mold, the top half of the pattern, flask, mold, or core is called the **cope**. The bottom half of any of these features is called the **drag**. A **core** is a sand (or metal) shape that is inserted into a mold to produce the internal features of a casting, such as holes or passages. Cores are produced in wood, metal, or plastic tooling, known as **core boxes**. A **core print** is a feature that is added to a pattern, core, or mold and is used to locate and support a core within the mold. The mold material and the cores then combine to produce a completed **mold cavity**, a shaped hole into which the molten metal is poured and solidified to produce the desired casting. A **riser** is an additional void in the mold that also fills with molten metal. Its purpose is to provide a reservoir of additional liquid that can flow into the mold cavity to compensate for any shrinkage that occurs during solidification. By designing so, the riser contains the last material to solidify, shrinkage voids should be located in the riser and not the final casting.

The network of connected channels used to deliver the molten metal to the mold cavity is known as the **gating system**. The **pouring cup** (or pouring basin) is the portion of the gating system that receives the molten metal from the pouring vessel and controls its delivery to the rest of the mold. From the pouring cup, the metal travels down a **sprue** (the vertical portion of the gating system), then along horizontal channels, called **runners**, and finally through controlled entrances, or **gates**, into the mold cavity. Additional channels, known as **vents**, may be included in a mold or core to provide an escape for the gases that are originally present in the mold or are generated during the pour. (These and other features of a gating system will be discussed later in the chapter and are illustrated in Figure 13.9.)

The **parting line** or **parting surface** is the interface that separates the cope and drag halves of a mold, flask, or pattern, and also the halves of a core in some core-making processes. **Draft** is the term used to describe the taper on a pattern or casting that permits it to be withdrawn from the mold. The draft usually tapers outward toward the parting line. Finally, the term **casting** is used to describe both the process and the product when molten metal is poured and solidified in a mold.

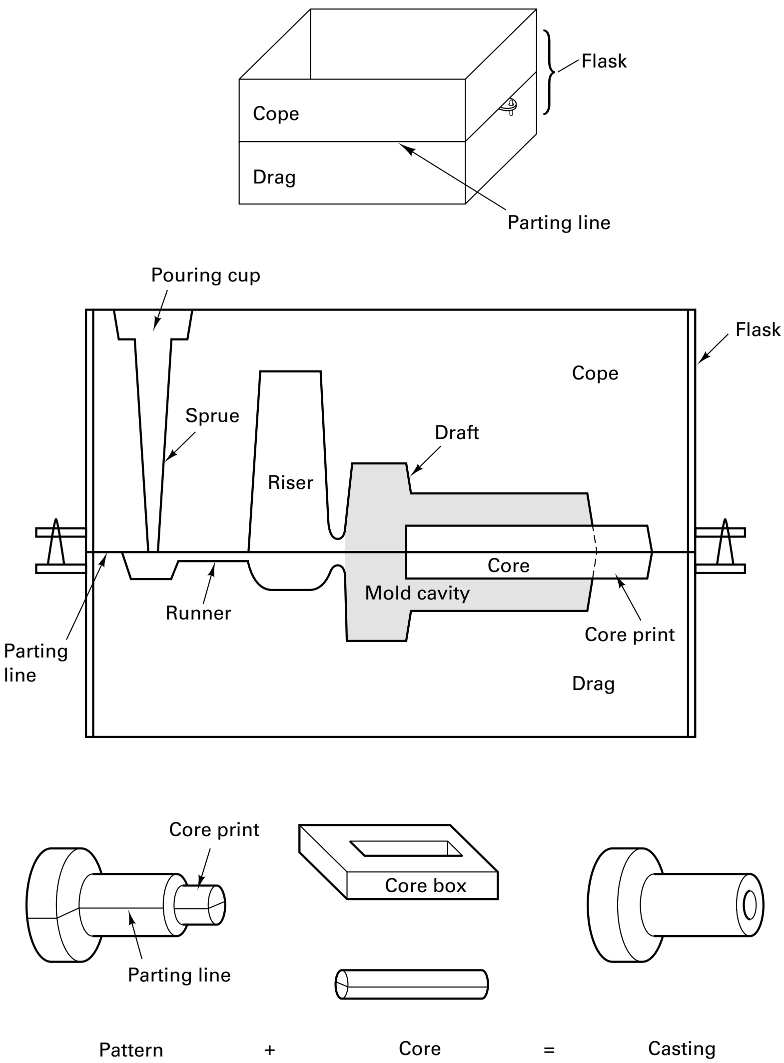


FIGURE 13.2 Cross section of a typical two-part sand mold indicating various mold components and terminology.

13.4 The Solidification Process

Casting is a **solidification** process where the molten material is poured into a mold and then allowed to freeze into the desired final shape. Many of the structural features that ultimately control product properties are set during solidification. Furthermore, many casting defects, such as **gas porosity** and **solidification shrinkage**, are also solidification phenomena, and they can be reduced or eliminated by controlling the solidification process.

Solidification is a two-stage, nucleation and growth, process, and it is important to control both of these stages. **Nucleation** occurs when stable particles of solid form from within the molten liquid. When a material is at a temperature below its melting point, the solid state has a lower energy than the liquid. As solidification occurs, there is a release of energy. At the same time, however, interface surfaces are created between the new solid and the parent liquid. Formation of these surfaces requires energy. For nucleation to proceed, there must be a net reduction or release of energy. As a result, nucleation generally begins at a temperature somewhat below the equilibrium melting point (the temperature where the internal energies of the liquid and solid are equal). The difference between the melting point and the actual temperature of nucleation is known as the amount of **undercooling**.

If nucleation can occur on some form of existing surface, the creation of a full surrounding interface is no longer necessary, and the required surface energy is reduced. Such surfaces are usually present in the form of mold or container walls, or solid impurity particles contained within the molten liquid. When ice cubes are formed in a tray, for example, the initial solid forms on the walls of the container. The same phenomena can be expected with metals and other engineering materials.

Each nucleation event produces a crystal or grain in the final casting. Because fine-grained materials (many small grains) possess enhanced mechanical properties, efforts may be made to promote nucleation. Particles of existing solid may be introduced into the liquid before it is poured into the mold. These particles provide the surfaces required for nucleation and promote the formation of a uniform, fine-grained product. This practice of introducing solid particles is known as **inoculation** or **grain refinement**.

The second stage in the solidification process is **growth**, which occurs as the heat of fusion is extracted from the liquid material. The direction, rate, and type of growth can be controlled by the way in which this heat is removed. **Directional solidification**, where the solidification interface sweeps continuously through the material, can be used to ensure the production of a sound casting. The molten material on the liquid side of the interface can flow into the mold to continuously compensate for the shrinkage that occurs as the material changes from liquid to solid. The relative rates of nucleation and growth control the size and shape of the resulting crystals. Faster rates of cooling generally produce products with finer grain size and superior mechanical properties.

Cooling Curves

Cooling curves, such as those introduced in Chapter 4, can be one of the most useful tools for studying the solidification process. By inserting thermocouples into a casting and recording the temperature versus time, one can obtain valuable insight into what is happening in the various regions.

Figure 13.3 shows a typical cooling curve for a pure or eutectic-composition material (one with a distinct melting point) and is useful for depicting many of the features and terms related to solidification. The **pouring temperature** is the temperature of the liquid metal when it first enters the mold. **Superheat** is the difference between the pouring temperature and the freezing temperature of the material. Most

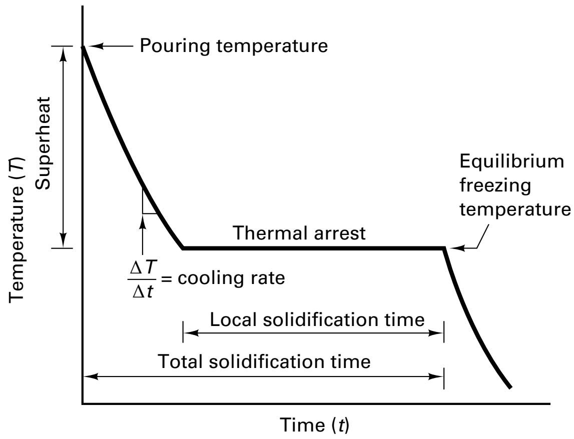


FIGURE 13.3 Cooling curve for a pure metal or eutectic-composition alloy (metals with a distinct freezing point) indicating major features related to solidification.

metals are poured at temperatures of 100–200°C (200–400°F) above which solid begins to form. The higher the superheat, the more time is given for the material to flow into the intricate details of the mold cavity before it begins to freeze. The **cooling rate** is the rate at which the liquid or solid is cooled and can be viewed as the slope of the cooling curve at any given point. The **thermal arrest** is the plateau in the cooling curve that occurs during the solidification of a material with fixed melting point. At this temperature, the energy or heat being removed from the mold comes from the latent heat of fusion that is being released during the solidification process. The time from the start of pouring to the end of solidification is known as the **total solidification time**. The time from the start of solidification to the end of solidification is the **local solidification time**.

If the metal or alloy does not have a distinct melting point, such as the copper–nickel alloy shown in **Figure 13.4**, solidification will occur over a range of temperatures. The **liquidus** temperature is the lowest temperature where the material is all liquid, and the **solidus** temperature is the highest temperature where it is all solid. The region between the liquidus and solidus temperatures is known as the **freezing range**. The onset and termination of solidification appear as slope changes in the cooling curve.

The actual form of a cooling curve will depend on the type of material being poured, the nature of the nucleation process, and the rate and means of heat removal from the mold. By analyzing experimental cooling curves, we can gain valuable insight into both the casting process and the cast product. Fast cooling rates and short solidification times generally lead to finer structures and improved mechanical properties.

Prediction of Solidification Time: Chvorinov's Rule

The amount of heat that must be removed from a casting to cause it to solidify depends on both the amount of superheating and the volume of metal in the casting. Conversely, the ability to

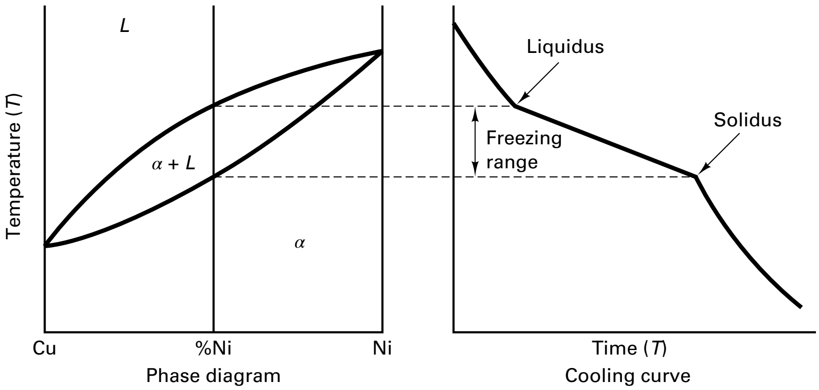


FIGURE 13.4 Phase diagram and companion cooling curve for an alloy with a freezing range. The slope changes indicate the onset and termination of solidification.

remove heat from a casting is directly related to the amount of exposed surface area through which the heat can be extracted and the environment surrounding the molten material (i.e., the mold and mold surroundings). These observations are reflected in **Chvorinov's rule**,[1] which states that the total solidification time, t_s, can be computed by:

$$t_s = B(V/A)^n \quad \text{where } n = 1.5 \text{ to } 2.0 \qquad (13.1)$$

The total solidification time, t_s, is the time from pouring to the completion of solidification; V is the volume of the casting; A is the surface area through which heat is extracted; and B is the **mold constant**. The mold constant, B, incorporates the characteristics of the metal being cast (heat capacity and heat of fusion), the mold material (heat capacity and thermal conductivity), the mold thickness, initial mold temperature, and the amount of superheat.

Test specimens can be cast to determine the value of B for a given mold material, casting material, and condition of casting. This value can then be used to compute the solidification times for other castings made under the same conditions. Because a riser and casting both lie within the same mold and fill with the same metal under the same conditions, Chvorinov's rule can be used to compare the solidification times of each and thereby ensure that the riser will solidify after the casting. This condition is absolutely essential if the liquid within the riser is to effectively feed the casting and compensate for solidification shrinkage. Aspects of riser design, including the use of Chvorinov's rule, will be developed later in this chapter.

Different cooling rates and solidification times can produce substantial variation in the structure and properties of the resulting casting. Die casting, for example, uses water-cooled metal molds, and the faster cooling produces higher-strength products than sand casting, where the mold material is more thermally insulating. Even variations in the type and condition of sand can produce different cooling rates. Sands with high moisture contents extract heat faster than ones with low moisture. **Table 13.1** presents a comparison of the properties of aluminum alloy 443 cast by the three different processes: sand casting (slow cool), permanent mold casting (intermediate cooling rate), and die casting (fast cool).

The Cast Structure

The products that result when a molten metal is poured into a mold and permitted to solidify may have as many as three distinct regions or zones. The rapid nucleation that occurs when molten metal contacts the cold mold walls results in the production of a **chill zone**, a narrow band of randomly oriented crystals on the surface of a casting. As additional heat is removed, the grains of the chill zone begin to grow inward, and the rate of heat extraction and solidification decreases. Because most crystals have directions of rapid growth, a selection process begins. Crystals with rapid-growth direction perpendicular to the casting surface grow fast and shut off adjacent grains whose rapid-growth direction is at some intersecting angle.

The favorably oriented crystals continue to grow, producing the long, thin columnar grains of a **columnar zone**. The properties of this region are highly directional because the selection process has converted the purely random structure of the surface into one of parallel crystals of similar orientation. **Figure 13.5** shows a cast structure containing both chill and columnar zones.

In many materials, new crystals then nucleate in the interior of the casting and grow to produce another region of spherical, randomly oriented crystals, known as the **equiaxed zone**. Low pouring temperatures, addition of alloy, and addition of inoculants can be used to promote the formation of this region, whose isotropic properties (uniform in all directions) are far more desirable than those of columnar grains.

Molten Metal Problems

Castings begin with molten metal, and there are a number of chemical reactions that can occur between molten metal and its surroundings. These reactions and their products can often lead to defects in the final casting. For example, oxygen and molten metal can react to produce metal oxides (a nonmetallic or ceramic material), which can then be carried away with the molten metal during the pouring and filling of the mold. **Dross** or

TABLE 13.1 Comparison of the As-Cast Properties of Alloy 443 Aluminum Cast by Three Different Processes

Process	Yield Strength (MPa/ksi)	Tensile Strength (MPa/ksi)	Elongation (%)
Sand Cast	55/8	131/19	8
Permanent Mold	62/9	158/23	10
Die Cast	110/16	227/33	9

[1]N. Chvorinov, "Theory of Casting Solidification," *Giesserei*, Vol. 27, 1940, pp. 177–180, 201–208, 222–225.

FIGURE 13.5 Internal structure of a cast metal bar showing the chill zone at the periphery, columnar grains growing toward the center, and a central shrinkage cavity. (Courtesy Ronald Kohser.)

slag can become trapped in the casting and impair surface finish, machinability, and mechanical properties. Material eroded from the linings of furnaces and pouring ladles, and loose sand particles from the mold surfaces, can also contribute nonmetallic components to the casting.

Dross and slag can be controlled by using special precautions during melting and pouring and by good mold design. Lower pouring temperatures or superheat slows the rate of dross-forming reactions. Fluxes can be used to cover and protect molten metal during melting, or the melting and pouring can be performed under a vacuum or protective atmosphere. Measures can be taken to agglomerate the dross and cause it to float to the surface of the metal, where it can be skimmed off prior to pouring. Special ladles can be used that extract metal from beneath the surface, such as those depicted in **Figure 13.6**. Gating systems can be designed to trap any dross, sand, or eroded mold material and keep it from flowing into the

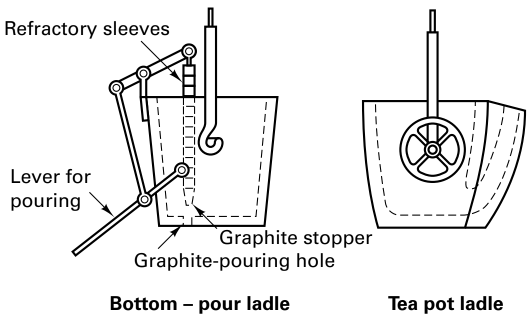


FIGURE 13.6 Two types of ladles are used to pour castings. Note how each extracts molten material from the bottom, avoiding transfer of the impure material from the top of the molten pool.

mold cavity. In addition, ceramic **filters** can be inserted into the feeder channels of the mold. These filters are available in a variety of shapes, sizes, and materials and will be discussed later in this chapter.

Liquid metals can also contain significant amounts of dissolved gas. When these materials solidify, the solid structure cannot accommodate as much gas, and the rejected atoms form bubbles or **gas porosity** within the casting. **Figure 13.7** shows the maximum solubility of hydrogen in aluminum as a function of temperature. Note the substantial decrease that occurs as the material goes from liquid to solid. **Figure 13.8** shows a small demonstration casting that has been made from aluminum where the liquid had been saturated with dissolved hydrogen.

Several techniques can be used to prevent or minimize the formation of gas porosity. One approach is to prevent the gas from initially dissolving in the molten metal. Melting can be performed under vacuum, in an environment of low-solubility gases, or under a protective flux that excludes contact with the air. Superheat temperatures can be kept low to minimize gas solubility. In addition, careful handling and pouring can do much to control the flow of molten metal and minimize the turbulence that brings air and molten metal into contact.

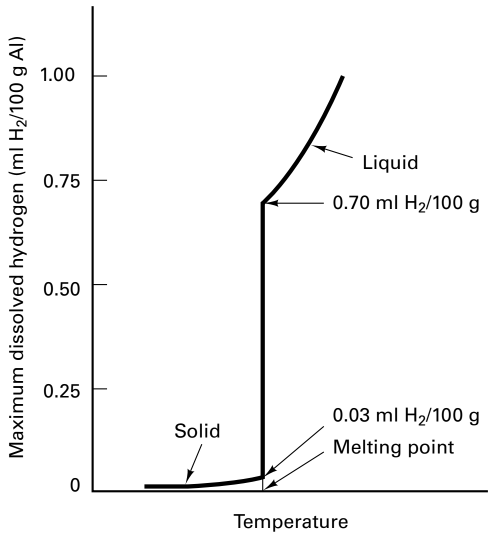


FIGURE 13.7 The maximum solubility of hydrogen in aluminum as a function of temperature.

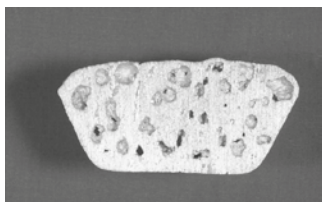


FIGURE 13.8 Demonstration casting made from aluminum that has been saturated in dissolved hydrogen. Note the extensive gas porosity. (Courtesy Ronald Kohser.)

Another approach is to remove the gas from the molten metal before it is poured into castings. **Vacuum degassing** sprays the molten metal through a low-pressure environment. Spraying creates a large amount of surface area, and the amount of dissolved gas is reduced as the material seeks to establish equilibrium with its new surroundings. (See a discussion of Sievert's law in any basic chemistry text.) Passing small bubbles of inert or reactive gas through the melt, known as **gas flushing**, can also be effective. In seeking equilibrium, the dissolved gases enter the flushing gas and are carried away. Bubbles of nitrogen or chlorine, for example, are particularly effective in removing hydrogen from molten aluminum. Ultrasonic vibrations, alone or with an assist gas, have also been shown to be quite effective in degassing aluminum alloys.

The dissolved gas can also be reacted with something to produce a low-density compound, which then floats to the surface and can be removed with the dross or slag. Oxygen can be removed from copper by the addition of phosphorus. Steels can be deoxidized with addition of aluminum or silicon. The resulting phosphorus, aluminum, or silicon oxides are then removed by skimming, or are left on the top of the container as the remaining high-quality metal is extracted from beneath the surface.

Fluidity and Pouring Temperature

When molten metal is poured to produce a casting, it should first *flow* into all regions of the mold cavity and then *freeze* into this new shape. It is vitally important that these two functions occur in the proper sequence. If the metal begins to freeze before it has completely filled the mold, defects known as **misruns** and **cold shuts** are produced.

The ability of a metal to flow and fill a mold, the "runniness" of the liquid, is known as **fluidity**, and casting alloys are often selected for this property. Fluidity affects the minimum section thickness that can be cast, the maximum length of a thin section, the fineness of detail, and the ability to fill mold extremities. Although no single method has been accepted to measure fluidity, various "standard molds" have been developed where the results are sensitive to metal flow. One popular approach, illustrated in **Figure 13.9**, produces castings in the form of a long, thin spiral that progresses outward from a central sprue. The length of the resulting casting will increase with increased fluidity.

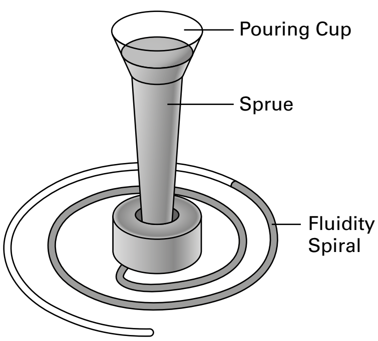


FIGURE 13.9 Fluidity test using a spiral mold. The distance that the liquid travels prior to solidification is taken as a measure of metal fluidity.

Fluidity is dependent on the composition, freezing temperature, and freezing range of the metal or alloy, as well as the surface tension of oxide films. The most important controlling factor, however, is usually the pouring temperature or the amount of superheat. The higher the pouring temperature, the higher the fluidity. Excessive temperatures should be avoided, however. At high pouring temperatures, chemical reactions between the metal and the mold, and the metal and its pouring atmosphere, are all accelerated. Dross formation is promoted, and larger amounts of gas can be dissolved.

If the metal is too runny, however, it may also flow into the small voids between the particles that compose a sand mold. The result of this intrusion is a casting surface that contains small particles of embedded sand, a defect known as **penetration**.

The Role of the Gating System

When molten metal is poured into a mold, the gating system conveys the material and delivers it to all sections of the mold cavity. The speed or rate of metal movement is important, as well as the amount of cooling that occurs while it is flowing. Slow filling and high loss of heat can result in misruns and cold shuts. Rapid rates of filling, on the other hand, can produce erosion of the gating system and mold cavity and might result in the entrapment of mold material in the final casting. It is imperative that the cross-sectional areas of the various channels be selected to regulate flow. The shape and length of the channels affect the amount of temperature loss. When heat loss is to be minimized, short channels with round or square cross sections (minimum surface area) are the most desirable. The gates are usually attached to the thickest or heaviest sections of a casting to control shrinkage, and to the bottom of the casting to minimize turbulence and splashing. For large castings, multiple gates and runners may be used to introduce metal to more than one point of the mold cavity.

Gating systems should be designed to minimize **turbulent flow**, which tends to promote absorption of gases, oxidation of the metal, and erosion of the mold. **Figure 13.10** shows a typical gating system for a mold with a horizontal parting line and can be used to identify some of the key components that can be optimized to promote the smooth flow of molten metal. Short sprues are desirable because they minimize the distance that the metal must fall when entering the mold and the kinetic energy that the metal acquires during that fall. Rectangular pouring cups prevent the formation of a vortex or spiraling funnel, which tends to suck gas and oxides into the sprue. Tapered sprues also prevent vortex formation. A large **sprue well** can be used to dissipate the kinetic energy of the falling stream and prevent splashing and turbulence as the metal makes the turn into the runner.

The smallest cross-sectional area in the gating system, known as the **choke**, serves to control the rate of metal flow. If the choke is located near the base of the sprue, flow through the runners and gates is slowed, and flow is rather smooth. If the choke is moved to the gates, the metal might enter the mold cavity with a fountain effect, an extremely turbulent mode of flow, but the small connecting area would enable easier separation of the casting and gating system.

Gating systems can also be designed to trap dross and sand particles and keep them from entering the mold cavity. Given sufficient time, the lower-density contaminants will rise to the top of the molten metal. Long, flat runners can be beneficial (but these promote cooling of the metal), as well as gates that exit from the lower portion of the runners. Because the first metal to enter the mold is most likely to contain the foreign matter (dross from the top of the pouring ladle and loose particles washed from the walls of the gating system), **runner extensions** and **runner wells** (see Figure 13.10) can be used to catch and trap this first metal and keep it from entering the mold cavity. These features are particularly effective with aluminum castings because aluminum oxide has approximately the same density as molten aluminum.

Screens or ceramic **filters** of various shapes, sizes, and materials can also be inserted into the gating system to trap foreign material. Wire mesh can often be used with the nonferrous metals, but ceramic materials are generally required for irons and steel. **Figure 13.11** shows several ceramic filters and depicts the two basic types—extruded and foam. The pores on the extruded ceramics are uniform in size and shape and provide parallel channels. The foams contain interconnected pores of various size and orientation, forcing the material to change direction as it negotiates its passage through the filter. Contaminant removal can be by either a particle entrapment or a wetting action, whereby the nonmetallic contaminant adheres to the filter surface as the metal, which does not wet, flows freely through.

Because these devices can also restrict the fluid velocity, streamline the fluid flow, or reduce turbulence, proper placement is an important consideration. To ensure removal of both dross and eroded sand, the filter should be as close to the mold cavity as possible, but because a filter can also act as the choke, it may be positioned at other locations, such as the base of the pouring cup, base of the sprue, or in one or more of the runners.

The specific details of a gating system often vary with the metal being cast. Turbulent-sensitive metals (such as aluminum and magnesium) and alloys with low melting points generally employ gating systems that concentrate on eliminating turbulence and trapping dross. Turbulent-insensitive alloys (such as steel, cast iron, and most copper alloys) and alloys with a high melting point generally use short, open gating systems that provide for quick filling of the mold cavity.

Solidification Shrinkage

Most metals and alloys undergo a noticeable volumetric contraction once they enter the mold cavity and begin to cool. **Figure 13.12** shows the typical changes experienced by a metal column as the material goes from superheated liquid to room-temperature solid. There are three principal stages of **shrinkage**: (1) *shrinkage of the liquid* as it cools to the temperature where solidification begins, (2) *solidification shrinkage* as the liquid turns into solid, and (3) *solid metal contraction* as the solidified material cools to room temperature.

The amount of liquid metal contraction depends on the coefficient of thermal contraction (a property of the metal being cast) and the amount of superheat. Liquid contraction is rarely a problem, however, because the metal in the gating system continues to flow into the mold cavity as the liquid already in the cavity cools and contracts.

As the metal changes state from liquid to crystalline solid, the new atomic arrangement is usually more efficient, and significant amounts of shrinkage can occur. The actual amount of shrinkage varies from metal to metal or alloy to alloy, as provided in **Table 13.2**. As indicated in that table, not all metals contract upon solidification. Some actually expand, such as gray

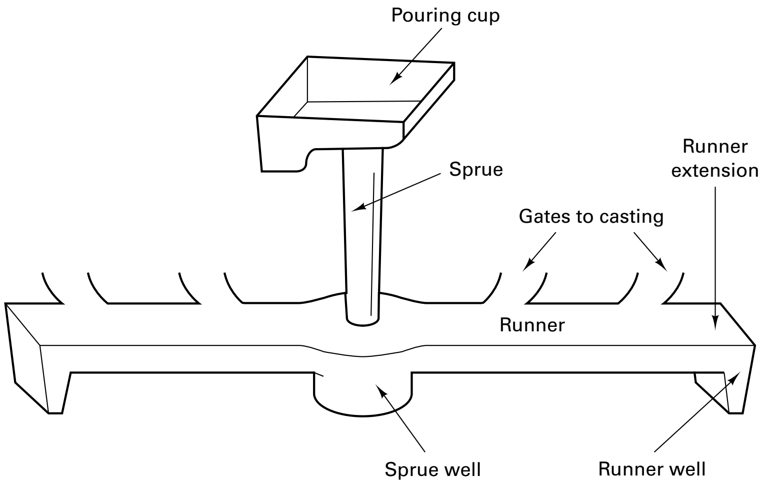


FIGURE 13.10 Typical gating system for a horizontal-parting-plane mold, showing key components involved in controlling the flow of metal into the mold cavity.

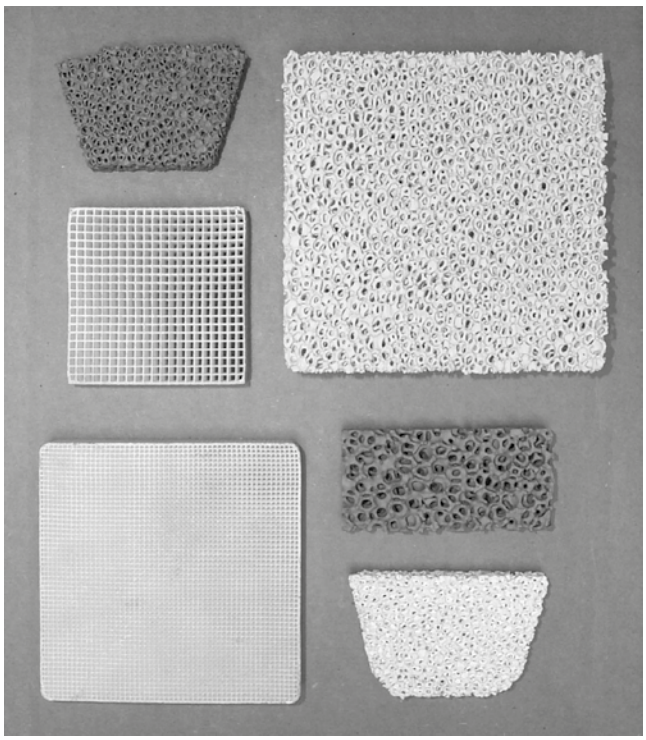


FIGURE 13.11 Various types of ceramic filters that may be inserted into the gating systems of metal castings. (Courtesy Ronald Kohser.)

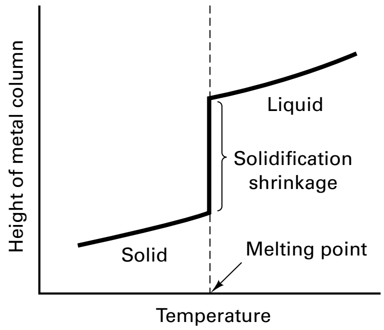


FIGURE 13.12 Dimensional changes experienced by a metal column as the material cools from a superheated liquid to a room-temperature solid. Note the significant shrinkage that occurs on solidification.

TABLE 13.2 Solidification Shrinkage of Some Common Engineering Metals (Expressed in Percent)

Aluminum	6.6
Copper	4.9
Magnesium	4.0
Zinc	3.7
Low-carbon steel	2.5–3.0
High-carbon steel	4.0
White cast iron	4.0–5.5
Gray cast iron	−1.9

cast iron, where low-density graphite flakes form as part of the solid structure.

When solidification shrinkage does occur, however, it is important to control the form and location of the resulting void. Metals and alloys with short freezing ranges, such as pure metals and eutectic alloys, tend to form large cavities or pipes. These can be avoided by designing the casting to have directional solidification where freezing begins farthest away from the feed gate or riser and moves progressively toward it. As the metal solidifies and shrinks, the mold cavity is continually being filled with additional liquid metal. When the flow of additional liquid is exhausted and solidification is complete, we hope that the final shrinkage void is located external to the desired casting in either the riser or the gating system.

Alloys with large freezing ranges have a period of time when the material is in a slushy (liquid plus solid) condition. As the material cools between the liquidus and solidus, the relative amount of solid increases and tends to trap small, isolated pockets of liquid. It is almost impossible for additional liquid to feed into these locations, and the resultant casting tends to contain small but numerous shrinkage pores dispersed throughout. This type of shrinkage is far more difficult to prevent by means of gating and risering, and a porous product may be inevitable. If a gas- or liquid-tight product is required, these castings may need to be impregnated (the pores filled with a resinous material or lower-melting-temperature metal) in a subsequent operation. Castings with dispersed porosity tend to have poor ductility, toughness, and fatigue life.

After solidification is complete, the casting will contract further as it cools to room temperature. This solid metal contraction is often called *patternmaker's contraction* because compensation for these dimensional changes should be made when the mold cavity or pattern is designed. Examples of these compensations will be provided later in this chapter. Concern arises, however, when the casting is produced in a rigid mold, such as the metal molds used in die casting. If the mold provides constraint during the time of contraction, tensile forces can be generated within the hot, weak casting, and cracking can occur (**hot tears**). It is often desirable, therefore, to eject the hot castings as soon as solidification is complete.

Risers and Riser Design

Risers are added reservoirs designed to fill with liquid metal, which is then fed to the casting as a means of compensating for solidification shrinkage. To effectively perform this function, the risers must solidify after the casting. If the reverse were true, liquid metal would flow from the casting toward the solidifying riser, and the casting shrinkage would be even greater. Hence, castings should be designed to produce directional solidification that sweeps from the extremities of the mold cavity toward the riser. In this way, the riser can continuously feed molten metal and will compensate for the solidification shrinkage of the entire mold cavity. **Figure 13.13** shows a three-level step block cast in aluminum with and without a riser. Note that the riser is positioned, therefore directional solidification moves from thin to thick, and the shrinkage void is moved from the casting to the riser. If a single directional solidification is not

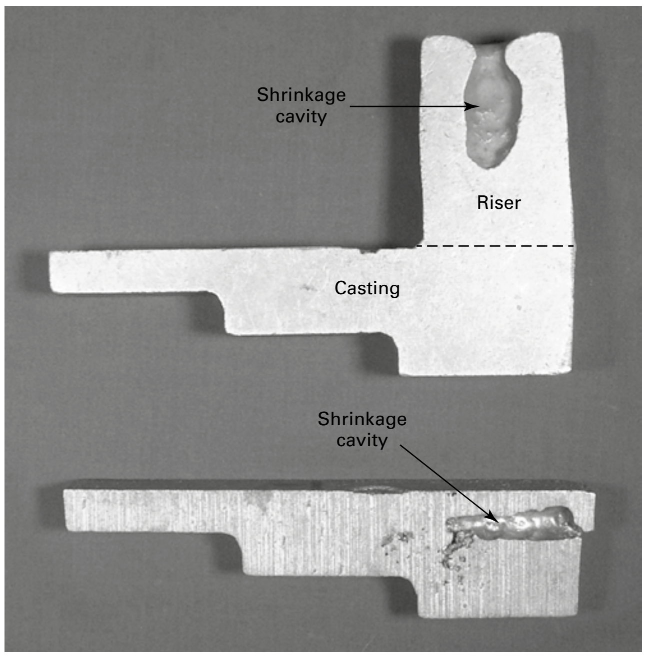


FIGURE 13.13 A three-tier step-block aluminum casting made with (top) and without (bottom) a riser. Note how the riser has moved the shrinkage void external to the desired casting. (Courtesy Ronald Kohser.)

possible, multiple risers may be required, with various sections of the casting each solidifying toward their respective riser.

The risers should also be designed to conserve metal. If we define the **yield** of a casting as the casting weight divided by the total weight of metal poured (complete gating system, risers, and casting), it is clear that there is a motivation to make the risers as small as possible, yet still able to perform their task. This is usually done through proper consideration of riser size, shape, and location, as well as the type of connection between the riser and casting.

A good shape for a riser would be the one that has a long freezing time. According to Chvorinov's rule, this would favor a shape with small surface area per unit volume. Although a sphere would make the most efficient riser, this shape presents considerable difficulty to both patternmaker and moldmaker. The most popular shape for a riser, therefore, is a cylinder, where the height-to-diameter ratio varies depending on the nature of the alloy being cast, the location of the riser, the size of the flask, and other variables. A one-to-one height-to-diameter ratio is generally considered to be ideal.

Risers should be located so that directional solidification occurs from the extremities of the mold cavity back toward the riser. Because the thickest regions of a casting will be the last to freeze, risers should feed directly into these locations. Various types of risers are possible. A **top riser** is one that sits on top of a casting. Because of their location, top risers have shorter feeding distances and occupy less space within the flask. They give the designer more freedom for the layout of the pattern and gating system. **Side risers** are located adjacent to the mold cavity and displaced horizontally along the parting line. **Figure 13.14** depicts both a top and a side riser. If the riser is contained entirely within the mold, it is known as a **blind riser**. If it is open to the atmosphere, it is called an **open riser**. Blind risers are usually larger than open risers because of the additional heat loss that occurs where the top of the riser is in contact with mold material.

Live risers (also known as *hot risers*) receive the last hot metal that enters the mold and generally do so at a time when the metal in the mold cavity has already begun to cool and solidify. Thus, they can be smaller than **dead** (or *cold*) **risers**, which fill with metal that has already flowed through the mold cavity. As shown in Figure 13.14, top risers are almost always dead risers. Risers that are part of the gating system are generally live risers.

The minimum size of a riser can be calculated from Chvorinov's rule by setting the total solidification time for the riser to be greater than the total solidification time for the casting. Because both cavities receive the same metal and are in the same mold, the mold constant, B, will be the same for both regions. Assuming that $n = 2$, and a safe difference in solidification time is 25% (the riser takes 25% longer to solidify than the casting), we can write this condition as

$$t_{\text{riser}} = 1.25\ t_{\text{casting}} \tag{13.2}$$

or

$$(V/A)^2_{\text{riser}} = 1.25\ (V/A)^2_{\text{casting}} \tag{13.3}$$

Calculation of the riser size then requires selection of riser geometry, which is generally cylindrical. For a cylinder of diameter D and height H, the volume and surface area can be written as:

$$V = \pi D^2 H/4$$
$$A = \pi DH + 2(\pi D^2/4)$$

Selecting a specific height-to-diameter ratio for the riser then enables Equation (13.3) to be written as a simple expression with one unknown, D. The volume-to-area ratio for the casting is computed for its particular geometry, and Equation (13.3) can then be solved to provide the size of the required riser. One should note that if the riser and casting share a surface, as with a blind top riser, the area of the common surface should be subtracted from both components because it will not be a surface of heat loss to either. It should also be noted that there are a number of methods to calculate riser size. The Chvorinov's rule method will be the only one presented here.

A final aspect of riser design is the connection between the riser and the casting. Because the riser must ultimately be separated from the casting, it is desirable that the connection area be as small as possible. On the other hand, the connection area must be sufficiently large so that the link does not freeze before solidification of the casting is complete. If the risers are placed close to the casting with relatively short connections, the mold material surrounding the link will receive heat from both the casting and the riser. It should heat rapidly and remain hot throughout the cast, thereby preventing solidification of the metal in the channel.

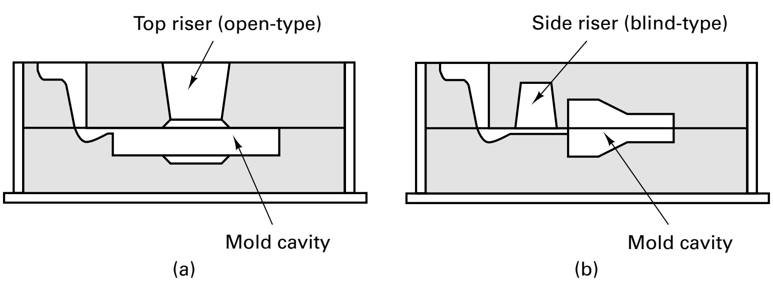


FIGURE 13.14 Schematic of a sand casting mold showing (a) an open-type top riser and (b) a blind-type side riser (right). The side riser is a live riser receiving the last hot metal to enter the mold. The top riser is a dead riser receiving metal that has flowed through the mold cavity.

Risering Aids

Various methods have been developed to assist the risers in performing their job. Some are intended to promote directional solidification, whereas others seek to reduce the number and size of the risers, thereby increasing the yield of a casting. These techniques generally work by either speeding the solidification of the casting (**chills**) or retarding the solidification of the riser (**sleeves** or toppings).

External chills are masses of high-heat-capacity and high-thermal-conductivity materials (such as steel, iron, graphite, or copper) that are placed in the mold adjacent to the casting to absorb heat and accelerate the cooling of various regions. Chills can promote directional solidification or increase the effective feeding distance of a riser. They can also be used to reduce the number of risers required for a casting. External chills are frequently covered with a protective wash, silica flour, or other refractory material to prevent bonding with the casting.

Internal chills are pieces of metal that are placed within the mold cavity to absorb heat and promote more rapid solidification. When the molten metal of the pour surrounds the chill, it absorbs heat as it seeks to come to equilibrium with its surroundings. Internal chills ultimately become part of the final casting, so they must be made from an alloy that is the same or compatible with the alloy being cast.

The cooling of risers can be slowed by methods that include (1) switching from a blind riser to an open riser, (2) placing **insulating sleeves** around the riser, and (3) surrounding the sides or top of the riser with **exothermic material** that supplies added heat just to the riser segment of the mold. The objective of these techniques is generally to reduce the riser size rather than promote directional solidification.

It is important to note that risers are not always necessary or functional. For alloys with large freezing ranges, risers would not be particularly effective, and one generally accepts the fine, dispersed porosity that results. For processes such as die casting, low-pressure permanent molding, and centrifugal casting, the positive pressures associated with the process provide the feeding action that is required to compensate for solidification shrinkage.

13.5 Patterns

Casting processes can be divided into two basic categories: (1) those for which a new mold must be created for each casting (the **expendable-mold processes**), and (2) those that employ a permanent, **reusable mold**. Most of the expendable-mold processes begin with some form of reusable **pattern**—a physical representation of the object to be cast, modified dimensionally to reflect both the casting process and the material being cast. Patterns can be made from a variety of materials. In order of increasing longevity, these include Styrofoam or wax (single-use), soft wood (100 molds), hard wood (500 molds), epoxies and urethanes (750 to 1000 molds), aluminum (2000 molds), and iron (5000 molds). Urethane is currently the material of choice for nearly half of all casting patterns.

The dimensional modifications that are incorporated into a pattern are called **allowances**, and the most important of these is the **shrinkage allowance**. Following solidification, a casting continues to contract as it cools to room temperature, the amount of this contraction being as much as 2% or 20 mm/m (¼ in./ft). To produce the desired final dimensions, the pattern (which sets the dimensions on solidification) must be slightly larger than the room-temperature casting. The exact amount of this shrinkage compensation depends on the metal that is being cast and can be estimated by the equation:

$$\Delta \text{ length} = \text{length } \alpha \, \Delta T \tag{13.4}$$

where α is the coefficient of thermal expansion and ΔT is the difference between the freezing temperature and room temperature. Typical allowances for some common engineering metals are

Cast iron	0.8–1.0%
Steel	1.5–2.0%
Aluminum	1.0–1.3%
Magnesium	1.0–1.3%
Brass	1.5%

Shrinkage allowances are often incorporated into a pattern using special **shrink rules**—measuring devices that are larger than a standard rule by an appropriate shrink allowance. For example, a shrink rule for brass would designate 0.1 meter at a length that is actually 0.1015 meters (1 ft would become 1 ft 3⁄16 in.), to accommodate the anticipated 1.5% shrinkage. A complete pattern made to shrink rule dimensions will produce a proper size casting after cooling.

Caution should be exercised when using shrink rule compensations, however, because thermal contraction may not be the only factor affecting the final dimensions. The various phase transformations discussed in Chapter 4 are often accompanied by significant dimensional expansions or contractions. Examples include eutectoid reactions, martensitic reactions, and graphitization.

In many casting processes, mold material is formed around the pattern, and the pattern is then extracted to create the mold cavity. To facilitate pattern removal, molds are often made in two or more sections that separate along mating surfaces of the parting line or parting plane. A flat parting line is usually preferred, but the casting design or molding practice may dictate the use of irregular or multiple parting surfaces. In general, the best parting line will be a flat plane that allows for proper metal flow into the mold cavity, requires the fewest cores and molding steps, and provides adequate core support and venting.

If the pattern contains surfaces that are perpendicular to the parting line (parallel to the direction of pattern withdrawal), friction between the pattern and the mold material as well as any horizontal movement of the pattern during extraction could induce damage to the mold. This damage could be particularly severe at the corners where the mold cavity intersects the parting surface. Such extraction damage can be minimized by incorporating a slight taper, or **draft**, on all pattern surfaces that are parallel to the direction of withdrawal. A slight withdrawal of the pattern will free it from the mold material on all surfaces, and it can then be further removed without damage to the mold. **Figure 13.15** illustrates the use of draft to facilitate pattern removal.

The size and shape of the pattern, the depth of the mold cavity, the method used to withdraw the pattern, the pattern material, the mold material, and the molding procedure all influence the amount of draft required. Draft is seldom less than 1 degree or 10 mm/m (⅛ in./ft), with a minimum taper of about 1.6 mm (1⁄16 in.) over the length of any surface. Because draft allowances increase the size of a pattern (and thus the size and weight of a casting), it is generally desirable to keep them to the minimum that will permit satisfactory pattern removal. Molding procedures that produce higher-strength molds and the use of mechanical pattern withdrawal can often enable reductions

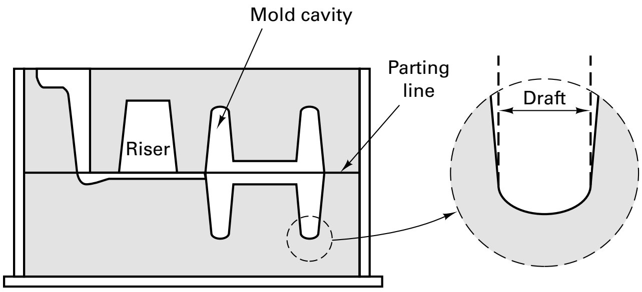


FIGURE 13.15 Two-part mold showing the parting line and the incorporation of a draft allowance on vertical surfaces.

in draft allowances. By reducing the taper, casting weight and the amount of subsequent machining can both be reduced.

When smooth machined surfaces are required, it may be necessary to add an additional **machining allowance**, or **finish allowance**, to the pattern. The amount of this allowance depends to a great extent on the casting process and the mold material. Ordinary sand castings have rougher surfaces than those of shell-mold castings. Die castings have smooth surfaces that may require little or no metal removal, and the surfaces of investment castings are even smoother. It is also important to consider the location of the desired machining and the presence of other allowances because the draft allowance may provide part or all of the extra metal needed for machining.

Some casting shapes require yet an additional allowance for **distortion**. Consider a U-shaped section where the arms are restrained by the mold at a time when the base of the U is shrinking. The result will be a final casting with outwardly sloping arms. If the design is modified to have the arms originally slope inward, the subsequent distortion will produce the desired final shape. Distortion depends greatly on the particular configuration of the casting, and casting designers must use experience and judgment to provide an appropriate distortion allowance.

If a casting is to be made in a multiuse metal mold, all of the "pattern allowances" should be incorporated into the machined cavity. The dimensions of this cavity will further change, however, as sequential casts raise the mold temperature to a steady-state level. An additional correction should be added to compensate for the thermal effect.

Similar allowances should be applied to the cores that create the holes and interior passages of a casting.

13.6 Design Considerations in Castings

To produce the best-quality product at the lowest possible cost, it is important that the designers of castings give careful attention to several process requirements. It is not uncommon for minor and readily permissible changes in design to greatly facilitate and simplify the casting of a component and also reduce the number and severity of defects.

One of the first features that must be considered by a designer is the *location* and *orientation of the parting plane*, an important part of all processes that use segmented or separable molds. The location of the parting plane can affect (1) the number of cores, (2) the method of supporting the cores, (3) the use of effective and economical gating, (4) the weight of the final casting, (5) the final dimensional accuracy, and (6) the ease of molding.

In general, it is desirable to minimize the use of cores. A change in the location or orientation of the parting plane can often assist in this objective. The change illustrated in **Figure 13.16** not only eliminates the need for a core but also reduces the weight of the casting by eliminating the need for draft. **Figure 13.17** shows another example of how a core can be eliminated by a simple design change. **Figure 13.18** shows six different parting line arrangements for the casting of a simple ring. Arrangements (a) through (e) provide flat and parallel side faces with draft tapers on the inner and outer diameters. The (f) alternative requires the use of a core, but might be preferred if draft cannot be tolerated on the inner and outer diameter surfaces. This figure also shows that simply noting the desired shape and the need to provide sufficient draft can provide considerable design freedom. Because mold closure may not always be consistent, consideration should also be given to the fact that dimensions across the parting plane are subject to greater variation than those that lie entirely within a given segment of the mold.

Control of the solidification process is also related to design. Those portions of a casting that have a high ratio of surface area to volume will experience more rapid cooling and will be stronger and harder than the other regions. Thicker or heavier sections will cool more slowly and may contain shrinkage cavities and porosity, or have weaker, large-grain-size structures.

An ideal casting would have uniform thickness at all locations. Ribs or other geometric features can often be used in place of thicker sections to impart additional strength while maintaining uniform wall thickness. When the section thickness must change, it is best if these changes are gradual, as indicated in the recommendations of **Figure 13.19**.

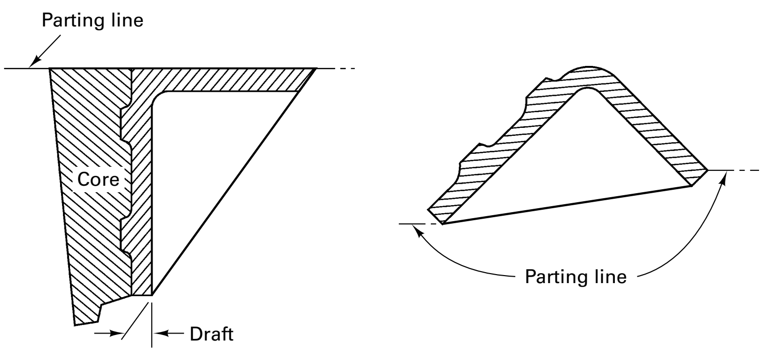


FIGURE 13.16 Elimination of a core by changing the location or orientation of the parting plane.

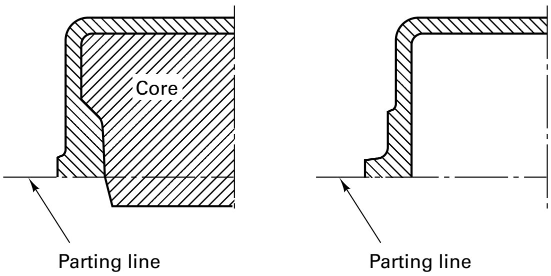


FIGURE 13.17 Elimination of a dry-sand core by a change in part design.

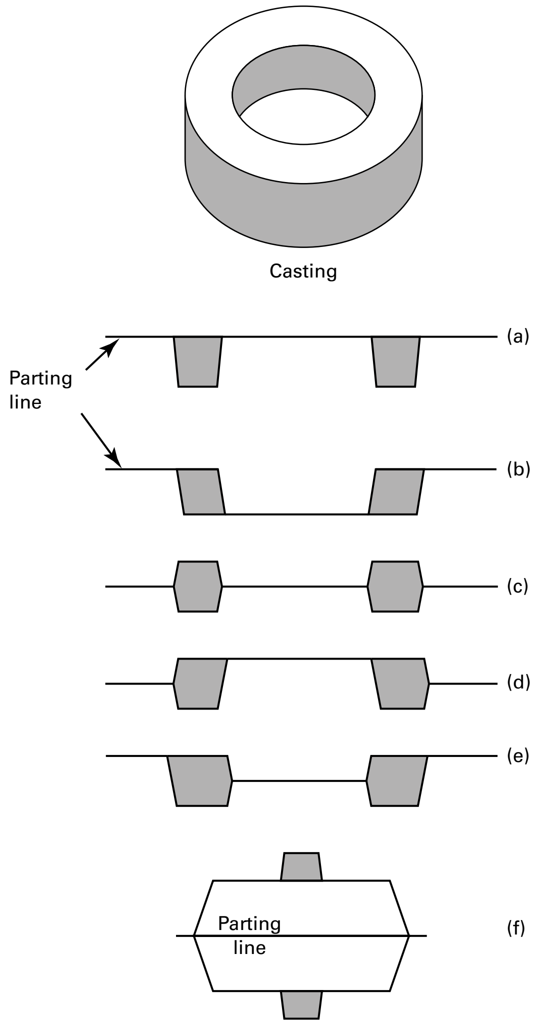


FIGURE 13.18 Multiple options to cast a simple ring with draft to the parting line. Evaluate the six options with respect to the following possible concerns: (1) flat and parallel side surfaces, (2) flat and parallel inner and outer diameters, (3) amount of material that must be removed if no tapers are allowed on any surfaces, and (4) possibility for nonuniform wall thickness if one of the mold segments is shifted with respect to the other.

When sections of castings intersect, as in **Figure 13.20a**, two problems can arise. The first of these is **stress concentration**. Generous **fillets** (inside radii) at all interior corners can better distribute stresses and help to minimize potential problems. If the fillets are excessive, however, the additional material can augment the second problem, known as **hot spots**. Thick sections, like those at the intersection in Figure 13.20a and those illustrated in **Figure 13.21**, cool more slowly than other locations and tend to be the sites of localized shrinkage. Where thick sections must exist, an adjacent riser is often used to feed the section during solidification and ensure that the shrinkage cavity will form external to the actual casting. Sharp exterior corners tend to cool faster than the other sections of a casting. By providing an exterior radius, the surface area can be reduced and cooling slowed to be more consistent with the surrounding material. **Figure 13.20b** shows a recommended modification to Figure 13.20a.

If sections intersect to form continuous ribs, like those in **Figure 13.22**, contraction occurs in opposite directions as each of the arms cool and shrink, and cracking may occur at the intersections, which are also local hot spots. By staggering the ribs, as shown in the lower portion of the left-side figure, the negative effects of thermal contraction and hot spots can be minimized. The bad design in the right-hand segment of Figure 13.22 can be improved by placing a cored hole through the center of the intersection, creating uniform thickness walls throughout. An even better design might be to use an oval-shaped core with the major dimension in the direction of the longest arms to provide the greatest reduction in shrinkage stresses. The best design, shown at the bottom of the right-hand segment, would be to use honeycomb ribs with thickness about 80% of the exterior walls.

The location of the parting line may also be an appearance consideration. A small amount of fin, or **flash**, is often present at the parting line, and when the flash is removed (or left in place if it is small enough), a line of surface imperfection results. If the location is in the middle of a flat surface, the

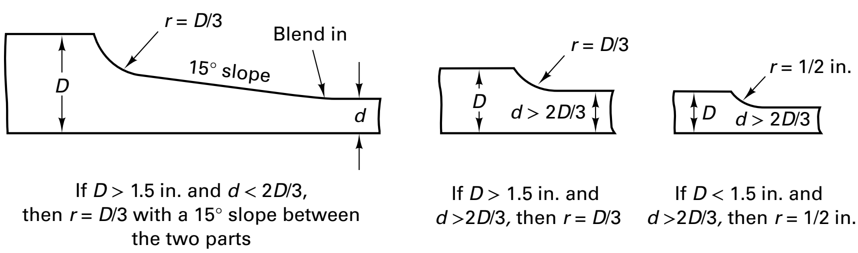


FIGURE 13.19 Typical guidelines for section change transitions in castings.

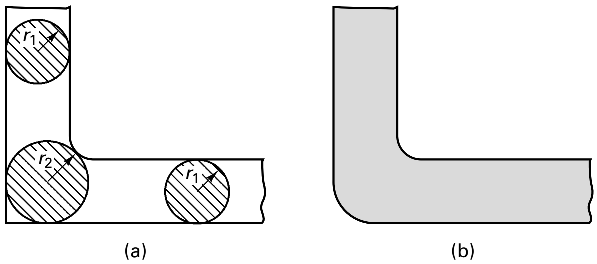


FIGURE 13.20 (a) The "hot spot" at section r_2 is caused by intersecting sections. (b) An interior fillet and exterior radius leads to more uniform thickness and more uniform cooling.

TABLE 13.3 Typical Minimum Section Thickness Values for Various Engineering Metals and Casting Processes

	Minimum Section Thickness (mm.)		
Casting Method	**Aluminum**	**Magnesium**	**Steel**
Sand Casting	3.18	3.96	4.75
Permanent Mold	2.36	3.18	—
Die Cast	1.57	2.36	—
Investment Cast	1.57	1.57	2.36
Plaster Mold	2.03	—	—

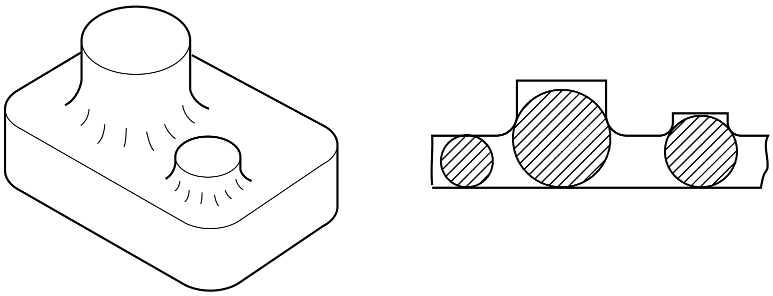


FIGURE 13.21 Hot spots often result from intersecting sections of various thickness.

imperfection will be clearly visible on the product. If the parting line can be moved to coincide with a corner, however, the associated "defect" will go largely unnoticed.

Thin-walled castings are often desired because of their reduced weight, but thin walls can often present manufacturing problems related to mold filling (premature freezing before complete fill). Minimum section thickness should always be considered when designing castings. Specific values are rarely given, however, because they tend to vary with the shape and size of the casting, the type of metal being cast, the method of casting, and the practice of an individual foundry. **Table 13.3** presents typical minimum thickness values for several cast materials and casting processes. Zinc die casting can now produce walls as thin as 0.5 mm.

Casting design can often be aided by **computer simulation**. The mathematics of fluid flow can be applied to **mold filling**, and the principles of heat transfer can be used for **solidification modeling**. The mathematical tools of finite element or finite difference calculations can be coupled with the use of high-speed computers to enable beneficial design changes before the manufacture of patterns or molds. Resulting mechanical properties, thermally induced casting stresses, and the amount and type of distortion can all be quantitatively predicted. The computer model in **Figure 13.23** shows the progressive solidification of a cast steel mining shovel adapter. Note the directional solidification back toward the riser at the left.

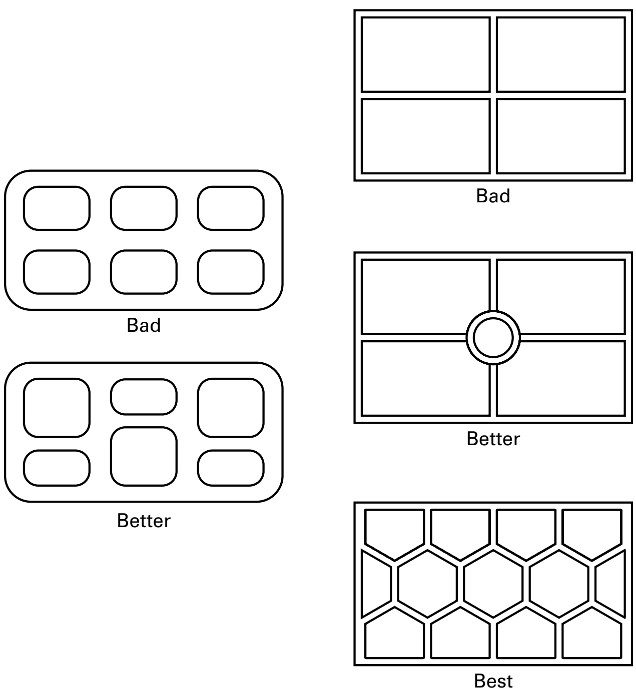


FIGURE 13.22 Design modifications to reduce cracking and hot spot shrinkage in ribbed castings.

13.7 The Casting Industry

The U.S. metal casting industry ships approximately 14 million pounds of castings every year, valued at over $18 billion, with ductile iron, gray iron, aluminum alloys, steel, and copper-base metals comprising the major portion. Metal castings form primary components in agricultural implements, construction equipment, mining equipment, valves and fittings,

FIGURE 13.23 Computer model showing the progressive solidification of a cast steel mining shovel adapter. As time passes (left-to-right) the material directionally solidifies back toward the riser at the left side of the casting. Light material is liquid; dark material is solid. (Copyright 2009, Giesseri-Verlag GmbH, Dusseldorf, Germany.)

metalworking machinery, power tools, pumps and compressors, railroad equipment, power transmission equipment, heating, refrigeration, and air conditioning equipment. Ductile iron pipe is a mainstay for conveying pressurized fluids, and household appliances and electronics all utilize metal castings. The average new vehicle contains more than 270 kg (600 lb) of castings, ranging from engine blocks and wheels to seat-belt retractors and air-bag frames.

Chapter 14 Review Questions

1. What are some of the factors that influence the selection of a specific casting process as a means of making a product?

2. What are the three basic categories of casting processes when classified by molds and patterns?

3. What metals are frequently cast into products?

4. SS What features combine to make cast iron and aluminum the most common cast metals?

5. SS Which type of casting is the most common and most versatile?

6. What is a casting pattern?

7. SS What are some of the materials used in making casting patterns? What features should be considered when selecting a pattern material?

8. What is the simplest and least expensive type of casting pattern?

9. What is a match plate, and how does it aid molding?

10. How is a cope-and-drag pattern different from a match-plate pattern? When might this be attractive?

11. What is the benefit of incorporating gates, runners, and risers onto a match plate?

12. When might separate cope-and-drag patterns be used instead of a match plate?

13. For what types of products might a loose-piece pattern be required?

14. What are the four primary requirements of molding sand?

15. In what ways might molding sand be a compromise material?

16. SS What are the components of a typical green-sand mixture?

17. What is a muller, and what function does it perform?

18. What are some of the properties or characteristics of foundry sands that can be evaluated by standard tests?

19. What is a standard rammed specimen for evaluating foundry sands, and how is it produced?

20. What is permeability, and why is it important in molding sands?

21. SS How does the ratio of water to clay affect the compressive strength of green sand? What is a good starting point ratio?

22. How is the hardness of molding sand determined?

23. How might compactability correlate with moisture content?

24. How does the size and shape of the sand grains relate to molding sand properties?

25. What are the attractive features of silica sand? A negative characteristic?

26. What is a sand expansion defect, and what is its cause?

27. How can sand expansion defects be minimized?

28. What are the pros and cons of olivine and zircon sands?

29. SS What causes “blows” to form in a casting, and what can be done to minimize their occurrence?

30. What features can cause the penetration of molten metal between the grains of the molding sand?

31. What are hot tears, and what can cause them to form?

32. When might hand ramming be the preferred method of packing sand?

33. Describe the distribution of sand density after compaction by sand slinging, jolting, squeezing, and a jolt–squeeze combination.

34. Describe the sequence of activity in match-plate molding.

35. SS How does vertically parted flaskless molding reduce the number of mold sections required to produce a series of castings?

36. What concern has limited the acceptance of the H-process?

37. What is stack molding?

38. SS How might extremely large molds be made?

39. What are the components of green sand?

40. What are some of the limitations or problems associated with green sand as a mold material?

41. What restricts the use of dry-sand molding?

42. What is a skin-dried mold?

43. What are some of the advantages and limitations of the sodium silicate–CO_2 process?

44. SS What provides the strength of no-bake sands?

45. What features or characteristics might justify the higher cost of no-bake sands (compared to green sand)? Make it more attractive than sodium silicate–CO_2?

46. What are some other terms used to describe no-bake molding material?

47. What is bench life? How does it relate to the sodium silicate–CO_2 process? No-bake? What may determine the bench life of green sand?

48. SS What material serves as the binder in the shell-molding process, and how is it cured?

49. Describe the steps of the shell-molding process.

50. Why do shell molds have excellent permeability and collapsibility?

51. What is the sand binder in the V-process? The Eff-set process?

52. What are a few of the attractive features of the V-process?

53. SS What types of geometric features might require the use of cores?

54. What is the primary limitation of green-sand cores?

55. How might core segments be joined prior to insertion into the mold?

56. What is the sand binder in the core-oil process, and how is it cured?

57. What is the binder in the hot-box core-making process?

58. What is the primary attraction of the cold-box core-making process? The primary negative feature?

59. SS What is shelf life? How is it different from bench life?

60. What is an attractive feature of air-set or no-bake core making? Of shell-molded cores?

61. SS Why is it common for greater permeability, collapsibility, and refractoriness to be required of cores than for the base molding sand?

62. How can the properties of cores be enhanced beyond those offered by the various core materials?

63. What is the function of a core print?

64. What is the role of chaplets, and why is it important that they not completely melt during the pouring and solidification of a casting?

65. Describe the steps of plaster molding.

66. SS Why are plaster molds only suitable for the lower-melting-temperature nonferrous metals and alloys?

67. How does the Antioch process provide permeability to plaster molds?

68. What is the primary performance difference between plaster and ceramic molds?

69. How is permeability provided to ceramic molds through the Shaw process?

70. SS For what materials might a graphite mold be required?

71. What materials are used to produce the expendable patterns for investment casting?

72. Describe the progressive construction of an investment casting mold.

73. Why are investment casting molds generally preheated prior to pouring?

74. Why are investment castings sometimes called “lost-wax” castings?

75. SS What are some of the attractive features of investment casting?

76. What recent development has made one-of-a-kind or small quantities of investment castings an economic feasibility?

77. SS How can hollow-like investment casting patterns reduce the possibility of costly shell cracking?

78. What are some of the advantages of counter-gravity investment casting over the conventional gravity pour approach?

79. What are some of the benefits of not having to remove the pattern from the mold (as in investment casting, **full-mold casting**, and lost-foam casting)?

80. What are some of the ways by which expanded polystyrene patterns can be made?

81. Because both use expanded polystyrene as a pattern, what is the primary difference between full-mold and lost-foam casting?

82. SS What are some of the attractive features of the evaporative pattern processes?

83. What is the objective of pressurized lost-foam casting?

84. What are some of the objectives of a shakeout operation?

85. How might castings be cleaned after shakeout?

86. What is the objective of ablation? The benefits?

87. What are the most common single-use mold processes?

88. What are the most common methods of core production?

Chapter 14 Problems

1. Although cores increase the cost of castings, they also provide a number of distinct advantages. The most significant is the ability to produce complex internal passages. They can also enable the production of difficult external features, such as undercuts, or allow the production of zero draft walls. Cores can reduce or eliminate additional machining, reduce the weight of a casting, and reduce or eliminate the need for multipiece assembly. Answer the following questions about cores.

a. The cores themselves must be produced, and generally have to be removed from coreboxes or molds. What geometric limitations might this impose? How might these limitations be overcome?

b. Cores must be positioned and supported within a mold. Discuss some of the limitations associated with core positioning and orientation. Consider the weight of a core, prevention of core fracture, minimization of core deflection, and possible buoyancy.

c. Because cores are internal to the casting, adequate venting is necessary to eliminate or minimize porosity problems. Discuss possible features to aid in venting.

d. How might core behavior vary with different materials being cast—steel versus aluminum, for example?

e. Discuss several of the reasons why cores may be made from a different material than the molding material used in the primary mold.

f. Core removal is another design concern. Discuss how several different core-making processes might perform in the area of removal. What are some ways to assist or facilitate core removal?

2. Several of the additive manufacturing processes can selectively deposit binder material between the grains of sand in a layer-by-layer approach. Molds or cores can be produced directly from computer files, eliminating the need for any patterns or tooling.

a. For what type or types of products might this approach be attractive?

b. What concerns might you have regarding permeability, collapsibility, or any of the other mold or mold material characteristics?

3. Additive manufacturing processes can also build shapes from various polymers and metals directly from computer files. These products could be used as patterns for the various sand casting and core-making processes.

a. Briefly discuss the advantages of this approach.

b. For the various additive materials and the intended use as a sand pattern, discuss features such as cost, wear resistance and mold life, and other consideration factors.

c. Wax or selected polymers could be used to produce the expendable patterns for investment casting. How might this expand the use of the investment casting process?

4. One of the fastest developing and rapidly changing areas of manufacturing is additive manufacturing, also known as 3-D printing. In addition to the more visible usage in the manufacture of both prototype and direct-usage products, the various methods have been applied in support roles to other, more traditional methods of manufacturing.

a. For the various sand-casting processes described in this chapter, describe how the additive processes can be utilized in a contributing manner.

b. How might the integration of additive manufacturing methods expand the capabilities of the sand-casting processes?

c. Answer questions 1 and 2 for the single-use pattern investment casting process.

d. How might the specific additive manufacturing processes used with investment casting be different from those used with sand casting?

5. Cast iron cookware can offer a number of attractive features. The seasoned finish has a nonstick nature, so less oil can be used in cooking. The material can withstand high cooking temperatures, making the products attractive for searing or frying. The excellent heat diffusion and retention makes it a good choice for long-cooking recipes, such as stews. The small amounts of iron that can leach into the food is considered to be a benefit, as opposed to the potentially negative concerns with the leaching of aluminum.

a. How is gray cast iron typically produced?

b. Which if the expendable-mold processes would appear to be appropriate for the casting of skillets, Dutch ovens, griddles, platters, and others?

c. What kind of problems could occur if the iron were poured too hot? Too cold?

d. What types of finishing operations might be performed on the castings after removal from the molds?

Chapter 14 Key Words

ablation
AFS permeability number
air-set
Antioch process
automatic match-plate molding
bench life
blows
ceramic mold casting
chaplets
cheek
Chemically bonded sands
clay content
cohesiveness
cold-box process
collapsibility
compactibility
compressive strength
cope
cope-and-drag patterns
core
core-oil process
core prints
counter-gravity investment casting
drag
dry-sand molds
dump core box
Eff-set process
evaporative pattern casting
expanded polystyrene (EPS)
expendable-mold casting processes
flask
follow board
full-mold casting
gas-hardened processes
gates
grain size
graphite
green compressive strength
green sand
green-sand cores
hand ramming
hardness
hot-box method
hot tears
H-process
investment casting
jolting
loose-piece pattern
lost-foam casting
lost-wax process
match plate
match-plate molding
moisture content
mold hardness
muller
no-bake sand
one-piece pattern
pattern
penetration
permeability
plaster molding
pressurized lost-foam casting
refractoriness
rubber molds
runners
sand expansion defects
sand slinger
shakeout
Shaw process
shelf life
shell cracking
shell molding
silica sand
single-piece cores
skin-dried mold
snap flask
sodium silicate
squeezing
split core box
split patterns
sprue
squeezing
stack molding
standard rammed specimen
tree
vacuum molding
vent passages
vertically parted flaskless molding
V-process
water glass

Chapter 14 CASE STUDY Trailer Hitch Component

Figure CS-14 shows the hitch ball component of a standard 2-in.-diameter trailer hitch. Based on required mechanical properties, the recommended material is a low-carbon, plain-carbon steel, with carbon content in the range of 0.15% to 0.25%. Consider the following possible means of manufacture:

a. Machine from 2-in.-diameter rod stock

b. Shell mold cast and machine parting line

c. Investment cast (no parting line)

d. Assemble from three simple shape pieces — ball, shaft, and washer

e. Assemble from two pieces — ball and shaft with upset region

f. Forge and machine parting line

g. Cold form from bar stock with two upset regions (ball and “washer”)

h. Other

For each of the alternatives, briefly discuss the pros and cons, considering such factors as: required equipment or tooling, amount of scrap generated, reasonable production rate, anticipated quality, required secondary processing, etc.

FIGURE CS-14 Dcwcreations/ iStock/ Getty Images.

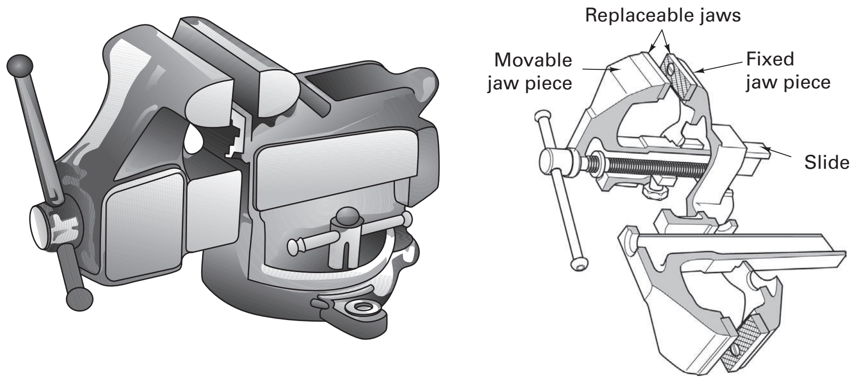
CASE STUDY Moveable and Fixed Jaw Pieces for a Heavy-duty Bench Vise

The figure presents a sketch of a standard bench vise and a cut-away sketch of the moveable and fixed jaw pieces of a heavy-duty vise that might see use in vocational schools, factories, and machine shops. The vise is intended to have a rated maximum clamping force of 15 tons. The slide of the moving jaw has been designed to be a 2-in. box channel. The jaw width is 5 in., the maximum jaw opening is 6 in., and the depth of the throat is 4 in. The designer has elected to use replaceable, serrated jaws and suggests that the material used for the receiving jaw pieces have a yield strength in excess of 35 ksi, with at least 15% elongation in a uniaxial tensile test (to assure that an overload or hammer impact would not produce brittle fracture).

1. Determine some possible combinations of material and process that could fabricate the desired shapes with the required properties. Of the alternatives presented, which would you prefer and why?

2. Would the components require some form of subsequent heat treatment? Consider the possibilities of stress relief, homogenization, or the establishment of desired final properties. What would you recommend?

3. One of your colleagues has suggested that the slides be finished with a coat of paint. Do you think a surface treatment is necessary or desirable for your selected material and process? If so, what would you recommend? If not, defend your recommendation.



Note: Shaded surfaces have been produced by cross-sectional cuts

(*Courtesy of Ronald Kohser.*)