CHAPTER



Casting Processes and Heat Treatment

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- This chapter describes the fundamentals of metal casting and the characteristics of casting processes, including:
- Mechanisms of the solidification of metals, characteristics of fluid flow, and the role of entrapped gases and shrinkage.
- Properties of casting alloys and their applications.
- Characteristics of expendable-mold and permanent-mold casting processes, their applications and economic considerations.
- Design considerations and simulation techniques for casting.
- Economic considerations.

Symbols

- A area, m^2
- C coefficient in Chvorinov's rule, s/m²
- *C*_L weight composition of liquid phase
- Co nominal weight composition
- *C_S* weight composition of solid phase
- D channel diameter, m
- f frictional loss
- g gravitational acceleration, 9.81 m/s²
 - elevation, m

h

- *L* weight fraction of liquid
- *n* exponent
- p pressure, N/m²
- Q volumetric flow rate, m³/s
- Re Reynolds number
- *S* weight fraction of solid
- T_L liquidus temperature, °C
- $T_{\rm S}$ solidus temperature, °C
- t time, s
- v velocity, m/s
- η viscosity, Ns/m²
- ρ mass density, kg/m³

5.1 Introduction

As described throughout this text, several methods can be used to shape materials into useful products. **Casting** is one of the oldest methods and was first used about 4000 B.C. to make ornaments, arrowheads, and various other objects. Casting processes basically involve the introduction

of molten metal into a mold cavity where, upon solidification, the metal takes the shape of the cavity. This process is capable of producing intricate shapes in a single piece, ranging in size from very large to very small, including those with internal cavities. Typical cast products are engine blocks, cylinder heads, transmission housings, pistons, turbine disks, railroad and automotive wheels, and ornamental artifacts.

All metals can be cast in, or nearly in, the final shape desired, often with only minor finishing operations required. With appropriate control of material and process parameters, parts can be cast with almost uniform properties throughout. As with all other manufacturing processes, a knowledge of certain fundamental aspects is essential to high quality production, with good surface finish, dimensional accuracy, strength, and lack of defects.

The important factors in casting operations are:

- **1. Solidification** of the metal from its molten state, and accompanying shrinkage;
- 2. Flow of the molten metal into the mold cavity;
- 3. Heat transfer during solidification and cooling of the metal in the mold; and
- 4. Mold material and its influence on the casting operation.

5.2 Solidification of Metals

An overview of the solidification of metals and alloys is presented in this section. The topics covered are essential to an understanding of the structures developed in casting and the structure-property relationships obtained in the casting processes described throughout this chapter.

Pure metals have clearly defined melting or freezing points, and solidification takes place at a constant temperature (Fig. 5.1a). When the temperature of the molten metal is reduced to the freezing point, the latent heat of fusion is given off while the temperature remains constant. At the end of this isothermal phase change, solidification is complete and the solid metal cools to room temperature. The casting contracts as it cools, due to (a) contraction from a superheated state to the metal's solidification temperature; and (b) cooling, as a solid, from the solidification temperature to room temperature (Fig. 5.1b). A significant density change also can occur as a result of phase change from liquid to solid.

Unlike pure metals, **alloys** solidify over a *range* of temperatures. Solidification begins when the temperature of the molten metal drops below the **liquidus**, and is completed when the temperature reaches the **solidus**. Within this temperature range the alloy is in a *mushy* or *pasty* state, whose composition and state are described by the particular alloy's phase diagram.

5.2.1 Solid Solutions

Two terms are essential in describing alloys: solute and solvent. **Solute** is the *minor* element (such as sugar or salt) that is added to the **solvent**, which is the *major* element (such as water). In terms of the elements involved



FIGURE 5.1 (a) Temperature as a function of time for the solidification of pure metals. Note that freezing takes place at a constant temperature. (b) Density as a function of time.

in a metal's crystal structure (see Section 3.2), the solute is the element (*solute atoms*) added to the solvent (*host atoms*). When the particular crystal structure of the solvent is maintained during alloying, the alloy is called a **solid solution**.

Substitutional solid solutions. If the size of the solute atom is similar to that of the solvent atom, the solute atoms can replace solvent atoms and form a *substitutional solid solution* (See Fig. 3.9). An example is brass, an alloy of zinc and copper, in which zinc (solute atom) is introduced into the lattice of copper (solvent atoms). The properties of brasses can thus be altered over a certain range by controlling the amount of zinc in copper.

Interstitial solid solutions. If the size of the solute atom is much smaller than that of the solvent atom, the solute atom occupies an interstitial position (as shown in Fig. 3.9) and forms an *interstitial solid solution*. A major example of interstitial solution is steel, an alloy of iron and carbon, in which carbon atoms are present in an interstitial position between iron atoms. As will be shown in Section 5.11, the properties of steel can thus be varied over a wide range by controlling the amount of carbon in iron. This is one reason that steel, in addition to being relatively inexpensive, is such a versatile and important material with a wide range of properties and applications.

5.2.2 Intermetallic Compounds

Intermetallic compounds are complex structures in which solute atoms are present among solvent atoms in specific proportions; some intermetallic compounds have solid solubility. The type of atomic bonds may range from metallic to ionic. Intermetallic compounds are strong, hard, and brittle. An example is copper in aluminum, where an intermetallic compound of $CuAl_2$ can be made to precipitate from an aluminum-copper alloy; this is an example of precipitation hardening (see Section 5.11.2).

5.2.3 Two-Phase Alloys

A solid solution is one in which two or more elements are soluble in a solid state, forming a single homogeneous material in which the alloying elements are uniformly distributed throughout the solid. There is, however, a limit to the concentration of solute atoms in a solvent-atom lattice, just as there is a limit to the solubility of sugar in water. Most alloys consist of two or more solid phases, and thus may be regarded as mechanical mixtures. Such a system with two solid phases is called a **two-phase system**, in which each phase is a homogeneous part of the total mass and has its own characteristics and properties.

A typical example of a two-phase system in metals is lead added to copper in the molten state. After the mixture solidifies, the structure consists of two phases: (a) one phase has a small amount of lead in solid solution in copper; and (b) another phase in which lead particles, approximately spherical in shape, are *dispersed* throughout the matrix of the primary phase (Fig. 5.2a). This copper-lead alloy has properties that are different from those of either copper or lead alone.

Alloying with finely dispersed particles (called *second-phase particles*) is an important method of strengthening alloys and controlling their properties. Generally, in two-phase alloys, the second-phase particles become obstacles to dislocation movement, which increases the alloy's strength (Section 3.3). Another example of a two-phase alloy is the aggregate structure shown in Fig. 5.2b; it contains two sets of grains, each with its own composition and properties. The darker grains may, for example, have a different structure than that of the lighter grains and be brittle, whereas the lighter grains may be ductile.

5.2.4 Phase Diagrams

A *phase diagram*, also called an **equilibrium diagram** or **constitutional diagram**, graphically illustrates the relationships among temperature, composition, and the phases present in a particular alloy system. *Equilibrium* means that the state of a system remains constant over an indefinite



FIGURE 5.2 (a) Schematic illustration of grains, grain boundaries, and particles dispersed throughout the structure of a two-phase system, such as lead-copper alloy. The grains represent lead in solid solution of copper, and the particles are lead as a second phase. (b) Schematic illustration of a two-phase system, consisting of two sets of grains: dark and light. Dark and light grains have their own compositions and properties.



FIGURE 5.3 Phase diagram for nickel-copper alloy system obtained by a low rate of solidification. Note that pure nickel and pure copper each have one freezing or melting temperature. The top circle on the right depicts the nucleation of crystals; the second circle shows the formation of dendrites; and the bottom circle shows the solidified alloy with grain boundaries.

period of time. *Constitutional* indicates the relationships among structure, composition, and physical makeup of the alloy.

An example of a phase diagram is shown in Fig. 5.3 for the nickelcopper alloy. It is called a **binary phase diagram** because there are two elements (nickel and copper) in the system. The left boundary (100% Ni) of this phase diagram indicates the melting point of nickel, and the right boundary (100% Cu) indicates the melting point of copper. (All percentages are by weight.) Note that for a composition of, say, 50% Cu-50% Ni, the alloy begins to solidify at a temperature of 1313°C, and solidification is complete at 1249°C. Above 1313°C, a homogeneous liquid of 50% Cu-50% Ni exists. When cooled slowly to 1249°C, a homogeneous solid solution consists of 50% Cu-50% Ni.

Between the liquidus and solidus curves at a temperature of, say, 1288°C, is a two-phase region: a *solid phase*, composed of 42% Cu-58% Ni, and a *liquid phase* of 58% Cu-42% Ni. To determine the solid composition, one must go left horizontally to the solidus curve and read down, to obtain 42% Cu-58% Ni. The liquid composition can be determined similarly by going to the right to the liquidus curve (58% Cu-42% Ni).

The completely solidified alloy in the phase diagram shown in Fig. 5.3 is a **solid solution**, because the alloying element (Cu, the solute atom) is completely dissolved in the host metal (Ni, the solvent atom), and each grain has the same composition. The mechanical properties of solid solutions of Cu-Ni depend on their composition; for example, by increasing the nickel content, the properties of copper are improved. The improvement is due to *pinning* (blocking) of dislocations at solute atoms of nickel, which may also be regarded as impurity atoms (See Fig. 3.9). As a result, dislocations cannot move as freely and, consequently, the strength of the alloy increases.

Lever rule. The composition of various phases in a phase diagram can be determined by a procedure called the *lever rule*. As shown in the lower portion of Fig. 5.3, a lever between the solidus and liquidus lines (called *tie line*) is first constructed, which is balanced (on the triangular support) at the nominal weight composition C_o of the alloy. The left end of the lever represents the composition C_S of the solid phase, and the right end of the figure that the liquid fraction is also indicated along this tie line, which ranges from 0 at the left (fully solid) to 1 at the right (fully liquid).

The lever rule states that the weight fraction of solid is proportional to the distance between C_o and C_L :

$$\frac{S}{S+L} = \frac{C_o - C_L}{C_S - C_L}.$$
(5.1)

Likewise, the weight fraction of liquid is proportional to the distance between C_S and C_o . Thus,

$$\frac{L}{S+L} = \frac{C_S - C_o}{C_S - C_L}.$$
(5.2)

Note that these quantities are fractions, and hence they must be multiplied by 100 to obtain percentages.

From inspection of the dashed line in Fig. 5.3 and for a nominal alloy composition of $C_o = 50\%$ Cu-50% Ni, it can be noted that because C_o is closer to C_L than it is to C_S , the solid phase contains less copper than the liquid phase. By measuring on the phase diagram and using the lever-rule equations, it can be seen that the composition of the solid phase is 42% Cu and of the liquid phase is 58% Cu (as stated in the middle circle at the right in Fig. 5.3).

Note that these calculations refer to copper. If the phase diagram in the figure is now reversed, so that the left boundary is 0% nickel (whereby nickel now becomes the alloying element in copper), these calculations give us the compositions of the solid and liquid phases in terms of nickel.

The lever rule is also known as the *inverse lever rule* because, as indicated by Eqs. (5.1) and (5.2), the amount of each phase is proportional to the length of the opposite end of the lever.

5.2.5 The Iron-Carbon System

The *iron-carbon binary system* is represented by the **iron-iron carbide phase diagram**, shown in Fig. 5.4a. Note that pure iron melts at a temperature of 1538°C, as shown at the left in Fig. 5.4a. As it cools, it first forms δ -iron, then γ -iron, and finally α -iron. Commercially pure iron contains up to 0.008% C, steels up to 2.11% C, and cast irons up to 6.67% C, although most cast irons contain less than 4.5% C.

- Ferrite. Alpha ferrite, or simply ferrite, is a solid solution of bodycentered cubic iron and has a maximum solid solubility of 0.022% C at a temperature of 727°C. Delta ferrite is stable only at very high temperatures and has no significant or practical engineering applications. Ferrite is relatively soft and ductile, and is magnetic from room temperature up to 768°C. Although very little carbon can dissolve interstitially in bcc iron, the amount of carbon significantly affects the mechanical properties of ferrite. Also, significant amounts of chromium, manganese, nickel, molybdenum, tungsten, and silicon can be contained in iron in solid solution, imparting certain desirable properties.
- **2.** Austenite. Between 1394°C and 912°C iron undergoes an *allotropic transformation* (see Section 3.2) from the bcc



FIGURE 5.4 (a) The iron-iron carbide phase diagram. (b) Detail view of the microstructures above and below the eutectoid temperature of 727°C. Because of the importance of steel as an engineering material, this diagram is one of the most important phase diagrams.

to fcc structure, becoming what is known as *gamma iron*, or more commonly, *austenite*. This structure has a solid solubility of up to 2.11% C at 1148°C, which is about two orders of magnitude higher than that of ferrite, with the carbon occupying interstitial positions. (Note that the atomic radius of Fe is 0.124 nm and for C it is 0.071 nm.) Austenite is an important phase in the heat treatment of steels, described in Section 5.11. It is denser than ferrite, and its single-phase fcc structure is ductile at elevated temperatures, thus it possesses good formability. Large amounts of nickel and manganese can also be dissolved in fcc iron to impart various properties. Austenitic steel is nonmagnetic at high temperatures, and austenitic stainless steels are nonmagnetic at room temperature.

3. Cementite. The right boundary of Fig. 5.4a represents *cementite*, also called **carbide**, which is 100% iron carbide (Fe₃C) with a carbon content of 6.67%. (This carbide should not be confused with various other carbides used for tool and die materials, described in Section 8.6.4.) Cementite is a very hard and brittle intermetallic compound (Section 5.2.2), and significantly influences the properties of steels. It can be alloyed with elements such as chromium, molybdenum, and manganese for enhanced properties.

5.2.6 The Iron-Iron Carbide Phase Diagram

Various microstructures can be developed in steels, depending on its carbon content and the method of heat treatment (Section 5.11). For example, consider iron with a 0.77% C content that is being cooled *very slowly* from a temperature of 1100°C in the austenite phase. The reason for the slow cooling rate is to maintain equilibrium; higher rates of cooling are used in heat treating (see Section 5.11). At 727°C, a reaction takes place in which austenite is transformed into alpha ferrite (bcc) and cementite. Because the solid solubility of carbon in ferrite is only 0.022%, the extra carbon forms cementite.

This reaction is called a **eutectoid** (meaning *eutecticlike*) reaction, indicating that at a certain temperature a single solid phase (austenite) is transformed into two solid phases, namely ferrite and cementite. The structure of the eutectoid steel is called **pearlite**, because, at low magnifications, it resembles mother of pearl. The microstructure of pearlite consists of alternate layers (*lamellae*) of ferrite and cementite (Fig. 5.4b); consequently, the mechanical properties of pearlite are intermediate between ferrite (soft and ductile) and cementite (hard and brittle).

In iron with less than 0.77% C, the microstructure formed consists of a pearlite phase (ferrite and cementite) and a ferrite phase. The ferrite in the pearlite is called *eutectoid ferrite*; the ferrite phase is called *proeutectoid ferrite* (*pro* meaning before), because it forms at a temperature higher than the eutectoid temperature of 727°C. If the carbon content is higher than 0.77%, the austenite transforms into pearlite and cementite. The cementite in the pearlite is called *eutectoid cementite*, and the cementite phase is called *proeutectoid cementite*, because it forms at a temperature higher than the eutectoid cementite, because it forms at a temperature higher than the eutectoid cementite.

P

Effects of alloying elements in iron. Although carbon is the basic element that transforms iron into steel, other elements are also added to impart various desirable properties. The effect of these alloying elements on the iron-iron carbide phase diagram is to shift the eutectoid temperature and eutectoid composition (the percentage of carbon in steel at the eutectoid point). The eutectoid temperature may be raised or lowered from 727°C, depending on the particular alloying element. Alloying elements always lower the eutectoid composition; that is, the carbon content becomes less than 0.77%. Lowering the eutectoid temperature means increasing the austenite range; thus, an alloying element, such as nickel, is known as an **austenite former**, because it has an fcc structure and thus tends to favor the fcc structure of austenite. Conversely, chromium and molybdenum have the bcc structure, causing these two elements to favor the bcc structure of ferrite; these elements are known as ferrite formers.

EXAMPLE 5.1 Determining the Amount of Phases in Carbon Steel

Given: A 10-kg, 1040 steel casting as it is being cooled slowly to the following temperatures: (a) 900°C; (b) 728°C; and (c) 726°C.

Find: Determine the amount of gamma and alpha phases in the steel casting.

Solution: (a) Referring to Fig. 5.4b, a vertical line is drawn at 0.40% C at 900°C. This is in the single-phase austenite region, so the percent gamma is 100 (10 kg) and percent alpha is zero. (b) At 728°C, the alloy is in the two-phase gamma-alpha field. When the phase diagram is drawn in greater detail, the weight percentages of each phase by the lever rule:

Percent alpha =
$$\left(\frac{C_{\gamma} - C_o}{C_{\gamma} - C_{\alpha}}\right) \times 100\% = \left(\frac{0.77 - 0.40}{0.77 - 0.022}\right) \times 100\% = 49.5\%$$
, or 4.95 kg
Percent gamma = $\left(\frac{C_o - C_{\alpha}}{C_{\gamma} - C_{\alpha}}\right) \times 100\% = \left(\frac{0.40 - 0.022}{0.77 - 0.022}\right) \times 100\% = 50.5\%$, or 5.05 kg

(c) At 726°C, the alloy will be in the two-phase alpha and Fe_3C region. No gamma phase will be present. Again, the lever rule is used to find the amount of alpha present:

Percent alpha =
$$\left(\frac{6.67 - 0.40}{6.67 - 0.022}\right) \times 100\% = 94.3\%$$
, or 9.43 kg

5.3 Cast Structures

The type of *cast structure* developed during solidification of metals and alloys depends on the composition of the particular alloy, the rate of heat transfer, and the flow of the liquid metal during the casting process. As described throughout this chapter, the structures developed, in turn, affect the properties of the castings.

5.3.1 Pure Metals

The typical grain structure of a pure metal that has solidified in a square mold is shown in Fig. 5.5a. At the mold walls the metal cools rapidly (*chill zone*) because the walls are at ambient or slightly elevated temperature, and as a result, the casting develops a solidified **skin** (*shell*) of fine *equiaxed grains*. The grains grow in the direction opposite to the heat transfer from the mold. Grains that have a favorable orientation, called **columnar grains**, grow preferentially (See middle of Fig. 5.5). Note that grains that have substantially different orientations are blocked from further growth.

5.3.2 Alloys

Because pure metals have limited mechanical properties, they are often enhanced and modified by **alloying**. The vast majority of metals used in engineering applications are some form of an **alloy**, defined as two or more chemical elements, at least one of which is a metal.

Solidification in alloys begins when the temperature drops below the liquidus, T_L , and is complete when it reaches the solidus, T_S (Fig. 5.6). Within this temperature range, the alloy is in a mushy or pasty state, with **columnar dendrites** (from the Greek *dendron* meaning akin to, and *drys* meaning tree). Note in the lower right of the figure the presence of liquid metal between the dendrite arms. Dendrites have three-dimensional arms and branches (*secondary arms*), which eventually interlock, as shown in Fig. 5.7. The width of the mushy zone (where both liquid and solid phases



FIGURE 5.5 Schematic illustration of three cast structures of metals solidified in a square mold: (a) pure metals, with preferred texture at the cool mold wall. Note in the middle of the figure that only favorable oriented grains grow away from the mold surface; (b) solid-solution alloys; and (c) structure obtained by heterogeneous nucleation of grains.



FIGURE 5.6 Schematic illustration of alloy solidification and temperature distribution in the solidifying metal. Note the formation of dendrites in the semi-solid (mushy) zone.



FIGURE 5.7 (a) Solidification patterns for gray cast iron in a 180-mm square casting. Note that after 11 min of cooling, dendrites reach each other, but the casting is still mushy throughout. It takes about two hours for this casting to solidify completely. (b) Solidification of carbon steels in sand and chill (metal) molds. Note the difference in solidification patterns as the carbon content increases. *Source:* After H.F. Bishop and W.S. Pellini.

are present) is important during solidification. This zone is described in terms of a temperature difference, known as the **freezing range**, as

Freezing range =
$$T_L - T_S$$
. (5.3)

Note in Fig. 5.6 that pure metals have a freezing range that approaches zero, and that the *solidification front* moves as a plane front, without forming a mushy zone. Eutectics solidify in a similar manner, with an approximately plane front. The type of solidification structure developed depends on the composition of the eutectic. For example, for alloys with a nearly symmetrical phase diagram, the structure is generally lamellar, with two or more solid phases present, depending on the alloy system. When the volume fraction of the minor phase of the alloy is less than about 25%, the structure generally becomes *fibrous*.

A short freezing range for alloys generally involves a temperature difference of less than 50°C, and a long freezing range, greater than 110°C. Ferrous castings typically have narrow semi-solid (mushy) zones, whereas aluminum and magnesium alloys have wide mushy zones. Consequently, these alloys are in a semi-solid state throughout most of the solidification process, which is the main reason that thixocasting is feasible with these alloys (see Section 5.10.6).

Effects of cooling rate. Slow cooling rates (on the order of 10^2 K/s) or long local solidification times result in coarse dendritic structures, with large spacing between the dendrite arms. For higher cooling rates (on the order of 10^4 K/s) or short local solidification times, the structure becomes finer, with smaller dendrite arm spacing. For still higher cooling rates (on the order of 10^6 to 10^8 K/s), the structures developed are *amorphous* (meaning without any ordered crystalline structure, as described in Sections 3.11.9 and 5.10.8).

The structures developed and the resulting grain size, in turn, influence the properties of the casting. For example, as grain size decreases, (a) the strength and ductility of the cast alloy increase (see *Hall–Petch equation*, Section 3.4.1); (b) microporosity (interdendritic shrinkage voids) in the casting decreases; and (c) the tendency for the casting to crack (*hot tearing*) during solidification decreases. Moreover, lack of uniformity in grain size and distribution within castings results in anisotropic properties.

5.3.3 Structure-Property Relationships

Because all castings must possess certain specific properties to meet design and service requirements, the relationships between the properties and the structures developed during solidification are important considerations. This section describes these relationships in terms of dendrite morphology and the concentration of alloying elements in various regions of the casting.

The compositions of dendrites and of the liquid metal in casting are given by the phase diagram of the particular alloy. When the alloy is cooled very slowly, each dendrite develops a uniform composition. Under normal cooling rates typically encountered in practice, however, cored **dendrites** are formed, which have a surface composition that is different from that at their centers (known as *concentration gradient*). The surface has a higher concentration of alloying elements than at the core of the dendrite, due to solute rejection from the core toward the surface during solidification of the dendrite (called **microsegregation**). The darker shading in the interdendritic liquid near the dendrite roots shown in Fig. 5.8 indicates that these regions have a higher solute concentration; consequently, microsegregation in these regions is much more pronounced than in others.

In contrast to microsegregation, macrosegregation involves differences in composition throughout the casting itself. In situations where the solidifying front moves away from the surface of a casting as a plane front (Fig. 5.9), lower-melting-point constituents in the solidifying alloy are driven toward the center (normal segregation); such a casting has a higher concentration of alloying elements at its center than at its surfaces. The opposite occurs in such dendritic structures as those for solid-solution alloys (Fig. 5.5b); that is, the center of the casting has a lower concentration of alloying elements (inverse segregation). The reason for this behavior is that the liquid metal (which has a higher concentration of alloying elements) enters the cavities developed from solidification shrinkage in the dendrite arms (that have solidified sooner). Another form



FIGURE 5.8 Schematic illustration of three basic types of cast structures: (a) columnar dendritic; (b) equiaxed dendritic; and (c) equiaxed nondendritic. *Source:* After D. Apelian.



FIGURE 5.9 Schematic illustration of cast structures in (a) plane front, single phase; and (b) plane front, two phase. *Source:* After D. Apelian.

of segregation is due to gravity (gravity segregation), whereby higher density inclusions or compounds sink and lighter elements (such as antimony in an antimony-lead alloy) float to the surface.

A typical cast structure of a solid-solution alloy, with an inner zone of equiaxed grains, is shown in Fig. 5.5b. The inner zone can be extended throughout the casting, as shown in Fig. 5.5c, by adding a nucleating agent called **inoculant** to the alloy. The inoculant induces nucleation of grains throughout the liquid metal (heterogeneous nucleation). An example is the use of TiB₂ in aluminum alloys to refine grains and improve mechanical properties.

Because of the presence of thermal gradients in a solidifying mass of liquid metal and because of the presence of gravity (hence density differences), *convection* influences the cast structures developed. Convection promotes the formation of a chill zone (See Fig. 5.5), refines the grain size, and accelerates the transition from columnar to equiaxed grains. The structure shown in Fig. 5.8b can also be obtained by increasing convection within the liquid metal, whereby dendrite arms separate (dendrite multiplication). Conversely, reducing or eliminating convection results in coarser and longer columnar dendritic grains.

Convection can be enhanced by using mechanical or electromagnetic methods. Because the dendrite arms are not particularly strong, they can be broken up by agitation or mechanical vibration in the early stages of solidification (see **rheocasting**, Section 5.10.6). This action results in finer grain size, with equiaxed nondendritic grains that are distributed more uniformly throughout the casting (Fig. 5.8c). A side benefit is the *thixotropic* behavior of alloys (i.e., the viscosity decreases when the liquid metal is agitated), leading to improved castability of the metal. Another form of semisolid metal forming is **thixotropic casting**, where a solid billet is first heated to a semisolid state and then injected into a die-casting die (Section 5.10.3).

5.4 Fluid Flow and Heat Transfer

5.4.1 Fluid Flow

A basic gravity casting system is shown in Fig. 5.10. The molten metal is poured through a **pouring basin** (*cup*); it then flows through the **sprue** to the **well**, and into **runners** and to the mold cavity. **Risers**, also called **feeders**, serve as reservoirs of molten metal to supply the metal necessary to prevent shrinkage, which could lead to porosity. Although such a **gating system** appears to be relatively simple, successful casting requires proper design and control of the solidification process to ensure adequate fluid flow during casting. One of the most important functions of the gating system is to *trap contaminants* (such as oxides and other inclusions) in the molten metal, by having the contaminants adhere to the walls of the gating system, thereby preventing their reaching the mold cavity. Moreover, a properly designed gating system avoids or minimizes such problems as premature cooling, turbulence, and gas entrapment. Even before it reaches



FIGURE 5.10 Cross section of a typical sand mold showing various features.

the mold cavity, the molten metal must be handled so as to avoid forming oxides on the molten metal surfaces (from exposure to the environment) or the introduction of impurities into the molten metal.

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

Bernoulli's theorem. Bernoulli's theorem is based on the principle of conservation of energy, and relates pressure, velocity, elevation of the fluid at any location in the system, and frictional losses. Thus,

$$b + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{Constant},$$
 (5.4)

where *h* is the elevation above a certain reference plane, *p* is the pressure at that elevation, ν is the velocity of the liquid at that elevation, ρ is the density of the fluid (assuming that it is incompressible), and *g* is the gravitational constant. Conservation of energy requires that at any particular location in the system, the following relationship be satisfied:

$$h_1 + \frac{p_1}{\rho g} + \frac{\nu_1^2}{2g} = h_2 + \frac{p_2}{\rho g} + \frac{\nu_2^2}{2g} + f.$$
(5.5)

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

Mass continuity. The mass continuity law states that for an incompressible liquid and in a system with impermeable walls, the rate of flow is constant; thus,

$$Q = A_1 v_1 = A_2 v_2, \tag{5.6}$$

where Q is the volumetric rate of flow (such as m³/s), A is the crosssectional area of the liquid stream, and v is the velocity of the liquid in that particular location. The subscripts 1 and 2 in Eq. (5.6) pertain to two different locations in the system. The permeability of the walls of the system is important because, otherwise, some liquid will permeate through (for example, in sand molds; Section 5.8.1) and the flow rate will decrease as the liquid travels through the system. Coatings are often used to inhibit such behavior in sand molds.

Sprue profile. An application of the two principles stated above is the traditional tapered design of sprues (Fig. 5.10), in which the shape of the sprue can be determined by using Eqs. (5.5) and (5.6). Assuming that the pressure at the top of the sprue is equal to the pressure at the bottom, and that there are no frictional losses in the system, the relationship between height and cross-sectional area at any point in the sprue is given by the parabolic relationship:

$$\frac{A_1}{A_2} = \sqrt{\frac{h_2}{h_1}},$$
 (5.7)

where, for example, subscript 1 denotes the top of the sprue and subscript 2 the bottom. Note that in a free-falling liquid, such as water from a faucet, the cross-sectional area of the stream decreases as it gains velocity downward. Thus, moving downward from the top, the cross-sectional area of the sprue must decrease. If a sprue is designed with a constant crosssectional area, regions may develop where the molten metal loses contact with the sprue walls. As a result, **aspiration** may occur, whereby air will be sucked in or be entrapped in the liquid. Straight-sided sprues require a *choking* mechanism at their bottom, consisting of either a *choke core* or a *runner choke*, as shown in Fig. 5.10. A choking mechanism slows down the fluid flow so that aspiration will not occur.

Modeling of mold filling requires the application of Eqs. (5.5) and (5.6); see also Section 5.12.5. Consider the situation shown in Fig. 5.10 where molten metal is poured into a pouring basin. The metal then flows through a sprue to a gate and runner, and fills the mold cavity. If the pouring basin has a cross-sectional area that is much larger than the sprue bottom, the velocity of the molten metal at the top of the pouring basin will be very low. If frictional losses are due to viscous dissipation of energy, then f in Eq. (5.5) can be taken as a function of vertical distance, and is often approximated as a linear function. The velocity of the molten metal leaving the gate is then obtained from Eq. (5.5) as

$$\nu = c\sqrt{2gh},\tag{5.8}$$

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

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

$$\nu = c\sqrt{2g}\sqrt{h-x}.$$
(5.9)

The flow rate through the gate will be the product of this velocity and the gate area, according to Eq. (5.6). The shape of the casting will determine the height as a function of time. Equation (5.9) allows calculation of the flow rate, and dividing the casting volume by the mean flow rate then gives the mold fill time.

Simulation of mold filling helps designers specify the runner diameter, and the size and number of sprues and pouring basins. To ensure that the runners do not choke prematurely, the fill time must be a small fraction of the solidification time (see Section 5.4.4). However, the velocity must not be so high as to erode the mold material (known as *mold wash*) or to result in too high of a Reynolds number (see below), because it may result in turbulence and associated air entrainment. Several computational tools (see Section 5.12.5) are now available to evaluate gating designs and help determine the size of the mold components.

Flow characteristics. An important consideration in fluid flow in gating systems is the presence of **turbulence**, as opposed to **laminar flow** of fluids. The **Reynolds number**, Re, is used to characterize this aspect of fluid flow; Re represents the ratio of the inertia to the viscous forces in fluid flow, and is expressed as

$$\operatorname{Re} = \frac{\nu D \rho}{\eta},\tag{5.10}$$

where v is the velocity of the liquid, D is the diameter of the channel, and ρ and η are the density and viscosity, respectively, of the liquid.

The higher the Reynolds number, the greater is the tendency for turbulent flow. In ordinary gating systems Re ranges from 2000 to 20,000; Re values of up to 2000 represent laminar flow. Between 2000 and 20,000 the flow is a mixture of laminar and turbulent, and is generally regarded as harmless in gating systems for casting. However, Re values over 20,000 represent severe turbulence, resulting in air entrainment and *dross* formation. Dross is the scum that forms on the surface of the molten metal as a result of the reaction of the liquid metal with air and other gases. Techniques for minimizing turbulence generally involve avoidance of sudden changes in the flow direction and in the geometry of channel cross sections of the gating system.

Dross or *slag* (nonmetallic products from mutual dissolution of flux and nonmetallic impurities) can be eliminated only by *vacuum casting* (Section 5.8.5). The reduction and control of dross or slag is another important consideration in fluid flow. This can be achieved by skimming

(using *dross traps*), properly designing pouring basins and gating systems, or using filters. Filters are usually made of ceramic, mica, or fiberglass. Their proper location and placement is important for effective filtering of dross and slag.

EXAMPLE 5.2 Design and Analysis of a Sprue for Casting

Given: The desired volume flow rate of the molten metal into a mold is $0.01 \text{ m}^3/\text{min}$. The top of the sprue has a diameter of 20 mm and its length is 200 mm.

Find: What diameter should be specified at the bottom of the sprue in order to prevent aspiration? What is the resultant velocity and Reynolds number at the bottom of the sprue if the metal being cast is aluminum and has a viscosity of 0.004 N-s/m²?

Solution: A pouring basin is typically provided on top of a sprue so that molten metal may be present above the sprue opening; however, this complication will be ignored in this case. Note that the metal volume flow rate is $Q = 0.01 \text{ m}^3/\text{min} = 1.667 \times 10^{-4} \text{ m}^3/\text{s}$. Let subscripts 1 and 2 refer to the top and bottom of the sprue, respectively. Since $d_1 = 20 \text{ mm} = 0.02 \text{ m}$,

$$A_1 = \frac{\pi}{4}d^2 = \frac{\pi}{4}(0.002)^2 = 3.14 \times 10^{-4} \text{ m}^2.$$

Therefore,

$$v_1 = \frac{Q}{A_1} = \frac{1.667 \times 10^{-4}}{3.14 \times 10^{-4}} = 0.531 \text{ m/s}.$$

Assuming no frictional losses and recognizing that the pressure at the top and bottom of the sprue is atmospheric, Eq. (5.5) gives

$$0.2 + \frac{(0.531)^2}{2(9.81)} + \frac{p_{\text{atm}}}{\rho g} = 0 + \frac{v_2^2}{2(9.81)} + \frac{p_{\text{atm}}}{\rho g},$$

or $v_2 = 1.45$ m/s. To prevent aspiration, the sprue opening should be the same as that required by flow continuity, or

$$Q = A_2 v^2 = 1.667 \times 10^{-4} \text{ m}^3/\text{s} = A_2(1.45 \text{ m/s}),$$

or $A_2 = 1.150 \times 10^{-4} \text{ m}^2$, and therefore d = 12 mm. The profile of the sprue will be parabolic, as suggested by Eq. (5.7). In calculating the Reynolds number, note from the inside front cover that the density of aluminum is 2700 kg/m³. The density for molten aluminum will of course be lower, but not significantly, so this value is sufficient for this problem. From Eq. (5.10),

$$\operatorname{Re} = \frac{\nu D\rho}{\eta} = \frac{(1.45)(0.012)(2700)}{0.004} = 11,745.$$

As stated above, this magnitude is typical for casting molds, representing a mixture of laminar and turbulent flow.

5.4.2 Fluidity of Molten Metal

A term commonly used to describe the ability of the molten metal to fill mold cavities is *fluidity*. This term consists of two basic factors: (1) characteristics of the molten metal; and (2) casting parameters. The following characteristics of molten metal influence fluidity:

- **1.** Viscosity. Fluidity decreases as viscosity and the viscosity index (its sensitivity to temperature) increase.
- 2. Surface tension. A high surface tension of the liquid metal reduces fluidity. Oxide films developed on the surface of the molten metal have a significant adverse effect on fluidity; an oxide film on the surface of pure molten aluminum, for example, triples the surface tension.
- **3. Inclusions.** As insoluble particles, inclusions can have a significant adverse effect on fluidity. This effect can be verified by observing the viscosity of a liquid, such as oil, with and without fine sand particles in it; it will be noted that the former will have lower viscosity.
- 4. Solidification pattern of the alloy. The manner in which solidification occurs, as described in Section 5.3, can influence fluidity. Moreover, fluidity is inversely proportional to the freezing range [see Eq. (5.3)]; thus, the shorter the range (as in pure metals and eutectics), the higher the fluidity becomes. Conversely, alloys with long freezing ranges (such as solid-solution alloys) have lower fluidity.

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

- 1. Mold design. The design and dimensions of such components as the sprue, runners, and risers all influence fluidity to varying degrees.
- 2. Mold material and its surface characteristics. The higher the thermal conductivity of the mold and the rougher its surfaces, the lower is fluidity. Heating the mold improves fluidity, although it also increases the solidification time, resulting in coarser grains and hence lower strength.
- **3. Degree of superheat.** Defined as the increment of temperature above an alloy's melting point, superheat improves fluidity by delaying solidification.
- 4. Rate of pouring. The lower the rate of pouring into the mold, the lower the fluidity, because the metal cools faster.
- 5. Heat transfer. Heat transfer directly affects the viscosity of the liquid metal, and hence its fluidity.

The term **castability** is generally used to describe the ease with which a metal can be cast to produce a part with good quality. Because this term also includes casting practices, the factors listed above have a direct effect on castability.

Tests for fluidity. Several tests have been developed to quantify fluidity, although none are accepted universally. In one such common test, the

molten metal is made to flow along a channel that is at room temperature; the distance the metal flows before it solidifies is a measure of its fluidity. Obviously, this length is a function of the thermal properties of the metal and the mold, as well as of the design of the channel. Still, such fluidity tests are useful and simulate casting situations to a reasonable degree.

5.4.3 Heat Transfer

A major consideration in casting is the heat transfer during the complete cycle from pouring to solidification and cooling of the casting to room temperature. *Heat flow* at different locations in the system depends on many factors, relating to the casting material and the mold and process parameters. For instance, in casting thin sections, the metal flow rates must be high enough to avoid premature chilling and solidification. On the other hand, the flow rate must not be so high as to cause excessive turbulence, with its detrimental effects on the properties of the casting.

A typical temperature distribution in the mold-liquid metal interface is shown in Fig. 5.6. As expected, the shape of the curve will depend on the thermal properties of the molten metal and the mold material, such as sand, metal, or a ceramic. Heat from the liquid metal being poured is given off through the mold wall and the surrounding air. The temperature drop at the air-mold and mold-metal interfaces is caused by the presence of boundary layers and imperfect contact at these interfaces.

5.4.4 Solidification Time

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

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

Solidification time =
$$C\left(\frac{\text{Volume}}{\text{Surface area}}\right)^n$$
, (5.11)

where *C* is a constant that reflects the mold material and the metal properties, including latent heat and temperature. The parameter n typically has a value between 1.5 and 2, and is usually taken as 2. Thus, a large sphere solidifies and cools to ambient temperature at a much lower rate than does a smaller sphere, because the volume of a sphere is proportional to the cube of its diameter whereas the surface area is proportional to the square of its diameter. Similarly, it can be shown that molten metal in a cube-shaped mold will solidify faster than in a spherical mold of the same volume.

The effects of mold geometry and elapsed time on skin thickness and its shape are shown in Fig. 5.11. The unsolidified molten metal has been poured from the mold at different time intervals, ranging from 5 s to 6 min. **FIGURE 5.11** Solidified skin on a steel casting; the remaining molten metal is poured out at the times indicated in the figure. Hollow ornamental and decorative objects are made by a process called slush casting, which is based on this principle. *Source:* After H.F. Taylor, J. Wulff, and M.C. Flemings



Note that the skin thickness increases with elapsed time, and that the skin is thinner at internal angles (location A in the figure) than at external angles (location B). As expected, the metal cools slower at internal angles than at external angles. Note that this operation is very similar to making hollow chocolate candies in various shapes.

EXAMPLE 5.3 Solidification Times for Various Solid Shapes

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

Find: Which piece will solidify the fastest and which one the slowest? Use n = 2.

Solution: The volume is unity, so from Eq. (5.11):

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

The respective surface areas are

Sphere:
$$V = \left(\frac{4}{3}\right)\pi r^3$$
, $r = \left(\frac{3}{4\pi}\right)^{1/3}$, and $A = 4\pi r^2 = 4\pi \left(\frac{3}{4\pi}\right)^{2/3} = 4.84$
Cube: $V = a^3$, $a = 1$, and $A = 6a^2 = 6$.
Cylinder: $V = \pi r^2 h = 2\pi r^3$, $r = \left(\frac{1}{2\pi}\right)^{1/3}$, and
 $A = 2\pi r^2 + 2\pi r h = 6\pi r^2 = 6\pi \left(\frac{1}{2\pi}\right)^{2/3} = 5.54$.

Therefore, the respective solidification times t are

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

Therefore, the cube-shaped casting will solidify the fastest, and the sphere-shaped casting will solidify the slowest.

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

TABLE 5.1 Volumetric solidification contraction or expansion for various cast metals.

5.4.5 Shrinkage

Metals generally shrink during solidification and cooling to room temperature, as shown in Fig. 5.1 and Table 5.1. *Shrinkage* in a casting causes dimensional changes and sometimes cracking and is a result of the following phenomena:

- 1. Contraction of the molten metal as it cools before it begins to solidify,
- 2. Contraction of the metal during phase change from liquid to solid (latent heat of fusion), and
- **3.** Contraction of the solidified metal (the casting) as its temperature drops to ambient temperature.

The largest potential amount of shrinkage occurs during the phase change of the material from liquid to solid; this can be reduced or eliminated through the use of risers or pressure-feeding of molten metal. The amount of contraction during the solidification of various metals is shown in Table 5.1. Note that some metals, such as gray cast iron, expand. The reason is that graphite has a relatively high specific volume, and when it precipitates as graphite flakes during solidification of the gray cast iron, it causes a net expansion of the metal. Shrinkage, especially that due to thermal contraction, is further discussed in Section 5.12.2 in connection with design considerations in casting.

5.5 Melting Practice and Furnaces

Melting practice is an important aspect of casting operations, because it has a direct bearing on quality. Furnaces are charged with melting stock,

consisting of liquid and/or solid metal, alloying elements, flux, and slag-forming constituents.

Fluxes are inorganic compounds that refine the molten metal by removing dissolved gases and various impurities. They have several functions, depending on the metal. For aluminum alloys, for example, there are cover fluxes (to form a barrier to oxidation), cleaning fluxes, drossing fluxes to protect the molten metal from oxidation, refining fluxes, and wall-cleaning fluxes (to reduce the detrimental effect that some fluxes have on furnace linings, particularly induction furnaces). Fluxes may be added manually or they can be injected automatically into the molten metal. To protect the surface of the molten metal against atmospheric reaction and contamination, as well as to refine the melt, the metal must be insulated against heat loss. Insulation typically is provided by covering the surface of the melt or mixing it with compounds that form a slag. In casting steels, for example, the composition of the slag includes CaO, SiO₂, MnO, and FeO.

The metal *charge* may be composed of commercially pure **primary met**als, which can include remelted or recycled scrap. Clean scrapped castings, gates, and risers may also be included in the charge. If the melting points of the alloying elements are sufficiently low, pure alloying elements are added for the desired composition in the melt. If the melting points are too high, the alloying elements do not mix readily with the low-meltingpoint metals; in this case, **master alloys (hardeners)** are often used. These usually consist of lower-melting point alloys with higher concentrations of one or two of the required alloying elements. Differences in specific gravity of master alloys should not be too high to cause segregation in the melt.

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

Electric-arc furnaces are used extensively in foundries. They have such advantages as high rate of melting (hence high production rate), much less pollution than the other types of furnaces, and the ability to hold the molten metal for any length of time for alloying purposes.

Induction furnaces are especially useful in smaller foundries and produce composition-controlled smaller melts. The *coreless induction furnace* consists of a crucible, completely surrounded with a water-cooled copper coil through which high frequency current passes. Because there is a strong electromagnetic stirring action during induction heating, this type of furnace has excellent mixing characteristics for the purposes of alloying and adding new charge of metal. The *core* or *channel furnace* uses a low frequency (as low as 60 Hz) and has a coil that surrounds only a small portion of the unit.

Crucible furnaces have been used extensively throughout history; they are heated with various fuels, such as commercial gases, fuel oil, fossil fuel, as well as electricity. These furnaces may be stationary, tilting, or movable. Most ferrous and nonferrous metals are melted in these furnaces.

Cupolas are basically refractory lined, vertical steel vessels that are charged with alternating layers of metal, coke, and flux. Although they require major investments, cupolas operate continuously, have high melting rates, and produce large amounts of molten metal.

Levitation melting involves magnetic suspension of the molten metal. An induction coil simultaneously heats a solid billet and stirs and confines the metal, thus eliminating the need for a crucible, which could be a source of contamination of the melt with oxide inclusions. The molten metal then flows downward into an investment-casting mold (see Section 5.9.2). Investment castings made by this method are free of refractory inclusions and gas porosity, and have uniform fine-grained structure.

Foundries and foundry automation. The casting operations described in rest of this chapter are typically carried out in *foundries*. Modern foundries have automated and computer-integrated facilities for all aspects of their operations, and produce castings at high production rates, at low cost, and with excellent quality control.

Foundry operations basically involve three separate activities. (a) Pattern and mold making, utilizing computer-aided design and additive manufacturing techniques (see Section 10.12); (b) melting the metals while controlling their composition and impurities; and (c) various operations, such as pouring the molten metal into molds (carried along conveyors), shake-out, cleaning, heat treatment, and inspection. All operations are automated, including the use of industrial robots (Section 14.7).

5.6 Casting Alloys

Chapter 3 summarized the properties of wrought structures. The general properties of various casting alloys and processes are summarized in Fig. 5.12 and Tables 5.2 through 5.5.

5.6.1 Ferrous Casting Alloys

The term **cast iron** refers to a family of ferrous alloys composed of iron, carbon (ranging from 2.11% to about 4.5%), and silicon (up to about 3.5%). Cast irons are usually classified according to their solidification morphology, and by their structure (ferrite, pearlite, quenched and tempered, or austempered). Cast irons have lower melting temperatures than steels, which is why the casting process is so suitable for iron with high carbon content.

Cast irons represent the largest amount (by weight) of all metals cast and they can easily be cast into complex shapes. They generally possess several desirable properties, such as high strength, wear resistance, hardness, and good machinability (Chapter 8).



FIGURE 5.12 Mechanical properties for various groups of cast alloys. Compare with various tables of properties in Chapter 3. *Source:* After Steel Society of America.

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						D		
	Sand	Shell	pattern	Plaster	Investment	mold	Die	Centrifugal
Typical materials cast	All	All	All	Nonferrous (Al, Mg, Zn, Cu)	All	All	Nonferrous (Al, Mg, Zn, Cu)	All
Mass (kg): minimum maximum	0.01 No limit	$0.01 \\ 100+$	$0.01 \\ 100+$	$0.01 \\ 50+$	$0.001 \\ 100+$	$0.1 \\ 300$	$< 0.01 \\ 50$	$0.01 \\ 5000+$
Typical surface finish $(\mu m R_a)$	5-25	1-3	5-25	1–2	0.3-2	2–6	1–2	2-10
Porosity ¹	3-5	45	3-5	4-5	S	2–3	1–3	1-2
Shape complexity ¹	1–2	2–3	1–2	1–2	1	2–3	3-4	3-4
Dimensional accuracy ¹	ŝ	2	ŝ	2	1	1	1	S
Section thickness (mm): minimum: maximum:	3 No limit	5	- 7	⊣	1 75	2 50	0.5 12	$\begin{array}{c} 2\\ 100 \end{array}$
Typ. dimensional tolerance	1.6-4 (0.25 for small)	± 0.003		$\pm 0.005 - 0.010$	± 0.005	± 0.015	$\pm 0.001 - 0.005$	± 0.015
Cost ¹ Equipment Pattern/die	3 1-5 5	3 2-3	2-3 2-3	3-5 3-5	3–5 2–3	77		
Labor	1-3	3 Wraelee	3	1-2	1-2 wraelee	3 ^{W/2,2} 1-2	5	5 Mandar
Typical lead time ⁻ Typical production rate ²	1-20	weeks 5-50	weeks 1-20	1-10	weeks 1-1000	weeks 5-50	weeks-months 2–200	1-1000
Minimum quantity ²	1	100	500	10	10	1000	10,000	10 - 10,000
Notes: 1. Relative rating, 1 best, 5 w and die costs and low labor o 2. Approximate values withou	orst. For example, di osts. These ratings a ot the use of ranid n	ie casting has re only genei rototyping te	s relatively low ral; significant cchnologies.	' porosity, mid- to variations can occ	low shape comp :ur depending on	lexity, high dir 1 the manufact	nensional accuracy, uring methods used	, high equipment L
	I Inter and and area area	- O I LAND						

TABLE 5.2General characteristics of casting processes.

Type of alloy	Castability*	Weldability*	Machinability*	Applications
Aluminum	G-E	F	G-E	Pistons, clutch housings, intake manifolds, engine blocks, heads, cross members, valve bodies, oil pans, suspension components
Copper	F-G	F	G-E	Pumps, valves, gear blanks, marine propellers
Gray Iron	Е	D	G	Engine blocks, gears, brake disks and drums, machine bases
Magnesium	G-E	G	E	Crankcase, transmission housings, automotive panel beams, steering components
Malleable iron	G	D	G	Farm and construction machinery, heavy-duty bearings, railroad rolling stock
Nickel	F	F	F	Gas turbine blades, pump and valve components for chemical plants
Nodular iron	G	D	G	Crankshafts, heavy-duty gears
Steel (carbon and low alloy)	F	Е	F-G	Die blocks, heavy-duty gear blanks, aircraft undercarriage members, railroad wheels
Steel (high alloy)	F	Е	F	Gas turbine housings, pump and valve components, rock crusher jaws
White iron (Fe ₃ C)	G	VP	VP	Mill liners, shot blasting nozzles, railroad brake shoes, crushers and pulverizers
Zinc	Е	D	E	Door handles, radiator grills, toys

TABLE 5.3 Typical applications for castings and casting characteristics.

*E, excellent; G, good; F, fair; VP, very poor; D, difficult.

			Ultimate		
Cast		Yield	tensile	Elonga- tion in	
iron	Туре	MPa	MPa	50 mm (%)	Typical applications
Gray	Ferritic	140	170	0.4	Pipe, sanitary ware
	Pearlitic	240	275	0.4	Engine blocks, machine tools
	Martensitic	550	550	0	Wear surfaces
Ductile	Ferritic	275	415	18	Pipe, general service
(Nodular)	Pearlitic	380	550	6	Crankshafts, highly stressed parts
	Tempered Martensite	620	825	2	High-strength machine parts, wear resistance
Malleable	Ferritic	240	365	18	Hardware, pipe fittings, general
					engineering service
	Pearlitic	310	450	10	Couplings
	Tempered	550	700	2	Gears, connecting rods
White	Pearlitic	275	275	0	Wear resistance, mill rolls

TABLE 5.4 Properties and typical applications of cast irons.

			X7 11	Ultimate	Elonga-	
		Casting	Yield	tensile	tion in	Hardness
Alloy	Condition	method*	MPa	MPa	(%)	(HB)
Aluminum						
195	T6	S	220	280	2	
319	Τ6	S	180	250	1.5	_
357	T6	S	296	345	2.0	90
380	F	D	165	331	3.0	80
390	F	D	241	279	1.0	120
Magnesium						
AZ63A	T4	S, P	95	275	12	—
AZ91A	F	D	150	230	3	_
EZ33A	T5	S, D	110	160	3	—
HK31A	Τ6	S, D	105	210	8	
QE22A	T6	S	205	275	4	—
Copper						
Brass C83600	—	S	177	255	30	60
Bronze C86500		S	193	490	30	98
Bronze C93700	—	Р	124	240	20	60
Zinc						
No. 3		D		283	10	82
No. 5		D		331	7	91
ZA27		Р	365	425	1	115

TABLE 5.5 Typical properties of nonferrous casting alloys.

*S, sand; D, die; P, permanent mold.

1. Gray cast iron. In this structure, graphite exists largely in the form of flakes (Fig. 5.13a). It is called *gray cast iron*, or *gray iron*, because when broken, the fracture path is along the graphite flakes and the surface has a gray, sooty appearance. The flakes act as stress raisers, thus greatly reducing ductility. Gray iron is weak in tension, although strong in compression, as are other brittle materials. On the other hand, the graphite flakes give this material the capacity to dampen vibrations by the internal friction (hence energy dissipation) caused by these flakes. Gray iron is thus a suitable and commonly used material for constructing structures and machine tool bases in which vibration damping is important (Section 8.12). Gray cast irons are specified by a two-digit ASTM designation. Class 20, for example, indicates that the material must have a minimum tensile strength of 140 MPa.

The basic types of gray cast iron are ferritic, pearlitic, and martensitic (see Section 5.11). In **ferritic gray iron**, also known as fully gray iron, the structure consists of graphite flakes in an alpha ferrite matrix. **Pearlitic gray iron** has a structure consisting of graphite





(b)



FIGURE 5.13 Cast iron microstructure. Magnification: $100 \times .$ (a) ferritic gray iron with graphite flakes; (b) ferritic nodular iron, (ductile iron) with graphite in nodular form; and (c) ferritic malleable iron, solidified as white cast iron, with the carbon present as cementite (Fe₃C), then heat treated to graphitize the carbon. in a matrix of pearlite; although still brittle, it is stronger than gray iron. **Martensitic gray iron** is obtained by austenitizing a pearlitic gray iron, followed by rapid quenching, to produce a structure of graphite in a martensite matrix; as a result, it is very hard. Gray iron castings have relatively few shrinkage cavities and little porosity. Typical uses include engine blocks, machine bases, electric-motor housings, pipes, and wear surfaces of machinery.

- 2. Ductile iron (nodular iron). In this structure, graphite is in *nodular* (*spheroid*) form (Fig. 5.13b), making ductile iron more shock resistant. The shape of graphite flakes can be modified into nodules (spheres) by small additions of magnesium and/or cerium to the molten metal prior to pouring. Ductile iron can be heat treated to make it ferritic, pearlitic, or to have a structure of tempered martensite. Typically used for machine parts, pipe, and crankshafts, ductile cast irons are specified by a set of two-digit numbers. Class or grade 80-55-06, for example, indicates that the material has a minimum tensile strength of 550 MPa, a minimum yield strength of 380 MPa, and a 6% elongation.
- 3. White cast iron. White cast iron is very hard, wear resistant, and brittle, because its structure contains large amounts of iron carbide instead of graphite. This structure is obtained either by rapid cooling of gray iron or by adjusting its composition by keeping the carbon and silicon content low. This cast iron is also called *white iron*, because the absence of graphite gives the fracture surface a white crystalline appearance. Because of its extreme hardness and wear resistance, white cast iron typically is used for liners for machinery that processes abrasive materials, rolls for rolling mills, and railroad-car brake shoes.
- 4. Malleable iron. Malleable iron is obtained by annealing white cast iron in an atmosphere of carbon monoxide and carbon dioxide, between 800°C and 900°C for up to several hours. During this process the cementite decomposes (*dissociates*) into iron and graphite. The graphite exists as *clusters* (Fig. 5.13c) in a ferrite or pearlite matrix, and thus has a structure similar to nodular iron, that imparts ductility, strength, and shock resistance, hence the term *malleable*. Typical uses include hardware and railroad equipment. Malleable irons are specified by a five-digit designation; for example, 35018 indicates that the yield strength of the material is 240 MPa, and its elongation is 18%.
- 5. Compacted-graphite iron. The compacted-graphite structure has short, thick, and interconnected flakes, with undulating surfaces and rounded extremities. The mechanical and physical properties of this cast iron are between those of flake graphite and nodular graphite cast irons. Compacted-graphite iron is easy to cast and has consistent properties throughout the casting. Typical applications include automotive engine blocks, crankcases, ingot molds, cylinder heads, and brake disks; it is particularly suitable for components at elevated temperatures and resists thermal fatigue. Its machinability is better than nodular iron.

- 6. Cast steels. The high temperatures required to melt steels (See Table 3.3) requires appropriate mold materials, particularly in view of the high reactivity of steels with oxygen. Steel castings possess properties that are more uniform (isotropic) than those made by mechanical working processes (see Chapter 6). Cast steels can be welded; however, welding alters the cast microstructure in the heat-affected zone (see Section 12.7), influencing the strength, ductility, and toughness of the base metal.
- 7. Cast stainless steels. Casting of stainless steels involves considerations similar to those for steels. Stainless steels generally have a long freezing range (see Section 5.3.2) and high melting temperatures, and develop various structures. Cast stainless steels are available in various compositions, and they can be heat treated and welded. The cast products have high heat and corrosion resistance. Nickel-based casting alloys, for example, are used for severely corrosive environments and service at very high temperatures.

5.6.2 Nonferrous Casting Alloys

Aluminum-based alloys. Cast alloys with an aluminum base have a wide range of mechanical properties, largely because of various hardening mechanisms and heat treatments to which they can be subjected. These castings are lightweight, hence also called *light-metal castings*, and have good machinability. However, except for alloys containing silicon, they generally have low resistance to wear and abrasion. Aluminum-based cast alloys have numerous applications, including automotive engine blocks, architectural, decorative, aerospace, and electrical components.

Magnesium-based alloys. Cast alloys with a magnesium base have good corrosion resistance and moderate strength (depending on the proper use of a protective coating system), and the particular heat treatment. They have very good strength-to-weight ratios and have been widely used for aerospace and automotive structural applications.

Copper-based alloys. Cast alloys with a copper base have the advantages of good electrical and thermal conductivity, corrosion resistance, nontoxicity (unless they contain lead), good machinability, and wear properties (thus suitable as bearing materials).

Zinc-based alloys. Cast alloys with a zinc base have good fluidity and good strength for structural applications. These alloys are widely used in die casting of structural shapes, electrical conduit, and corrosion-resistant parts.

High-temperature alloys. With a wide range of properties and applications, these alloys typically require temperatures of up to 1650°C for casting titanium and superalloys, and higher for refractory alloys. Typical applications include jet and rocket engine components, which otherwise would be difficult or uneconomical to produce by other means.

5.7 Ingot Casting and Continuous Casting

Traditionally, the first step in metal processing is the casting of the molten metal into a solid form (**ingot**) for further processing. In ingot casting, the molten metal is poured (*teemed*) from the ladle into ingot molds, in which the metal solidifies; this is basically equivalent to sand casting or to permanent mold casting. Molten metal is poured into the permanent molds, yielding the microstructure shown in Fig. 5.5. Gas entrapment can be reduced by bottom pouring, using an insulated collar on top of the mold, or by using an exothermic compound that produces heat when it contacts the molten metal (hot top). These techniques reduce the rate of cooling and result in a higher yield of high quality metal. The cooled ingots are then removed (*stripped*) from the molds and lowered into *soaking pits*, where they are reheated to a uniform temperature of about 1200°C for subsequent processing. Ingots may be square, rectangular, or round in cross section, and their weight ranges from a few hundred to tens of thousands of kilograms.

5.7.1 Ferrous Alloy Ingots

Several reactions take place during solidification of an ingot that have an important influence on the quality of the steel produced. For example, significant amounts of oxygen and other gases can dissolve in the molten metal during steelmaking, leading to porosity defects (see Section 5.12.1). Because the solubility limit of gases in the metal decreases sharply as its temperature decreases, much of these gases cavitate during solidification of the metal. The rejected oxygen combines with carbon and forms carbon monoxide, which causes porosity in the solidified ingot. Depending on the amount of gas evolved during solidification, three types of steel ingots can be produced.

- 1. Killed steel is fully deoxidized steel; that is, oxygen is removed and thus porosity is eliminated. In the deoxidation process, the dissolved oxygen in the molten metal is made to react with elements (typically aluminum) that are added to the melt; vanadium, titanium, and zirconium also are used. These elements have an affinity for oxygen and form metallic oxides; with aluminum, the product is called aluminum-killed steel. The term *killed* comes from the fact that the steel lies quietly in the mold.
- 2. Semi-killed steel is partially deoxidized steel. It contains some porosity, generally in the upper central section of the ingot, but otherwise has little or no pipe (see Section 5.12.1), and thus scrap is reduced. Piping is less because it is compensated for by the presence of porosity in that region. Semi-killed steels are economical to produce.
- 3. In a **rimmed steel**, which generally has less than 0.15% carbon, the evolved gases are only partially killed or controlled by the addition of elements, such as aluminum. Rimmed steels have little or no piping, with a ductile skin, and with good surface finish.

5.7.2 Continuous Casting

Conceived in the 1860s, *continuous casting*, or **strand casting**, was first developed for casting non-ferrous metal strip. It is now widely used for steel production and at low cost. A continuous casting system is shown schematically in Fig. 5.14a. The molten metal in the ladle (not shown) is cleaned and equalized in temperature, by blowing nitrogen gas through it for 5 to 10 min. The metal is then poured into a refractory-lined intermediate pouring vessel (**tundish**), where impurities are skimmed off.



FIGURE 5.14 (a) The continuous-casting process for steel. Typically, the solidified metal descends at a speed of 25 mm/s. Note that the platform is about 20 m above ground level. *Source: Metalcaster's Reference and Guide*, American Foundrymen's Society. (b) Continuous casting using support or guide rollers to allow transition from a vertical pour zone to horizontal conveyors. (c) Continuous strip casting of nonferrous metal strip.

Before starting the casting process, a solid *starter*, or *dummy bar*, is inserted into the bottom of the mold. The molten metal is then poured and solidifies on the starter bar (See bottom of Fig. 5.14a). The bar is withdrawn at the same rate the metal is poured, along a path supported by rollers (called *pinch rolls*). The cooling rate is such that the metal develops a solidified skin (shell) to support itself during its travel downward, at speeds typically around 25 mm/s. The shell thickness at the exit end of the mold is about 12–18 mm. Additional cooling is provided by water sprays along the travel path of the solidifying metal. The molds are generally coated with graphite, or a similar solid lubricant, to reduce friction and adhesion at the mold-metal interfaces. The molds also vibrated to further reduce friction and sticking.

The continuously cast metal is cut into desired lengths by shearing or torch cutting, or it may be fed directly into a rolling mill for further reductions in thickness and for shape rolling of products, such as channels and I-beams (Section 6.3.5). Continuously-cast metals have more uniform composition and properties than those made by ingot casting. Although the thickness of the steel strand is typically about 250 mm, it can be 12 mm or less. The thinner strand reduces the number of rolling operations required and thus improves productivity.

5.7.3 Strip Casting

In strip casting, thin slabs or strips are produced from molten metal, which solidifies in manner similar to strand casting, but the hot solid is then rolled to form the final shape (Fig. 5.14b). The compressive stresses developed in rolling serve to reduce any porosity in the material, improving the properties. Strip casting eliminates a hot rolling operation in the production of metal strips or slabs. Final thicknesses on the order of 2–6 mm can be obtained for carbon, stainless, and electrical steels (used in making the iron cores of motors, transformers, and generators) and other metals.

5.8 Expendable-Mold, Permanent-Pattern Casting Processes

Casting processes are generally classified according to (a) mold materials; (b) molding processes; and (c) methods of feeding the mold with the molten metal (See also Table 5.2). The two major categories are *expendable-mold* and *permanent-mold* casting (Section 5.10). Expendable-mold processes are further categorized as *permanent pattern* and *expendable pattern* processes. Expendable molds typically are made of sand, plaster, ceramics, and similar materials, which generally are mixed with various **binders** or bonding agents.

5.8.1 Sand Casting

The *sand casting* process consists of (a) placing a pattern, having the shape of the desired casting, in sand to make an imprint; (b) incorporating a

gating system; (c) filling the resulting cavity with molten metal; (d) allowing the metal to solidify; (e) breaking away the sand mold; and (f) removing the casting and finishing it. Examples of parts made by sand casting are engine blocks, cylinder heads, machine-tool bases, and housings for pumps and motors. While the origins of sand casting date to ancient times (See Table 1.1), it is still the most prevalent form of casting. In the United States alone, about 15 million tons of metal are cast by this method each year.

Sands. Sand, the product of the disintegration of rocks over extremely long periods of time, is inexpensive and suitable as mold material because of its resistance to high temperatures. Most sand-casting operations use silica sands (SiO₂). There are two general types of sand: *naturally bonded* (*bank sand*) and *synthetic* (*lake sand*). Because its composition can be controlled more accurately, synthetic sand is preferred by most foundries.

Several factors are considered in the selection of sand for molds. Sand having fine, round grains can be closely packed and forms a smooth mold surface. Good **permeability** of molds and cores allows gases and steam evolved during casting to escape easily. The mold should have good **collapsibility**, because the casting shrinks while cooling. Fine sand enhances mold strength but lowers mold permeability. Sand is typically conditioned before use. *Mulling machines* are used to uniformly mull (mixing thoroughly) sand with additives. Clay is typically used as a cohesive agent to bond the sand particles, giving the sand higher strength.

Types of sand molds. The major components of a typical sand mold are shown in Fig. 5.10. There are three basic types of sand molds: green-sand, cold-box, and no-bake molds. The most common mold material is *green molding sand*, the term green referring to the fact that the sand in the mold is moist or damp while the metal is being poured into it. Green molding sand is a mixture of sand, clay, and water, and is the least expensive in making molds.

In the **skin-dried** method, the mold surfaces are dried, either by storing the mold in air or drying it with torches; the molds may also be baked. These molds are generally used for large castings because of their high strength; also, they are stronger than green-sand molds and impart better dimensional accuracy and surface finish to the casting. However, distortion of the mold is greater, the castings are more susceptible to hot tearing (because of the lower collapsibility of the mold), and the production rate is lower because of the length of drying time required.

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

Patterns. *Patterns*, which are used to mold the sand mixture into the shape of the casting, may be made of wood, plastic, or metal; they can

also use additive manufacturing techniques (Section 10.12). Patterns may also be made from a combination of materials to reduce wear in critical regions. The selection of a pattern material depends on the size and shape of the casting, the dimensional accuracy, the quantity of castings required, and the molding process to be used. Because patterns are repeatedly used to make molds, the strength and durability of the pattern material selected must be sufficient for the number of castings the mold is expected to produce. Patterns are usually coated with a **parting agent** to facilitate their removal from the molds.

Patterns can be designed with a variety of features for specific applications as well as for economic considerations: (a) **One-piece patterns** are generally used for simpler shapes and low-quantity production; they are typically made of wood, and are inexpensive; (b) **split patterns** are two-piece patterns, made so that each part forms a portion of the cavity for the casting, thus allowing the casting of complicated shapes; and (c) **match-plate patterns** are a common type of mounted pattern, in which two-piece patterns are constructed, by securing each half of one or more split patterns to the opposite sides of a single plate. In such patterns, the gating system can be mounted on the drag side of the pattern.

Cores. Cores are utilized for castings with internal cavities or passageways, such as in automotive engine blocks or valve bodies. They are placed in the mold cavity prior to pouring, and are removed from the casting during shakeout. Cores must possess certain strength, permeability, ability to withstand heat, and collapsibility. They are typically made of sand aggregates and are anchored by **core prints**, which are recesses in the mold to support the core and to provide vents for the escape of gases. To keep the core from shifting during casting, metal supports (called **chaplets**) may be used to anchor the core in place. Cores are shaped in core boxes, which are used much as patterns are used to form sand molds. The sand can be packed into the boxes with sweeps or blown into the box by compressed air from *core blowers*.

Sand-molding machines. The sand mixture is compacted around the pattern by molding machines. These machines eliminate arduous labor and produce higher-quality castings by manipulating the mold in a controlled manner. Mechanization of the molding process can further be assisted by jolting the assembly, in which the flask, the molding sand, and the pattern are all placed on a pattern plate, mounted on an anvil and jolted upward by air pressure at rapid intervals. The inertial forces compact the sand around the pattern.

In vertical flaskless molding the halves of the pattern form a vertical chamber wall against which the sand is blown and compacted. The mold halves are then packed horizontally, with the parting line oriented vertically, and moved along a pouring conveyor.

Sandslingers fill the flask uniformly with sand, under a stream of high pressure. *Sandthrowers* are used to fill large flasks, and are typically operated by machine. An impeller in the machine throws sand from its blades

or cups at such high speeds that the sand is placed and compressed, so that additional compaction is unnecessary.

In impact molding, the sand is compacted by controlled explosion or instantaneous release of compressed gases, producing molds with uniform strength and good permeability. In vacuum molding, also known as the "V" process, the pattern is covered tightly with a thin plastic sheet. A flask is then placed over the pattern and is filled with sand. A second sheet of plastic is placed on top of the sand, and a vacuum action compresses and hardens the sand to allow the pattern to be withdrawn. Both halves of the mold are made this way and then assembled. During pouring of molten metal, the mold remains under vacuum but the casting cavity does not. When the metal has solidified, the vacuum is turned off and the sand falls away, releasing the casting.

The sand casting operation. The sequence of operations in sand casting is shown in Fig. 5.15. After the mold has been shaped and the cores have been placed in position, the two halves (cope and drag) are closed (Fig. 5.10), clamped, and weighted down (to prevent the separation of the mold sections under the pressure exerted when the molten metal is poured in). The design of the gating system is important for proper delivery of the molten metal into the mold cavity. Turbulence must be minimized, air and gases must be allowed to escape by vents or other means, and proper temperature gradients must be established and maintained to eliminate shrinkage and porosity. The design of *risers* also is important for supplying the necessary amount of molten metal during solidification of the casting. Note that the pouring basin may also serve as a riser for this purpose. After solidification, the casting is shaken out of its mold and the sand and oxide layers, adhering to the casting, are removed by vibration (using a shaker) or by sand blasting. The risers and gates are then removed by sawing, trimming in dies, abrasive disks, or by oxyfuel-gas cutting,

Almost all commercially used alloys can be sand cast. The surface finish largely depends on the mold materials. Although dimensional accuracy is not as good as that of other casting processes (See Table 5.2), intricate shapes can be cast, such as cast-iron engine blocks, transmission housings, machinery frames and very large propellers for ocean liners. Sand casting can be economical for relatively small as well as large production runs; equipment costs are generally low.

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






FIGURE 5.16 Schematic illustration of the shell-molding process, also called the *dump-box* technique.

5.8.2 Shell-Mold Casting

Shell-mold casting (Fig. 5.16) has grown significantly because it can produce many types of castings with close dimensional tolerances, good surface finish, and at a low cost. In this process, a mounted pattern, made of a ferrous metal or aluminum, is heated to 175°C to 370°C, coated with a parting agent, such as silicone, and is clamped to a box or chamber containing a fine sand containing a 2.5–4% thermosetting resin binder (such as phenol-formaldehyde), which coats the sand particles. The sand mixture is then turned over the heated pattern, coating it evenly. The assembly is often placed in an oven for a short period of time to complete the curing of the resin. The shell hardens around the pattern and is then removed, using built-in ejector pins. Two half-shells are made in this manner and are bonded or clamped together in preparation for pouring.

The shells are light and thin, usually 5-10 mm, and thus their thermal characteristics are different from those for thicker molds. The thin shells allow gases to escape during solidification of the metal. The mold is generally used vertically and is supported by surrounding it with steel shot. The mold walls are relatively smooth, resulting in low resistance to molten metal flow and producing castings with sharper corners, thinner sections, and smaller projections than are possible in green-sand molds. Several castings can be made in a single mold, using a multiple gating system.

Applications include small mechanical parts requiring high precision, gear housings, cylinder heads, and connecting rods; the process is also widely used in producing high-precision molding cores, such as engine-block water jackets.

Shell-mold casting may be more economical than other casting processes, depending on various production factors, particularly energy cost. The relatively high cost of metal patterns becomes a smaller factor as the size of production run increases. The high quality of the finished casting can significantly reduce the costs for subsequent cleaning, machining, and other finishing operations. Complex shapes can be produced with less labor, and the process can be automated fairly easily.

Sodium silicate process. The mold material in this process is a mixture of sand and 1 to 6% sodium silicate (*waterglass*), or various other chemicals, as the binder for sand. The mixture is then packed around the pattern and hardened by blowing CO_2 gas through it. Also known as *silicate-bonded sand* or the carbon-dioxide process, this process is also used to make cores, reducing their tendency to tear, because of their flexibility at elevated temperatures.

Rammed graphite molding. Rammed graphite is used to make molds for casting reactive metals, such as titanium and zirconium, because these metals react vigorously with silica. The molds are packed, much like sand molds, then air dried, baked at 175°C, and fired at 870°C. They are then stored under controlled humidity and temperature. The casting procedures are similar to those for sand molds.

5.8.3 Plaster-Mold Casting

The *plaster-mold casting* process and the ceramic-mold and investmentcasting processes are known as **precision casting**, because of the high dimensional accuracy and good surface finish obtained. Typical parts made are lock components, gears, valves, fittings, tooling, and ornaments, weighing as little as 1 g. The mold is made of *plaster of paris* (gypsum, or calcium sulfate), with the addition of talc and silica flour to improve strength and control the time required for the plaster to set. These components are mixed with water and the resulting slurry is poured over the pattern.

After the plaster sets, usually within 15 min, the pattern is removed and the mold is dried. The mold halves are then assembled to form the mold cavity and are preheated to about 120°C for 16 hrs; the molten metal is then poured into the mold. Because plaster molds have very low permeability, the gases evolved during solidification of the metal cannot escape; consequently, the molten metal is poured either in a vacuum or under pressure. The permeability of plaster molds can be substantially increased by the *Antioch* process. The molds are dehydrated in an autoclave (pressurized oven) for 6–12 hrs, then rehydrated in air for 14 hrs. Another method of increasing permeability is to use foamed plaster, containing trapped air bubbles.

Patterns for plaster molding are generally made of aluminum alloys, thermosetting plastics, brass, or zinc alloys; wood patterns are not suitable, due to the presence of water-based slurry. Because there is a limit to the maximum temperature that the plaster mold can withstand, generally about 1200°C, plaster-mold casting is used only for casting aluminum, magnesium, zinc, and some copper-based alloys. The castings have fine detail and good surface finish. Since plaster molds have lower thermal conductivity than other types of molds, the castings cool slowly, resulting in more uniform grain structure, with less warpage and better mechanical properties.

5.8.4 Ceramic-Mold Casting

The *ceramic-mold casting* process, also called **cope-and-drag investment casting**, is another precision casting process; it is similar to the plaster-mold process, with the exception that it uses refractory mold materials suitable for high-temperature applications. The slurry is a mixture of fine-grained zircon ($ZrSiO_4$), aluminum oxide, and fused silica; they are mixed with bonding agents, and poured over the pattern (Fig. 5.17) which has been placed in a flask. The pattern may be made of wood or metal. After setting, the molds (ceramic facings) are removed, dried, burned off to remove volatile matter, and baked. The molds are then clamped firmly and are used as for all-ceramic molds. In the related *Shaw* process, the ceramic facings are backed by fireclay to make the molds stronger.

The high-temperature resistance of the refractory molding materials allows these molds to be used in casting ferrous and high-temperature alloys, stainless steels, and tool steels. Although the process is somewhat expensive, the castings have good dimensional accuracy and surface finish over a wide range of sizes and intricate shapes, with some parts weighing as much as 700 kg. Typical parts made are impellers, cutters for machining, dies for metalworking, and molds for making plastic or rubber components.

5.8.5 Vacuum Casting

The *vacuum-casting process*, also called *counter-gravity low-pressure* (CL) *process*, but not to be confused with the vacuum-molding process



FIGURE 5.17 Sequence of operations in making a ceramic mold.



FIGURE 5.18 Schematic illustration of the vacuum-casting process. Note that the mold has a bottom gate. (a) before and (b) after immersion of the mold into the molten metal. *Source:* After R. Blackburn.

described in Section 5.8.1, is shown in Fig. 5.18. A mixture of fine sand and urethane is molded over metal dies and cured with amine vapor. The mold is then held with a robot arm and partially immersed into molten metal in an induction furnace. The metal may be melted in air (*CLA process*) or in a vacuum (*CLV process*). The vacuum reduces the air pressure inside the mold to about two-thirds of atmospheric pressure, drawing the molten metal into the mold cavities through a gate at the bottom of the mold. After the mold is filled, it is withdrawn from the molten metal. The furnace is at a temperature usually 55°C above the liquidus temperature; consequently, the metal begins to solidify within a fraction of a second.

This process is an alternative to investment, shell-mold, and green-sand casting, and is particularly suitable for thin-walled (0.75 mm) complex shapes and with uniform properties. Carbon and low- and high-alloy steel and stainless steel parts, weighing as much as 70 kg, can be vacuum cast. These parts, which are often in the form of superalloys for gas turbines, may have walls as thin as 0.5 mm. The process can be automated and production costs are similar to those for green-sand casting.

5.9 Expendable-Mold, Expendable-Pattern Casting Processes

5.9.1 Expendable-Pattern Casting (Lost Foam Process)

The *expendable-pattern casting process* uses a polystyrene pattern, which evaporates upon contact with the molten metal, to form a cavity for the casting, as shown in Fig. 5.19. The process is also known as *evaporative-pattern* or *lost-foam casting*, and under the trade name *Full-Mold* process.



FIGURE 5.19 Schematic illustration of the expendable-pattern casting process, also known as lost-foam or evaporative-pattern casting.

It is one of the more important casting processes for ferrous and nonferrous metals, particularly for the automotive industry. First, raw expandable polystyrene (EPS) beads, containing 5–8% pentane (a volatile hydrocarbon), are placed in a preheated die, typically made of aluminum. The polystyrene expands and takes the shape of the die cavity; additional heat is applied to fuse and bond the beads together. The die is then cooled and opened, and the pattern is removed. Complex patterns may also be made by bonding various individual pattern sections, using hot-melt adhesive (Section 12.14.1).

The pattern is then coated with a water-based refractory slurry, dried, and placed in a flask. The flask is filled with loose fine sand, which surrounds and supports the pattern; it is periodically compacted by various means. Then, without removing the pattern, the molten metal is poured into the mold. This action immediately vaporizes the pattern and fills the mold cavity, completely replacing the space previously occupied by the polystyrene pattern. The heat degrades (depolymerizes) the polystyrene, and the degradation products are vented into the surrounding sand. In a modification of this process, the polystyrene pattern is surrounded by a ceramic sell (*Replicast*[®] *C-S process*; see below).

The molten metal flow velocity in the mold depends on the rate of degradation of the polymer. The flow is basically laminar, with Reynolds numbers in the range of 400–3000 (see Section 5.4.1). The velocity

of the metal-polymer pattern front is estimated to be in the range of 0.1–1 m/s, and can be controlled by producing patterns with cavities or hollow sections. Because the polymer requires considerable energy to degrade, large thermal gradients are present at the metal-polymer interface. In other words, the molten metal cools faster than it would if it were poured into a cavity; this has important effects on the microstructure throughout the casting and also leads to directional solidification of the metal.

Typical parts made are aluminum engine blocks, cylinder heads, crankshafts, brake components, manifolds, and machine bases. The evaporativepattern casting process is also used in the production of metal-matrix composites (Section 11.14).

The evaporative-pattern process has the following characteristics: (a) The process is relatively simple, because there are no parting lines, cores, or riser systems; hence it has design flexibility; (b) inexpensive flasks are satisfactory for this process; (c) polystyrene is inexpensive and can be easily processed into patterns with complex shapes, various sizes, and fine surface detail; (d) the casting itself requires minimum cleaning and finishing operations; (e) the operation can be automated and is economical for long production runs; and (f) the cost of producing the die used for expanding the polystyrene beads to make the pattern can be high.

In a modification of the evaporative-pattern process, called the $Replicast^{\textcircled{B}}$ C-S process, a polystyrene pattern is surrounded by a ceramic shell; then the pattern is burned out prior to pouring the molten metal into the mold. The principal advantage of this process over investment casting (which uses wax patterns, Section 5.9.2) is that carbon pickup into the metal is avoided entirely. Further developments in evaporative-pattern casting include the production of metal-matrix composites (Section 11.14). During molding of the polymer pattern, fibers or particles are embedded throughout, which then become an integral part of the casting. Other techniques include the modification and grain refinement of the casting by using grain refiners and modifier master alloys.

5.9.2 Investment Casting (Lost Wax Process)

The *investment-casting* process, also called the *lost wax* process, was first used during the period 4000–3000 в.с. Typical parts made are mechanical components such as gears, cams, valves, and ratchets; parts up to 1.5 m in diameter and weighing as much as 1140 kg have been successfully cast by this process. The sequence involved in investment casting are shown in Fig. 5.20.

The pattern is made by injecting *semisolid* or *liquid* wax or plastic into a metal die in the shape of the pattern, or is made through additive manufacturing methods (Section 10.12). The pattern is then removed and dipped into a slurry of refractory material, such as very fine silica and binders, ethyl silicate, and acids. After this initial coating has dried, the pattern is coated repeatedly to increase its thickness. (The term *investment* comes from investing the pattern with the refractory material.) Wax patterns require careful handling, because they are not strong enough to withstand the forces involved during mold making. The one-piece mold is dried in air



FIGURE 5.20 Schematic illustration of investment casting (lost wax process). Castings by this method can be made with very fine detail and from a variety of metals. *Source:* Steel Founders' Society of America.

and heated to a temperature of 90°C to 175°C for about 4 hrs (depending on the metal to be cast), to drive off the water of crystallization (chemically combined water). After the metal has been poured and has solidified, the mold is broken up and the casting is removed.

Several patterns can be joined to make one mold, called a tree (Fig. 5.20), significantly increasing the production rate. For small parts, the tree can be inserted into a permeable flask and filled with a liquid slurry investment. The investment is then placed into a chamber and evacuated, to remove air bubbles, until the mold solidifies. The flask is usually placed in a vacuum-casting machine, so that the molten metal is drawn into the permeable mold and onto the part, producing fine detail.

The labor and materials involved can make the lost-wax process costly, but little or no finishing is required. The process is capable of producing intricate shapes from a wide variety of ferrous and nonferrous metals and alloys, with parts generally weighing from 1 g to 100 kg and as much as 1140 kg. It is suitable for casting high-melting-point alloys, with a good surface finish and close dimensional tolerances.

Ceramic-shell investment casting. A variation of the investment-casting process is *ceramic-shell investment casting*. It uses the same type of wax or plastic pattern, which is dipped (a) first into a slurry with colloidal silica or ethyl silicate binder; (b) then into a fluidized bed of fine-grained fused silica or zircon flour; and (c) then into coarse-grain silica, to build up additional coatings and thickness to withstand the thermal shock of pouring. The process is used extensively for precision casting of steels, aluminum, and high-temperature alloys, and is economical. If ceramic cores are used in the process, they are removed by leaching them with caustic solutions under high pressure and temperature.

The molten metal may be poured in a vacuum, to extract evolved gases and reduce oxidation, further improving the quality of the casting. The castings made by this and as well as other processes may be subjected to hot isostatic pressing (see Section 11.3.3) to further reduce microporosity. Aluminum castings, for example, are subjected to a gas pressure of up to about 100 MPa at 500°C.

5.10 Permanent-Mold Casting Processes

Permanent molds are used repeatedly and are designed so that the casting can be easily removed and the mold reused. The molds are made of metals that maintain their strength at high temperatures. Because metal molds are better heat conductors than the expendable molds, described above, the solidifying casting is subjected to a higher rate of cooling. This, in turn, affects the microstructure and grain size within the casting, as described in Section 5.3.

In permanent-mold casting, two halves of a mold are made from steel, bronze, refractory metal alloys, or graphite (*semipermanent mold*). The mold cavity and the gating system are machined into the mold itself, and thus become an integral part of the mold. If required, cores are made of metal or sand aggregate, and are placed in the mold prior to casting. Typical core materials are shell or no-bake cores, gray iron, low-carbon steel, and hot-work die steel. Inserts may also be used for various parts of the mold.

In order to increase the life of permanent molds, the surfaces of the mold cavity may be coated with a refractory slurry, or sprayed with graphite every few castings. The coatings also serve as parting agents and thermal barriers to control the rate of cooling of the casting. Mechanical ejectors, such as pins located in various parts of the mold, may be necessary for removal of complex castings. Ejectors usually leave small round impressions on castings and gating systems, as they do in injection-molding of plastics (see Section 10.10.2).

The molds are clamped together by mechanical means and are heated to facilitate metal flow and reduce damage (*thermal fatigue*, see Section 3.9.5) to the dies. The molten metal then flows through the gating system, fills the mold cavity, and, after solidification, the molds are opened and the casting is removed. Special methods of cooling the mold include water or

the use of air-cooled fins. The casting operation is automated, especially for large production runs.

Used mostly for aluminum, magnesium, and copper alloys (because of their generally lower melting points), as well as steels cast in graphite or heat-resistant metal molds, the castings have good surface finish, close dimensional tolerances, and uniform and good mechanical properties. Typical parts made include automobile pistons, cylinder heads, connecting rods, gear blanks for appliances, and kitchenware. Because of the high cost of dies, permanent-mold casting is not economical for small production runs. Moreover, because of the difficulty in removing the casting from the mold, intricate shapes cannot be cast by this process, although intricate internal cavities can be cast using sand cores.

5.10.1 Slush Casting

It was noted in Fig. 5.11 that a solidified skin first develops in a casting and that this skin becomes thicker with time. Hollow castings with thin walls can be made by permanent-mold casting using this principle in a process called *slush casting*. The molten metal is poured into the metal mold, and after the desired thickness of solidified skin is obtained, the mold is inverted (slung) and the remaining liquid metal is poured out. The mold halves are then opened and the casting is removed. This process is suitable for small production runs, and is typically used for making ornamental and decorative objects and toys, from low-melting-point metals, such as zinc, tin, and lead alloys.

5.10.2 Pressure Casting

In the *pressure-casting* process, also called *pressure pouring* or *low-pressure casting* (Fig. 5.21), the molten metal is forced upward into a graphite or metal mold, by gas pressure which is maintained until the metal has completely solidified in the mold. In a similar system, the molten metal may also be forced upward by a vacuum, which also removes dissolved gases and produces castings with lower porosity.

5.10.3 Die Casting

The *die-casting* process, developed in the early 1900s, is an example of permanent-mold casting, in which the molten metal is forced into the die cavity at pressures ranging from 0.7 to 700 MPa. The European term *pressure die casting*, or simply die casting, described in this section, is not to be confused with the term *pressure casting*, described in Section 5.10.2. Typical parts made by die casting include transmission housings, valve bodies, motors, business machine and appliance components, hand tools, and toys. The weight of most castings ranges from less than 90 g to about 25 kg.

1. Hot-chamber process. The *hot-chamber* process (Fig. 5.22) involves the use of a piston, which traps a specific volume of molten metal and forces it into the die cavity through a gooseneck and nozzle. The pressures range up to 35 MPa, with an average of about 15 MPa.



FIGURE 5.22 Schematic illustration of the hot-chamber die-casting process.

The metal is held under pressure until it solidifies in the die. To improve die life and to aid in rapid metal cooling (thus improving productivity), dies are usually cooled by circulating water or oil through various passageways in the die block. Low-melting-point alloys, such as zinc, tin, and lead, are commonly cast by this process. Cycle times typically range up to 900 shots (individual injections) per hour for zinc, although very small components, such as zipper teeth, can be cast at more than 300 shots per minute.

2. Cold-chamber process. In the *cold-chamber* process (Fig. 5.23) molten metal is introduced into the injection cylinder (*shot chamber*). The shot chamber is not heated, hence the term cold chamber. The metal is forced into the die cavity at pressures typically ranging from 20 to 70 MPa, although they may be as high as 150 MPa. The machines may be horizontal or vertical. Aluminum, magnesium, and



FIGURE 5.23 Schematic illustration of the cold-chamber die-casting process. These machines are large compared to the size of the casting, because high forces are required to keep the two halves of the die closed under pressure.

copper alloys are often cast by this method, although other metals, including ferrous metals, are also cast. Molten metal temperatures start at about 600°C for aluminum and magnesium alloys, and increase considerably for copper-based and iron-based alloys.

Process capabilities and machine selection. Because of the high pressures involved in die casting, the dies have a tendency to part unless clamped together tightly. The machines are rated according to the clamping force that can be exerted. The capacities of commercially available machines range from about 23 to 2700 metric tons. Other factors involved in the selection of die-casting machines include die size, piston stroke, shot pressure, and cost.

Dies may be made single cavity, multiple cavity (several identical cavities), combination cavity (several different cavities), or unit dies (simple small dies that can be combined in two or more units in a master holding die). Dies are usually made of hot-work die steels or mold steels (see Section 3.10.4). Die wear increases with the temperature of the molten metal. **Heat-checking** of the dies (surface cracking from repeated heating and cooling) can be a problem. When die materials are selected and maintained properly, dies may last more than half a million shots before die wear becomes significant. Alloys, except magnesium alloys, generally require lubricants, which typically are water base, with graphite or other compounds in suspension. Because of the high cooling capacity of water, these lubricants also are effective in keeping die temperatures low. Lubricants (as parting agents) are usually applied as thin coatings on die surfaces.

Highly automated, die casting has the capability for high production rates, with good strength, high-quality parts with complex shapes, and good dimensional accuracy and surface detail, thus requiring little or no subsequent machining or finishing operations (*net-shape forming*; see also Section 1.6). Components such as pins, shafts, and fasteners can be cast integrally (**insert molding**; see also Section 10.10.2) in a process similar to placing wooden sticks in popsicles. Ejector marks remain, as do small amounts of *flash* (thin material squeezed out between the dies; see Section 6.2.3) at the die parting line.

The properties and applications of die-cast materials are given in Table 5.6. Die casting can compete favorably with other casting and manufacturing methods, sheet metal stamping and forging. Because the molten metal chills rapidly at the die walls, the casting has a fine-grain and hard skin, with strength that is than in the center. Consequently, the strength-to-weight ratio of die-cast parts increases with decreasing wall thickness. With good surface finish and dimensional accuracy, die casting can produce bearing surfaces that would normally be machined. Equipment costs, particularly the cost of dies, are somewhat high, but labor costs are generally low because the process usually is semi- or fully automated.

Alloy	Yield strength MPa	Ultimate tensile strength MPa	Elonga- tion in 50 mm (%)	Applications
Aluminum 380 (3.5 Cu-8.5 Si)	320	160	2.5	Appliances, automotive components, electrical motor frames and housings, engine blocks
Aluminum 13 (12 Si)	300	150	2.5	Complex shapes with thin walls, parts requiring strength at elevated temperatures
Brass 858 (60 Cu)	380	200	15	Plumbing fixtures, lock hardware, bushings, ornamental castings
Magnesium AZ91B (9 Al–0.7 Zn)	230	160	3	Power tools, automotive parts, sporting goods
Zinc No. 3 (4 Al)	280	—	10	Automotive parts, office equipment, household utensils, building hardware, toys
Zinc No. 5 (4 Al–1 Cu)	320	_	7	Appliances, automotive parts, building hardware, business equipment

TABLE 5.6 Properties and typical applications of common die-casting alloys.

Overcasting. A technology seen as critical for reducing vehicle weight is to *overcast* aluminum or magnesium, using a steel or copper insert to form a *hybrid casting*. This method allows the high strength of steel or corrosion resistance and heat transfer capabilities of copper to be locally applied, while exploiting the low density of aluminum and magnesium. Typically, an insert is placed in a die-casting mold (see also *insert molding*, Section 10.10.2), although permanent-mold casting is also often used for overcasting. Overcasting requires careful design of parts, as the adhesion of aluminum and magnesium on steel is poor, and mechanical features, such as grooves, bosses, and ribs are essential to ensure proper joint integrity.

5.10.4 Centrifugal Casting

The *centrifugal casting* process utilizes the inertial forces caused by rotation to force the molten metal into the mold cavities. There are three methods of centrifugal casting:

1. True centrifugal casting. Hollow cylindrical parts, such as pipes, gun barrels, and lampposts, can be produced by this technique, as shown in Fig. 5.24, in which molten metal is poured into a rotating mold. The axis of rotation is usually horizontal but can also be vertical for short parts. The molds are made of steel, iron, or graphite, and may be coated with a refractory lining to increase mold life. Mold surfaces can be shaped so that pipes with various outer patterns and shapes can be cast; the inner surface of the casting remains cylindrical because the molten metal is uniformly distributed by centrifugal forces. However, because of density differences in the radial direction, the lighter elements, such as dross, impurities, and pieces of the refractory lining, tend to collect on the inner surface of the casting.

Cylindrical parts, ranging from 13 mm to 3 m in diameter and 16 m long, can be cast centrifugally; wall thicknesses typically range from 6 to 125 mm. The pressure generated by the centrifugal force is high (as much as



FIGURE 5.24 Schematic illustration of the centrifugal casting process. Pipes, cylinder liners, and similarly shaped hollow parts can be cast by this process.



FIGURE 5.25 (a) Schematic illustration of the semicentrifugal casting process. Wheels with spokes can be cast by this process. (b) Schematic illustration of casting by centrifuging. The molds are placed at the periphery of the machine, and the molten metal is forced into the molds by centrifugal forces.

150 times gravitational acceleration), which is necessary for casting thick-walled parts. Castings of good quality, dimensional accuracy, and external surface detail are obtained by this process. In addition to pipes, typical parts made are bushings, engine cylinder liners, street lamps, and bearing rings, with or without flanges.

- **2.** Semicentrifugal casting. An example of *semicentrifugal* casting is shown in Fig. 5.25a. This method is used to cast parts with rotational symmetry, such as a wheel with spokes.
- **3.** Centrifuging. Also called *centrifuge casting*, mold cavities of any shape are placed at a distance from the axis of rotation. The molten metal is poured at the center and is forced into the mold by centrifugal forces (Fig. 5.25b). The properties within the castings vary by the distance from the axis of rotation, mainly because air bubbles in the molten metal are pushed toward the axis of rotation.

5.10.5 Squeeze Casting

The *squeeze-casting* process involves solidification of the molten metal under high pressure, thus it is a combination of casting and forging (Fig. 5.26). The machinery typically includes a die, punch, and ejector pins. The pressure applied by the punch keeps the entrapped gases in solution, especially hydrogen in aluminum alloys. Moreover, the high pressure at the die-metal interfaces promotes heat transfer, and the resulting higher cooling rate produces a fine microstructure, with good mechanical properties and limited microporosity. The pressures in squeeze casting are typically higher than those in pressure die casting, but lower than those for hot or cold forging (Section 6.2). Ferrous or nonferrous parts can be made to *near-net shape* (see also Section 1.6), with complex shapes and fine surface detail. Typical products made by squeeze casting include automotive wheels, mortar bodies (a short-barreled cannon), brake drums, and valve bodies.



FIGURE 5.26 Sequence of operations in the squeeze-casting process. This process combines the advantages of casting and forging.

5.10.6 Semisolid Metal Forming (Thixocasting) and Rheocasting

In the *semisolid metal forming process* (developed in the 1970s and also called *semisolid metalworking*), the metal or alloy has a nondendritic and fine-grained structure when it enters the die or the mold. The alloy exhibits *thixotropic* behavior (its viscosity decreases when agitated), hence this process is also known as **thixoforming** or **thixocasting**. For example, at rest and above its solidus temperature, the alloy has the consistency of butter, but when agitated vigorously its consistency is more like machine oil.

Thixotropic behavior has been utilized in developing machines and technologies combining casting and forging of parts, with cast billets that are forged when 30–40% liquid, or in a mushy state. Processing metals in their mushy state also has led to developments in *mushy-state extrusion*, similar to injection molding (described in Section 10.2.2), *forging*, and *rolling* (hence the term *semisolid metalworking*). These processes are also used in making parts from specially designed casting alloys, wrought alloys, and metal-matrix composites (Section 11.14). They also have the capability for blending granules of different alloys, called *thixoblending*, for specific applications.

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

The main advantages of thixocasting are that the semisolid metal is just above the solidification temperature when injected into a die, resulting in reductions in solidification and cycle times, and thereby increased productivity. Furthermore, shrinkage porosity is reduced because of the lower superheat involved. Parts made include control arms, brackets, and steering components. The advantages of semisolid metal forming over die casting are (a) the structures developed are homogeneous, with uniform properties, lower porosity, and high strength; (b) both thin and thick parts can be made; (c) casting alloys as well as wrought alloys can be used; (d) parts can subsequently be heat treated; and (e) the lower superheat results in shorter cycle times; however, material and overall costs generally are higher than those for die casting.

In **rheocasting**, a slurry (a solid suspended in a liquid) is obtained from a melt furnace and is cooled, and then magnetically stirred prior to injecting it into a mold or die. Rheocasting has been successfully applied to aluminum and magnesium, and has been used to make engine blocks, crankcases (as for motorcycles or lawn mowers), and various marine applications.

5.10.7 Casting Techniques for Single-Crystal Components

Casting techniques can best be illustrated by describing the casting of gas turbine blades, which are generally made of nickel-based superalloys. The procedures involved can also be used for other alloys and components.

Conventional casting of turbine blades. The conventional casting process involves investment casting, using ceramic molds (See Fig. 5.17). The molten metal is poured into the mold and begins solidifying at the ceramic walls. The grain structure developed is polycrystalline, and the presence of grain boundaries makes this structure susceptible to creep and cracking along those boundaries under the centrifugal forces at elevated temperatures.

Directionally solidified blades. In the *directional solidification* process (Fig. 5.27a), the ceramic mold is prepared basically by investment casting techniques and is preheated by radiant heating. The mold is supported by a water-cooled chill plate. After the metal is poured into the mold, the assembly is lowered slowly, whereby crystals begin to grow at the chill-plate surface. The blade is directionally solidified, with longitudinal (but no transverse) grain boundaries. Consequently, the blade is stronger in the direction of centrifugal forces developed in the gas turbine, that is, in the longitudinal direction.

Single-crystal blades. In the process for single-crystal blades, first made in 1967, the mold is prepared by investment casting techniques. It has a constriction in the shape of a corkscrew (Figs. 5.27b and c), allowing only one crystal through it. As the assembly is lowered slowly, a single crystal grows upward through the constriction and begins to grow in the mold. Strict control of the rate of movement is necessary in this process. The solidified mass in the mold is a single-crystal blade. Although more expensive than other blades (the largest blades are over 15 kg and can





(c)

FIGURE 5.27 Methods of casting turbine blades: (a) directional solidification; (b) method to produce a single-crystal blade; and (c) a single-crystal blade with the constriction portion still attached. *Source:* (a) and (b) After B.H. Kear, (c) Courtesy of ASM International.

cost over \$6000 each), the absence of grain boundaries makes these blades resistant to creep and thermal shock, imparting a longer and more reliable service life.

Single-crystal growing. Single-crystal growing is a major activity in the manufacture of microelectronic devices (see Chapter 13). There are two basic methods of crystal growing. In the **crystal pulling** method, known as the *Czochralski process* (Fig. 5.28a), a seed crystal is dipped into the molten metal, and then pulled at a rate of about 10 μ m/s while rotating at about 1 rev/s. The liquid metal begins to solidify on the seed, and the crystal structure of the seed is continued throughout the part. *Dopants* (alloying elements) may be added to the liquid metal to impart specific electrical properties. Single crystals of silicon, germanium, and various metals such as palladium, silver, and gold are grown by this process. Single crystal ingots up to 400 mm in diameter and over 2 m in length have been produced by this technique; 200 and 300 mm cylinders are more common in the production of silicon wafers for integrated circuit manufacture (Chapter 13).

The second technique for crystal growing is the **floating zone** method (Fig. 5.28b). Starting with a rod of polycrystalline silicon, resting on a single crystal, an induction coil heats these two pieces while moving slowly upward. The single crystal grows upward while maintaining its orientation. Thin wafers are then cut from the rod, cleaned, and polished for use in microelectronic device fabrication (see Chapter 13). Because of the limited diameters that can be produced in this process, it is has largely been



FIGURE 5.28 Two methods of crystal growing: (a) crystal pulling (Czochralski process) and (b) floating-zone method. Crystal growing is especially important in the semiconductor industry. (c) A single-crystal silicon ingot produced by the Czochralski process. *Source:* Courtesy of Intel Corp.

replaced by the Czochralski process (Fig. 5.28) for silicon, but is still used for cylinder diameters under 150 mm because it is a cost-effective method for producing single crystal cylinders in small quantities.

5.10.8 Rapid Solidification

First developed in the 1960s, *rapid solidification* involves cooling the molten metal at rates as high as 10^6 K/s, whereby it does not have sufficient time to crystallize. These alloys are called **amorphous alloys** or **metallic glasses**, because they do not have a long-range crystalline structure (see Section 3.2). They typically contain iron, nickel, and chromium, that are alloyed with carbon, phosphorus, boron, aluminum, and silicon. Among other effects, rapid solidification results in a significant extension of solid solubility, grain refinement, and reduced microsegregation.

Amorphous alloys exhibit excellent corrosion resistance, good ductility, high strength, very little magnetic hysteresis loss, high resistance to eddy currents, and high permeability. The last three properties are utilized in making magnetic steel cores used in transformers, generators, motors, lamp ballasts, magnetic amplifiers, and linear accelerators, with greatly improved efficiency. Another major application is rapidly-solidified superalloy powders, which are consolidated into near-net shapes for use in aerospace engines. Amorphous alloys are produced in the form of wire, ribbon, strip, and powder. In one process called **melt spinning** (Fig. 5.29), the alloy is melted (by induction in a ceramic crucible) and propelled, under high gas pressure, at very high speed against a rotating copper disk (chill block) where it chills rapidly (splat cooling).



FIGURE 5.29 (a) Schematic illustration of the melt-spinning process to produce thin strips of amorphous metal. (b) Photograph of nickel-alloy production through melt-spinning. *Source:* Courtesy of Siemens AG.

5.11 Heat Treatment

The various microstructures developed during metal processing can be modified by *heat treatment* techniques, involving controlled heating and cooling of the alloys at various rates (also known as **thermal treatment**). These treatments induce phase transformations that greatly influence mechanical properties, such as strength, hardness, ductility, toughness, and wear resistance of the alloys. The effects of thermal treatment depend primarily on the alloy, its composition and microstructure, the degree of prior cold work, and the rates of heating and cooling during heat treatment.

5.11.1 Heat Treating Ferrous Alloys

The microstructural changes that occur in the iron-carbon system (Section 5.2.5) are described below.

Pearlite. If the ferrite and cementite lamellae in the pearlite structure (see Section 5.2.6) of the eutectoid steel are thin and closely packed, the microstructure is called **fine pearlite**. If the lamellae are thick and widely spaced, the structure is called **coarse pearlite**. The difference between the two depends on the rate of cooling through the eutectoid temperature, a reaction in which austenite is transformed into pearlite. If the rate of cooling is relatively high (as in air), the structure is fine pearlite is produced; if slow (as in a furnace), it is coarse pearlite.

The transformation from austenite to pearlite (and for other structures) is best illustrated by Figs. 5.30b and c. These diagrams are called isothermal transformation (IT) diagrams or time-temperature-transformation (TTT) diagrams. They are constructed from the data in Fig. 5.30a, which



FIGURE 5.30 (a) Austenite to pearlite transformation of iron-carbon alloys as a function of time and temperature. (b) Isothermal transformation diagram obtained from (a) for a transformation temperature of 675°C. (c) Microstructures obtained for a eutectoid iron-carbon alloy as a function of cooling rate.

shows the percentage of austenite transformed into pearlite as a function of temperature and time. The higher the temperature and/or the longer the time, the higher is the percentage of austenite transformed to pearlite. Note that for each temperature, a minimum time is required for the transformation to start and that sometime later, all the austenite is transformed to pearlite.

Spheroidite. When pearlite is heated to just below the eutectoid temperature and held at that temperature for a period of time, say for a day at 700°C, the cementite lamellae (Fig. 5.4b) transform to *spherical* shapes (*spheroidites*). Unlike the lamellar shape of cementite, which acts as stress raisers, spheroidites are less conducive to stress concentration, because of their rounded shapes. Consequently, this structure has higher toughness and lower hardness than the pearlite structure. In this form it can be cold worked and the spheroidal particles prevent the propagation of any cracks within the material during working.

Bainite. Visible only under electron microscopy, *bainite* has a very fine microstructure, consisting of ferrite and cementite. It can be produced in steels by alloying and at cooling rates that are higher than those required for transformation to pearlite. This structure, called *bainitic steel*, is generally stronger and more ductile than pearlitic steel at the same hardness level.

Martensite. When austenite is cooled rapidly (such as by quenching in water), its fcc structure is transformed to a *body-centered tetragonal* (bct) structure. This structure can be described as a body-centered rectangular prism that is slightly elongated along one of its principal axes, called *martensite*. Because it does not have as many slip systems as a bcc structure and the carbon is in interstitial positions, martensite is extremely hard and brittle, lacks toughness, and therefore has limited use. Martensite transformation takes place almost instantaneously (Fig. 5.30c), because it does not involve the diffusion process (a time-dependent phenomenon that is the mechanism in other transformations).

Because of the different densities of the various phases in the structure, transformations involve volume changes. For example, when austenite transforms to martensite, its volume increases (hence density decreases) by as much as 4%. A similar but smaller volume expansion also occurs when austenite transforms to pearlite. These expansions and the resulting thermal gradients in a quenched part can cause the development of internal stresses within the body, which may cause parts to crack during heat treatment, as in **quench cracking** of steels, caused by rapid cooling during quenching.

Retained austenite. If the temperature at which the alloy is quenched is not sufficiently low, only a portion of the structure is transformed to martensite. The rest is *retained austenite*, which is visible as white areas in the structure along with dark needlelike martensite. Retained austenite can cause dimensional instability and cracking of the part and lowers its hardness and strength.

Tempered martensite. *Tempering* is a heating process that reduces martensite's hardness and improves its toughness. The body-centered tetragonal martensite is heated to an intermediate temperature, where it transforms to a two-phase microstructure, consisting of body-centered cubic alpha ferrite and small particles of cementite. Longer tempering time and higher temperature decrease martensite's hardness. The reason is that the cementite particles coalesce and grow, and the distance between the particles in the soft ferrite matrix increases as the less stable, smaller carbide particles dissolve.

Hardenability of ferrous alloys. The capability of an alloy to be hardened by heat treatment is called its *hardenability*; it is a measure of the depth of hardness that can be obtained by heating and subsequent quenching. (The term hardenability should not be confused with hardness, which is the resistance of a material to indentation or scratching.) Hardenability of ferrous alloys depends on their carbon content, the grain size of the austenite, and the alloying elements. The **Jominy test** has been developed in order to determine alloy hardenability.

Quenching media. Quenching may be carried out in water, brine (saltwater), oils, molten salts, or air, as well as caustic solutions, polymer solutions, and various gases. Because of the differences in the thermal conductivity, specific heat, and heat of vaporization of these media, the rate of cooling (severity of quench) also will be different. In relative terms and in decreasing order, the cooling capacity of several quenching media is: (a) agitated brine 5; (b) still water 1; (c) still oil 0.3; (d) cold gas 0.1; and (e) still air 0.02. Agitation is also a significant factor in the rate of cooling. In tool steels the quenching medium is specified by a letter (See Table 3.5), such as W for water hardening, O for oil hardening, and A for air hardening. The cooling rate also depends on the surface area-to-volume ratio of the part [see Eq. (5.11)]. The higher this ratio, the higher is the cooling rate; thus, for example, a thick plate cools more slowly than a thin plate with the same surface area.

Water is a common medium for rapid cooling; however, the heated metal may form a **vapor blanket** along its surfaces from water-vapor bubbles that form when water boils at the metal-water interfaces. This blanket creates a barrier to heat conduction because of the lower thermal conductivity of the vapor. Agitating the fluid or the part helps to reduce or eliminate the blanket. Also, water may be sprayed on the part under high pressure. Brine is an effective quenching medium because salt helps to nucleate bubbles at the interfaces, thus improving agitation. However, brine can corrode the part. **Die quenching** is a term used to describe the process of clamping the part to be heat treated to a die, which chills selected regions of the part. In this way cooling rates and warpage can be controlled.

5.11.2 Heat Treating Nonferrous Alloys and Stainless Steels

Nonferrous alloys and some stainless steels generally cannot be heat treated by the techniques for ferrous alloys, because nonferrous alloys



FIGURE 5.31 (a) Phase diagram for the aluminum-copper alloy system. (b) Various microstructures obtained during the age-hardening process.

do not undergo phase transformations as steels do. Heat-treatable aluminum alloys (see Section 3.11.1), copper alloys, and martensitic and precipitation-hardening stainless steels are hardened and strengthened by **precipitation hardening**. This is a technique in which small particles of a different phase (called *precipitates*) are uniformly dispersed in the matrix of the original phase (See Fig. 5.2a). Precipitates form because the solid solubility of one element (one component of the alloy) in the other is exceeded.

Three stages are involved in the precipitation-hardening process, which can best be described by referring to the phase diagram for the aluminumcopper system, given in Fig. 5.31. For an alloy with a composition of 95.5% Al-4.5% Cu, a single-phase (κ) substitutional solid-solution of copper (solute) in aluminum (solvent) exists between 500° and 570°C. The κ phase is aluminum rich, has an fcc structure, and is ductile. Below the lower temperature, that is, below the lower solubility curve, two phases are present: κ and θ (a hard intermetallic compound of CuAl₂). This alloy can be heat treated and its properties modified by solution treatment or precipitation.

Solution treatment. In *solution treatment* the alloy is heated to within the solid-solution κ phase, say 540°C, and cooled rapidly, such as by quenching in water. The structure obtained soon after quenching (A in Fig. 5.31b) consists only of the single phase κ ; this alloy has moderate strength and very good ductility.

Precipitation hardening. The structure obtained in A in Fig. 5.31b can be strengthened by *precipitation hardening*. The alloy is reheated to an intermediate temperature and held there for a period of time, during which precipitation takes place. The copper atoms diffuse to nucleation sites and combine with aluminum atoms, producing the theta phase, which form as submicroscopic precipitates (shown in B by the small dots within the grains of the κ phase). This structure is stronger than that in A, although it is less ductile; the increase in strength is attributed to increased resistance to dislocation movement in the region of the precipitates.

Aging. Because the precipitation process is one of time and temperature, it is also called aging, and the property improvement is known as *age hardening*. If carried out above room temperature, the process is called **artificial aging**. Several aluminum alloys harden and become stronger over a period of time at room temperature, by a process known as **natural aging**. These alloys are first quenched and then, if required, are formed at room temperature into various shapes, and allowed to develop strength and hardness by natural aging. Natural aging can be slowed by refrigerating the quenched alloy.

In the precipitation process, as the reheated alloy is held at that temperature for an extended period of time, the precipitates begin to coalesce and grow. They become larger but fewer, as shown by the larger dots in *C* in Fig. 5.31b. This process is called **overaging**, which makes the alloy softer and less strong, although the part treated has better dimensional stability over time. There is an optimal time-temperature relationship in the aging process to develop desired properties. An aged alloy can be used only up to a certain maximum temperature in service, otherwise it will overage and lose some of its strength and hardness.

Maraging. This is a precipitation-hardening treatment process for a special group of high-strength iron-based alloys; the word *maraging* is derived from the words *mar*tensite and *aging*. In this process, one or more intermetallic compounds (Section 5.2.2) are precipitated in a matrix of low-carbon martensite. A typical maraging steel may contain 18% nickel and other elements, and aging is done at 480°C. Hardening by maraging does not depend on the cooling rate, thus full uniform hardness can be obtained throughout large parts and with minimal distortion. Typical uses of maraging steels are for dies and tooling for casting, molding, forging, and extrusion.

5.11.3 Case Hardening

The heat treatment processes described thus far involve microstructural alterations and property changes in the *bulk* of a part by *through hard-ening*. In many cases, however, alteration of only the *surface* properties of a part (hence the term *case hardening*) is desirable, particularly for improving resistance to surface indentation, fatigue, and wear. Typical applications include gear teeth, cams, shafts, bearings, fasteners, pins, automotive clutch plates, and tools and dies. Through hardening of these

parts would not be desirable, because a hard part generally lacks the necessary toughness for these applications; a small surface crack, for example, can propagate rapidly through the whole part and cause total failure.

Several surface-hardening processes include (Table 5.7): carburizing (*gas, liquid,* and *pack carburizing*), carbonitriding, cyaniding, nitriding, boronizing, and flame and induction hardening. Basically, the component is heated in an atmosphere containing such elements as carbon, nitrogen, or boron, that alter the composition, microstructure, and properties of surfaces to various degrees.

For steels with sufficiently high carbon content, surface hardening takes place without the need for any of these additional elements; only the processes described in Section 5.11.1 are needed to alter the microstructures, usually by flame hardening or induction hardening. Laser beams and electron beams are also used effectively to harden both small and large surfaces and for through hardening of relatively small parts.

Because case hardening is a localized heat treatment, case-hardened parts have a hardness gradient. Typically, the hardness is greatest at the surface and decreases below the surface, and the rate of decrease depends on the composition of the metal and the process variables. Surface-hardening techniques can also be used for *tempering* (see Section 5.11.1), thereby modifying the properties of surfaces that have been subjected to heat treatment. Several other processes and techniques for surface hardening, such as shot peening and surface rolling, improve wear resistance and various other characteristics, as described in Section 4.5.1.

Decarburization. This is a phenomenon in which carbon-containing alloys lose carbon from their surfaces as a result of heat treatment or by hot working in a medium (usually oxygen) that reacts with the carbon. Decarburization is undesirable, because it adversely affects the hardenability of the surfaces of the part by lowering the carbon content; it also affects the hardness, strength, and fatigue life of steels by significantly lowering their endurance limit. Decarburization is best avoided by processing the alloy in an inert atmosphere or a vacuum, or by using neutral salt baths during heat treatment.

5.11.4 Annealing

Annealing is a general term to describe the restoration of a cold-worked or heat-treated part to its original properties, so as to increase its ductility (hence formability), reduce hardness and strength, or modify its microstructure. Annealing is also used to relieve residual stresses (Section 2.10) in a manufactured part for improved subsequent machinability and dimensional stability. The term annealing also applies to thermal treatment of glasses (Section 11.11.2) and weldments (Chapter 12).

The annealing process typically involves the following sequence: (1) heating the part to a specific range of temperature; (2) holding it at that temperature for a period of time (called *soaking*); and (3) cooling it slowly. The process may be carried out in an inert or controlled atmosphere, or is performed at low temperatures to prevent or minimize surface oxidation

	Metals	Element added to		General	Typical
Process	hardened	surface	Procedure	characteristics	applications
Carburizing	Low-carbon steel (0.2% C), alloy steels (0.08–0.2% C)	U	Heat steel at 870°C to 950°C in an atmosphere of carbonaceous gases (gas carburizing) or carbon-containing solids (pack carburizing). Then quench.	A hard, high-carbon surface is produced. Hardness 55–65 HRC. Case depth <0.5–1.5 mm. Some distortion of part during heat treatment.	Gears, cams, shafts, bearings, piston pins, sprockets, clutch plates
Carbonitriding	Low-carbon steel	C and N	Heat steel at 700°C to 800°C in an atmosphere of carbonaceous gas and ammonia. Then quench in oil.	Surface hardness 55–62 HRC. Case depth 0.07–0.5 mm. Less distortion than in carburizing.	Bolts, nuts, gears
Cyaniding	Low-carbon steel (0.2% C), alloy steels (0.08–0.2% C)	C and N	Heat steel at 760°C to 845°C in a molten bath of solutions of cyanide (e.g., 30% sodium cyanide) and other salts.	Surface hardness up to 65 HRC. Case depth 0.025–0.25 mm. Some distortion.	Bolts, nuts, screws, small gears
Nitriding	Steels (1% Al, 1.5% Cr, 0.3% Mo), alloy steels (Cr, Mo), stainless steels, high-speed steels	Z	Heat steel at 500°C to 600°C in an atmosphere of ammonia gas or mixtures of molten cyanide salts. No further treatment.	Surface hardness up to 1100 HV. Case depth 0.1–0.6 mm and 0.02–0.07 mm for high speed steel.	Gears, shafts, sprockets, valves, cutters, boring bars
Boronizing	Steels	В	Part is heated using boron-containing gas or solid in contact with part.	Extremely hard and wear-resistance surface. Case depth 0.025–0.075 mm.	Tool and die steels
Flame hardening	Medium-carbon steels, cast irons	None	Surface is heated with an oxyacetylene torch, then quenched with water spray or other quenching methods.	Surface hardness 50–60 HRC. Case depth 0.7–6 mm. Little distortion.	Axles, crankshafts, piston rods, lathe beds, and centers
Induction hardening	Same as above.	None	Metal part is placed in copper induction coils and is heated by high frequency current, then quenched.	Same as above.	Same as above.

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TABLE 5.7 OI





of the part. Annealing temperatures may be higher than the recrystallization temperature, depending on the degree of cold work (hence *stored energy*, see Section 2.12.1). The recrystallization temperature for copper, for example, ranges between 200°C and 300°C, whereas the annealing temperature required to fully recover the original properties ranges from 260°C to 650°C, depending on the degree of prior cold work.

Full annealing is a term used for annealing ferrous alloys, generally low- and medium-carbon steels. The steel is heated to above A_1 or A_3 (Fig. 5.32), and cooling takes place slowly, say 10°C per hour, in a furnace after it is turned off. The structure obtained in full annealing is coarse pearlite, which is soft and ductile, and has small uniform grains. Excessive softness in the annealing of steels can be avoided if the entire cooling cycle is carried out in still air. Normalizing is a process in which the part is heated to a temperature of A_3 or A_{cm} to transform the structure to austenite. The structure obtained is fine pearlite, with small uniform grains, and the process results in higher strength and hardness, and lower ductility than in full annealing. Normalizing generally refines the grain structure, produces uniform structure (*homogenization*), decreases residual stresses, and improves machinability.

Process annealing. In *process annealing*, also called *intermediate annealing*, subcritical annealing or *in-process annealing*), the part is annealed to restore its ductility, a portion or all of which may have been exhausted by work hardening during prior cold working. In this way, the part can be worked further into the final desired shape. If the temperature is too high and/or the time of annealing is too long, grain growth may result, with adverse effects on the formability of annealed parts.

Stress-relief annealing. Residual stresses may have been induced during forming, machining, or other shaping processes, or are caused by volume changes during phase transformations. To reduce or eliminate these stresses, the part is subjected to *stress-relief annealing*, or simply **stress**

relieving. The temperature and time required for this process depend on the material and the magnitude of residual stresses present. For steels, for example, the part is heated to below A_1 as shown in Fig. 5.32, thus avoiding phase transformations; cooling is slow, such as in still air. Stress relieving promotes dimensional stability in cases where subsequent relaxing of residual stresses may cause part distortion over a period of time; it also reduces the tendency for stress-corrosion cracking (Section 3.8.2).

5.11.5 Tempering

If steels are hardened by heat treatment, *tempering* reduces residual stresses and increases ductility and toughness. The steel is heated to a specific temperature, depending on composition, and then cooled at a prescribed rate. Alloy steels may undergo **temper embrittlement**, caused by the segregation of impurities along the grain boundaries, at temperatures between 480°C and 590°C. The term tempering is also used for glasses (see Section 11.11.2).

In **austempering**, the heated steel is quenched from the austenitizing temperature rapidly enough to avoid formation of ferrite or pearlite. It is held at a certain temperature until isothermal transformation from austenite to bainite is complete; it is then cooled to room temperature (usually in still air) at a moderate rate, to avoid thermal gradients within the part. The quenching medium most commonly used is molten salt, and at temperatures ranging from 160° to 750° C.

Austempering is often substituted for conventional quenching and tempering, either to (a) reduce the tendency for cracking and distortion during quenching; or (b) improve ductility and toughness while maintaining hardness. Because of the relatively short cycle time, austempering is economical for numerous applications. In *modified austempering*, a mixed structure of pearlite and bainite is obtained. The best example of this practice is **patenting**, which provides high ductility and moderately high strength, such as patented wire (Section 6.5.3).

In martempering (marquenching), steel or cast iron is quenched from the austenitizing temperature into a hot fluid medium (such as hot oil or molten salt). It is held at that temperature until the temperature is uniform throughout the part, and then cooled at a moderate rate (such as in air) to avoid temperature gradients within the part. The part is then tempered, because the structure thus obtained is primarily untempered martensite and thus it is not suitable for most applications. Martempered steels have a lower tendency to crack, distort, or develop residual stresses during heat treatment. For steels with lower hardenability, process that is suitable is *modified martempering*, in which the quenching temperature is lower and hence the cooling rate is higher.

In **ausforming**, also called **thermomechanical processing**, the steel is formed into desired shapes within controlled ranges of temperature and time, to avoid formation of nonmartensitic transformation products.

The part is then cooled at various rates to obtain the desired microstructures. Ausformed parts have superior mechanical properties.

5.11.6 Cryogenic Treatment

In *cryogenic tempering*, the temperature of steel is lowered from room temperature to -180° C, at a rate of as low as 2°C per minute in order to avoid thermal shock. The part is then maintained at this temperature for 24 to 36 hrs; the conversion of austenite to martensite occurs slowly but almost completely, as compared to typically only 50 to 90% in conventional quenching. As a result, additional precipitates of carbon, with chromium, tungsten and other elements, form, the grain structure is refined, and the residual stresses are relieved. After the 24 to 36 hr soak time, the parts are tempered to stabilize the martensite.

Cryogenically treated steels have higher hardness and wear resistance than untreated steels. For example, the wear resistance of D-2 tool steels (see Section 3.10.3) can increase by over 800% after cryogenic treatment, although most tool steels show a 100–200% increase in tool life (see Section 8.3). Applications of cryogenic treatment include tools and dies, aerospace materials, golf club heads, gun barrels, and dental instruments.

5.11.7 Design for Heat Treating

In addition to the metallurgical factors described above, successful heat treating involves design considerations so as to avoid certain problems, such as cracking, warping, and development of nonuniform properties throughout the part. The cooling rate during quenching must be uniform, particularly with complex shapes of varying cross sections and thicknesses; this is to avoid severe temperature gradients within the part, which can lead to thermal stresses, cause cracking, residual stresses, and stress-corrosion cracking.

As a general guideline, (a) parts should have as nearly uniform thicknesses as possible or the transition between regions of different thicknesses should be smooth; (b) internal or external sharp corners should be avoided; (c) parts with holes, grooves, keyways, splines, and unsymmetrical shapes may be difficult to heat treat, because they may crack during quenching; (d) large surfaces with thin cross sections may warp; and (e) hot forgings and hot-rolled products may have a *decarburized skin*, and thus may not properly respond to heat treatment.

5.11.8 Cleaning, Finishing, and Inspection of Castings

After solidification and removal from the mold or die, castings are generally subjected to several additional processes. In sand casting, the casting is shaken out of its mold and the sand, and oxide layers adhering to the castings are removed by vibration or by sand blasting. Castings may also be cleaned electrochemically or by pickling them with chemicals to remove surface oxides, which could adversely affect their machinability (Section 8.5).

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

TABLE 5.8	Casting processes and	their advantages	and limitations.
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Finishing operations for castings may include straightening or forging them with dies, and machining or grinding, to obtain final dimensions.

Several methods are available for inspection of castings to determine their quality and the presence of any defects. Castings may be inspected visually or optically for surface defects. Subsurface and internal defects are investigated using nondestructive techniques, described in Section 4.8.1. Test specimens are removed from various sections of a casting and tested for strength, ductility and other mechanical properties, and to determine the presence and location of any internal defects.

Pressure tightness of such cast components as valves, pumps, and pipes is usually determined by sealing the openings in the casting and pressurizing it with water, oil, or air, and inspected for leaks.

5.12 Design Considerations

Certain guidelines and design principles pertaining to casting have been developed over many years. Although these principles were established primarily through practical experience, analytical methods and computeraided design and manufacturing techniques (Chapter 15) are now in wide use, improving productivity and the quality of castings. Some of the advantages and limitations of casting processes that impact design are given in Table 5.8.

5.12.1 Defects in Castings

Depending on casting design and the practices employed, several defects can develop in castings. The International Committee of Foundry Technical



FIGURE 5.33 Various types of (a) internal and (b) external chills (dark areas at corners), used in castings to eliminate porosity caused by shrinkage. Chills are placed in regions where there is a larger volume of metal, as shown in (c).

Associations has developed standardized nomenclature, consisting of seven basic categories of casting defects:

- 1. Metallic projections, consisting of fins, flash, rough surfaces, or massive projections, such as swells.
- 2. Cavities, consisting of rounded or rough internal or exposed cavities, including blowholes, pinholes, and shrinkage cavities (See *porosity*, and Fig. 5.33).
- 3. Discontinuities, such as cracks, cold or hot tears, and cold shuts. If the solidifying metal is constrained from shrinking freely, cracking and tearing can occur. Coarse grains and the presence of low-melting segregates along the grain boundaries increase the tendency for hot tearing. *Cold shut* is an interface in a casting that lacks complete fusion, because of the meeting of two streams of partially solidified metal.
- 4. Defective surface, such as surface folds, laps, scars, adhering sand layers, and oxide scale.
- 5. Incomplete casting, such as misruns (due to premature solidification in a certain region in the casting), insufficient volume of metal poured, molten metal being at too low a temperature or pouring the metal too slowly, and runout (due to loss of metal from the mold after pouring).
- 6. Incorrect dimensions or shape, owing to such factors as improper shrinkage allowance, pattern mounting error, uneven contraction, deformed pattern, or warped casting. As discussed in Section 5.7, a pipe defect may result from metal shrinkage. A pipe refers to a surface that shrinks away from a mold, generally leaving a concave depression.

7. Inclusions, which form during melting, solidification, or molding. Inclusions may form (a) during melting because of reaction of the molten metal with the environment (usually oxygen) or the crucible material; (b) chemical reactions between components in the molten metal; (c) slags and other foreign material entrapped in the molten metal; (d) reactions between the metal and the mold material; and (e) spalling of the mold and core surfaces. All of these indicate the importance of maintaining melt quality and continuously monitoring the conditions of the molds.

Generally nonmetallic, inclusions are regarded as harmful, because they act as stress raisers and thus reduce the strength of the casting. Hard inclusions (spots) in a casting may chip or damage cutting tools during subsequent machining operations. Inclusions can be filtered out during processing of the molten metal.

Porosity. *Porosity* is detrimental to the ductility of a casting and its surface finish, making it permeable and affecting the pressure tightness of a cast pressure vessel. Porosity in a casting may be caused either by *shrinkage* or *trapped gases*, or both. Porosity due to shrinkage is explained by the fact that thin sections in a casting solidify sooner than thick sections; as a result, the molten metal cannot enter into the thicker regions where the surfaces have already solidified, This condition leads to porosity in the thicker section, because the metal has to contract but is prevented from doing so by the solidified skin. **Microporosity** can also develop when the liquid metal solidifies and shrinks between dendrites and between dendrite branches (See Fig. 5.8).

Porosity due to shrinkage can be reduced or eliminated by various means, including the following:

- 1. Adequate liquid metal should be provided to prevent cavities caused by shrinkage.
- 2. Internal or external chills typically are used in sand casting (Fig. 5.33), to increase the solidification rate in thicker regions. Internal chills are usually made of the same material as the castings; external chills may be made of the same material or may be made of iron, copper, or graphite.
- 3. Making the temperature gradient steep, using, for example, mold materials that have high thermal conductivity.
- 4. Subjecting the casting to hot isostatic pressing (see Section 11.3.3); this is a costly method and is used mainly for critical components, as in aircraft parts.

Porosity due to gases is due to the fact that liquid metals have much greater **solubility** for gases than do solids (Fig. 5.34). When a metal begins to solidify, the dissolved gases are expelled from the solution, causing porosity. Gases may also be result of reactions of the molten metal with the mold materials; they either accumulate in regions of existing porosity, such as in interdendritic areas of the casting, or they cause microporosity, particularly in cast iron, aluminum, and copper.

Dissolved gases may be removed from the molten metal by flushing or purging it with an inert gas or by melting and pouring the metal in a



FIGURE 5.34 Solubility of hydrogen in aluminum. Note the sharp decrease in solubility as the molten metal begins to solidify.

vacuum. If the dissolved gas is oxygen, the molten metal can be *deoxidized*; steel is usually deoxidized with aluminum or silicon, and copper-based alloys, with copper alloy containing 15% phosphorus.

Whether microporosity is a result of shrinkage or is caused by gases may be difficult to determine. If the porosity is spherical and has smooth walls (much like the shiny surfaces of holes in Swiss cheese), it generally is from trapped gases. If the walls are rough and angular, porosity is likely from shrinkage between dendrites. Gross porosity (*macroporosity*) is from shrinkage, and is generally called **shrinkage cavities**.

5.12.2 General Design Considerations

There are two types of design issues in casting: (a) geometric features, tolerances, etc., that should be incorporated into the part; and (b) mold features that are required to produce the desired casting. Robust design (see also Section 16.2) of castings usually involves the following steps:

- 1. Design the part so that the shape is easily cast; several design considerations are described throughout this chapter.
- 2. Select a casting process and a material that is suitable for the part, its size, required production quantity, and mechanical properties. Often, steps 1 and 2 have to be specified simultaneously, which can be a demanding design challenge.
- 3. Locate the parting line of the mold or die.
- 4. Locate and design the gating system, to allow uniform feeding of the mold cavity with molten metal, including risers, sprue, and screens.
- 5. Select an appropriate runner geometry for the system.
- 6. Locate mold features, such as sprues, screens, and risers, as appropriate.
- 7. Ensure that proper controls and good practices are all in place.

Design of cast parts. The following considerations are important in designing castings:

1. Corners, angles, and section thickness. Sharp corners, angles, and fillets should be avoided as much as possible, because they act as stress raisers and may cause cracking and tearing of the metal, as well as of the dies, during solidification. Fillet radii should be selected so as to reduce stress concentrations and to ensure proper liquid-metal flow during pouring. The radii usually range from 3 to 25 mm, although smaller radii may be permissible in small castings and in specific applications. On the other hand, if the fillet radii are too large, the volume of the material in those regions is also large and the rate of cooling is lower.

Section changes in castings should be smoothly blended into each other. The location of the largest circle that can be inscribed in a particular region is critical (Figs. 5.35a to c). Because the cooling rate in regions with larger circles is lower, they result in **hot spots**; these regions can then lead to **shrinkage cavities** and **porosity** (Fig. 5.35d). Cavities at hot spots can be eliminated using small cores. It is important to try to maintain uniform cross sections and wall thicknesses



FIGURE 5.35 (a) Suggested design modifications to avoid defects in castings. Note that sharp corners are avoided to reduce stress concentrations; (b, c, d) examples of designs showing the importance of maintaining uniform cross sections in castings to avoid hot spots and shrinkage cavities.



FIGURE 5.36 Rib designs for use on thin sections or flat surfaces to control or eliminate warping. Note the progression of designs: from left to right, the rib designs have improved castability and reliability.

throughout the casting so as to avoid or minimize shrinkage cavities. Although they increase the production cost, *metal chills* or *paddings* can eliminate or minimize hot spots (See Fig. 5.33).

- 2. Flat areas. Large flat areas (plain surfaces) should be avoided, because they may warp during cooling or develop poor surface finish, due to uneven flow of metal during pouring. A common technique is to break up flat surfaces with staggered ribs and serrations (see below).
- 3. Ribs. One method of producing parts with uniform thickness is to eliminate large, bulky volumes in the casting, as shown in Fig. 5.35. However, this can result in a loss in stiffness, and, especially with flat regions, it can lead to warping. One solution is to use ribs or support structure on the casting, as shown in Fig. 5.36; these are usually placed on the side that is less visible. Ribs should, in general,

have a thickness around 80% of the adjoining member thickness, and they should be deeper than their strut thickness. It is usually beneficial to have the ribs solidify before the members they adjoin. Ribs should not be used on both sides of a casting, and they should not meet at acute angles, because of complications in molding.

- 4. Shrinkage. To avoid cracking of the casting during cooling, allowances should be made for shrinkage. In castings with intersecting ribs, the tensile stresses developed can be reduced by staggering the ribs or by modifying the intersection geometry. Pattern dimensions should also provide for shrinkage of the metal during solidification and cooling. Allowances for shrinkage, known as **patternmaker's shrinkage allowances**, typically range from about 10 to 20 mm/m.
- 5. Draft. A small draft (taper) is typically provided in sand-mold patterns, to enable removal of the pattern without damaging the mold. Drafts generally range from 5 to 15 mm/m. Depending on the quality of the pattern, draft angles usually range from 0.5° to 2°. The draft angles on inside surfaces are typically twice this range; they have to be so because the casting shrinks inward toward the core.
- 6. Dimensional tolerances. Tolerances depend on the particular casting process, casting size, and type of pattern used. They should be as wide as possible, within the limits of good part performance, as otherwise the cost of the casting increases. In commercial practice, dimensional tolerances are usually in the range of ± 0.8 mm for small castings, and may be as much as ± 6 mm for large castings.
- 7. Lettering and markings. It is common practice to include some method of part identification in castings, such as letters, numbers, or corporate logos. These features can be depressions on the surface of the casting or they can protrude from the surface. In sand casting, for example, a pattern plate is produced by machining on a CNC mill (Section 8.10); it is simpler to machine letters into the pattern surface, resulting to sunken letters. In die casting, on the other hand, it is simpler to machine letters into the die, resulting to protruding letters.
- 8. Finishing operations. It is important to consider any subsequent machining and finishing operations that may be performed on castings. For example, if a hole is to be drilled, it is better to locate it on a flat surface than on a curved surface of the casting, to prevent the drill from wandering. An even better design would incorporate a small dimple, as a starting point for the drilling operations. Castings should also include features that allow them to be easily clamped into machine tools for subsequent finishing operations.

Parting line location. The location of the parting line is an important consideration, because it influences mold design, ease of molding, number and shape of cores required, method of support, and the gating system. A casting should be oriented in the mold such that its larger portion is relatively lower and that the height of the casting is minimized. Orientation of the casting also determines the distribution of porosity; consider casting of aluminum, for example, where porosity is due in part to hydrogen gas
bubbles gases, and these will float upward (due to buoyancy), resulting in a higher porosity on the top regions. Recall also from Fig. 5.34 that hydrogen is soluble in liquid metal but not in solid; thus, critical surfaces should be oriented so that they face downwards.

A properly oriented casting can then have its parting line specified (See Fig. 5.10). In general, the parting line should be (a) along a flat plane, rather than be contoured; (b) at the corners or edges of castings, rather than on flat surfaces in the middle of the casting, so that the *flash* at the parting line (material squeezing out between the two halves of the mold) will not be as visible; (c) placed as low as possible relative to the casting for less dense metals, such as aluminum and magnesium alloys, and located at about the mid-height for denser metals, such as steels; and (d) in sand casting, it is typical that the runners, gates, and the sprue well are all placed in the drag on the parting line.

Gate design and location. Gates are the connections between the runners and the part to be cast. Some of the considerations in designing gating systems are as follows:

- 1. Multiple gates are often preferable, and are especially necessary for large castings. Multiple gates have the benefits of allowing lower pouring temperature, and also reduce the temperature gradients in the casting.
- 2. Gates should feed into thick sections of castings.
- **3.** A fillet should be used where a gate meets a casting, so as to produce less turbulence than for abrupt junctions.
- 4. A gate closest to the sprue should be placed sufficiently away from it so that it can be easily removed; this distance may be as small as a few mm for small castings, and up to 500 mm for large parts.
- 5. The minimum gate length should be 3 to 5 times the gate diameter, on the metal being cast. Its cross section should be sufficiently large to allow filling of the mold cavity, and it should be smaller than the runner cross section.
- 6. Curved gates should be avoided; when necessary, a straight section in the gate should be located immediately adjacent to the casting.

Runner design. The runner is a horizontal distribution channel that receives molten metal from the sprue and delivers it to the gates. A single runner is used for simple parts, but two-runner systems can be specified for more complicated castings. Runners are also used to trap dross (a mixture of oxide and metal that forms on the surface of molten metals) and keep it from entering the gates and the mold cavity. Commonly, dross traps are placed at the ends of runners, and the runner projects above the gates, to ensure that the metal in the gates is tapped from below the surface.

Designing other mold features. The main goal in designing a *sprue* (described in Section 5.4.1) is to achieve the required metal flow rates while preventing aspiration or excessive dross formation. Flow rates are

determined such that turbulence is avoided, but the mold is filled quickly as compared to the solidification time required. A *pouring basin* can be used to ensure that the metal flow into the sprue is uninterrupted. Also, if the level of molten metal is retained in the pouring basin during pouring, then the dross will float and will be prevented from entering the mold cavity. *Filters* are used to trap large contaminants; they also serve to slow the metal and make the flow more laminar. *Chills* can be used to speed solidification of metal in a particular region of a casting.

5.12.3 Design Principles for Expendable-Mold Casting

Expendable-mold casting processes have certain specific design considerations, that are mainly concerned with mold material, part size, and the casting method. Important design considerations are described below.

- 1. *Mold layout*. The features in the mold must be placed logically and compactly, including gates when necessary. Solidification should begin at one end of the mold and progresses in a uniform front across the casting, with risers solidifying last. Although traditionally mold layout has been based on experience, commercial computer programs are now available for this task (see Section 5.12.5). Based on finite-difference algorithms, these techniques allow the simulation of mold filling and the rapid evaluation of mold layouts.
- 2. *Riser design*. A major concern in the design of castings is the size and placement of risers (See Fig. 5.10). Risers are essential in controlling the progression of the solidification front across a casting, and are an important feature in mold layout. Blind risers are good design features, and retain heat longer than open risers. Risers are designed according to five basic rules:
 - a. The metal in the riser must not solidify before the casting does; this is usually ensured by avoiding the use of small risers and by using cylindrical risers with small aspect ratios (height to cross section). Spherical risers are the most efficient shape, but are difficult to cast.
 - **b.** The riser volume must be large enough to provide sufficient liquid metal necessary to compensate for shrinkage in the casting.
 - **c.** Junctions between the casting and the riser should not develop a *hot spot*, where shrinkage porosity can occur.
 - **d.** Risers must be placed such that liquid metal can be delivered to locations where it is most needed.
 - e. There must be sufficient pressure to drive the liquid metal into locations in the mold where it is needed; risers are therefore not as useful for metals with low density, such as aluminum alloys, than for those with a higher density, such as steel and cast irons.
- **3.** *Machining allowance.* Because most expendable-mold castings require some additional finishing operations, such as machining and grinding, allowances must be made in casting design. Machining

allowances, which are included in pattern dimensions, depend on the type of casting, and they increase with the size and section thickness of castings. Allowances usually range from about 2 to 5 mm for small castings, and to more than 25 mm for large castings.

5.12.4 Design Principles for Permanent-Mold Casting

General design guidelines and examples for permanent-mold casting are shown schematically for die casting in Fig. 5.37. Note that the cross sections have been reduced in order to decrease the solidification time and also save material. Special considerations are also involved in designing tooling for die casting. Although designs may be modified to eliminate the draft for better dimensional accuracy, a draft angle of 0.5° or even 0.25° is usually required, as otherwise galling (localized seizure or sticking of material) may occur between the casting and the dies, and cause part distortion.



FIGURE 5.37 Suggested design modifications to avoid defects in castings. *Source:* After the North American Die Casting Association.

Die-cast parts are nearly-net shaped, typically requiring only the removal of gates and minor trimming, to remove flashing and other minor defects. The surface finish and dimensional accuracy of die-cast parts are very good (See Table 5.2), and, in general, they do not require a machining allowance.

5.12.5 Computer Modeling of Casting Processes

Casting processes involve complex interactions among material and process variables, a quantitative study of these interactions is thus essential to the proper design and the production of high quality castings. Advances in computer processing speeds and development of more powerful software have enabled modeling of various aspects of casting design and operations. These advances include studies in fluid flow, heat transfer, and the microstructures developed during solidification. The benefits of modeling include faster response to design changes, increased productivity, improved quality, and easier planning and cost estimating.

Modeling of *fluid flow* is based on Bernoulli's and the continuity equations, described in Section 5.4.1. The models predict the behavior of the hot metal during pouring into the gating system and its travel into the mold cavity, as well as velocity and pressure distributions in the whole system. Modeling of *heat transfer* in casting includes coupling of fluid flow and heat transfer, and the effects of surface conditions, thermal properties of the materials involved, and natural and forced convection on cooling of the casting. Recall that surface conditions vary during solidification, as a layer of air develops between the casting and the mold wall due to shrinkage. Similar studies involve modeling of the development of *microstructures* in casting. These studies encompass heat flow, temperature gradients, nucleation and growth of crystals, formation of dendritic and equiaxed structures, impingement of grains on each other, and movement of the liquid-solid interface during solidification.

Modeling is now capable of predicting, for example, the width of the mushy zone (See Fig. 5.6) during solidification, the development of grain size in castings, and the capability to calculate isotherms (giving insight into possible hot spots and subsequent development of shrinkage cavities). With advances in computer-aided design and manufacturing (see Chapter 14), modeling has become easier to implement. Several commercial software programs are now available on modeling and casting processes, including SOLIDCast, NovaCast, ProCAST, and Magmasoft.

5.13 Economics of Casting

It has been noted throughout this chapter that some casting processes require more labor than others, some require expensive dies and machinery, and some take much more time than others to complete the operation. Each of these factors, outlined in Table 5.2, affects, to various degrees, the overall cost of a casting operation. As described in greater detail in Chapter 15, the total cost of a product includes the costs of (a) materials, (b) dies and tooling, (c) equipment, and (d) labor. Preparations for casting a product include making molds and dies that require materials, machinery, time, and effort, which all contribute to costs. Although relatively little cost is involved in molds for sand casting, die-casting dies require expensive materials and a great deal of machining and preparation. Facilities also are required for melting and pouring the molten metal into the molds or dies, including furnaces and related equipment, their costs depending on the level of automation desired. Finally, costs are also involved in cleaning and inspecting castings.

The labor required in casting operations can vary considerably, depending on the particular process and level of automation. Investment casting, for example, requires a great deal of labor because of the large number of steps involved in this operation. Conversely, operations such as highly automated die casting can maintain high production rates with little labor required.

The cost of equipment per cast part (*unit cost*) decreases as the number of parts increases (Fig. 5.38); sustained high production rates can then justify the high cost of dies and machinery. If demand is relatively small, however, the cost per part increases rapidly. It then becomes more economical to manufacture the part by sand casting or by other manufacturing methods. Note that Fig. 5.38 can also include other casting processes suitable for making the same part. The two processes compared (for example, sand and die casting) produce castings with significantly different dimensional and surface-finish characteristics, thus not all manufacturing decisions should be based purely on economic considerations. In fact, parts can usually be made by more than one or two processes (See, for example, Fig. 1.8); thus, the final decision depends on both economic as well as technical considerations. The competitive aspects of manufacturing processes are described in greater detail in Chapter 15.





CASE STUDY 5.1 Sand Casting of a Tractor Hitch

Farm implements such as mowers, aerators, and post hole diggers, are attached to tractors through a hitch; the Easy Hitch is a design by Greenwell Manufacturing that eases attachment of these implements to a standard tractor, easing the requirement that the tractor be precisely aligned with the implement for attachment. The Easy Hitch, shown in Fig. 5.39a, was originally constructed from a welded assembly, with five plate pieces that needed to be plasma cut (Section 9.14.2), formed (Section 7.5), machined (Chapter 8), and arc welded (Section 12.3).

Further, to allow proper assembly, all of the holes shown had to be machined and tapped (Section 8.9.4) to make sure that they would align properly for attachment to the tractor. Not surprisingly, this is a laborious process that also required considerable skill.

Dotson Iron Castings was approached by Greenwell Manufacturing to investigate the possibility of converting the welded assembly to a more simple design using sand casting. The final result is shown in Fig. 5.39b. To obtain this design:

- 1. Dotson combined the welded components into one cast part, so that the housing could be produced in one pour in a sand casting operation (Section 5.8.1).
- **2.** The material selected was D80-55-06 ductile iron (pearlitic ductile cast iron from Table 5.4) to withstand the dynamic stresses encountered by the coupling.
- 3. Before finalizing the design, computer generated mold filling simulations were conducted to ensure the molten metal filled the mold with minimal turbulence and produced a casting without hot spots or excessive porosity.
- 4. Lettering and part identification that had been previously painted on (and were subject to damage) were incorporated into the casting.



FIGURE 5.39 Casting of the Easy Hitch. (a) Original design, with a housing made from a welded assembly of five components and finish machining. (b) Redesigned Easy Hitch, constructed of a sand cast housing.

5. The mounting holes were reinforced with a boss and the holes in the as-cast condition were properly aligned, eliminating the need for drilling and tapping to ensure the hitch could be assembled properly.

The two videos show the design and construction steps for the pattern plate and a video of an actual pour. The resulting design confirmed the mold fill simulations, and high-quality parts were produced without any further design iterations.

In testing, the cast design demonstrated a 150kN capacity, which was an improvement of over 20 kN compared to the welded assembly. A larger version demonstrated a 200 kN capacity, representing an improvement of over 40 kN from the welded design.

Around 10,000 of the smaller hitch and 5,000 of the larger hitch are produced annually. Typical order quantities are 1,000, which are ideal for automated foundries. Dotson casts and finish grinds at a rate of 160 castings per hour.

Not only does the cast design outperform the welded design, but the customer realized a 50% reduction in cost compared to the labor-intensive fabrication.

Source: Courtesy of Dotson Iron Castings and Greenwell Manufacturing.

SUMMARY

- Metal casting is among the oldest and most common manufacturing processes. Solidification of pure metals takes place at a clearly defined constant temperature, whereas solidification of alloys occurs over a range of temperatures. Phase diagrams are important for identifying the solidification point or points for metals and alloys. (Sections 5.1 and 5.2)
- The composition and cooling rate of the melt affect the size and shape of grains and dendrites, and thus influence the properties of the casting. (Section 5.3)
- Most metals shrink during solidification, although gray cast iron and a few others actually expand. The resulting loss of dimensional accuracy and s cracking are difficulties that can arise during solidification and cooling. Several basic categories of casting defects have been identified. (Section 5.3)
- In casting, the molten metal or alloy typically flows through a variety of passages, including pouring basins, sprues, runners, risers, and gating systems, before reaching the mold cavity. Bernoulli's theorem, the

continuity law, and the Reynolds number are the analytical tools used in designing an appropriate system and in eliminating defects associated with fluid flow. Heat transfer affects fluid flow and solidification time in casting. Solidification time is a function of the volume of a casting and its surface area (Chvorinov's rule). (Section 5.4)

- Melting practices have a direct effect on the quality of castings; factors that affect melting include: (a) inorganic compounds or fluxes that are added to the molten metal to remove dissolved gases and various impurities; (b) the type of furnace used; and (c) foundry operations, including pattern and mold making, pouring of the melt, removal of castings from molds, cleaning, heat treatment, and inspection. (Section 5.5)
- Several ferrous and nonferrous casting alloys are available, with a wide range of properties, casting characteristics, and applications. Because castings are often designed and produced to be assembled with other mechanical components and into structures, various other considerations are also important, such as weldability, machinability, and surface conditions. (Section 5.6)
- The traditional ingot-casting process has been largely replaced for many continuous-casting methods for both ferrous and nonferrous metals. (Section 5.7)
- Casting processes are generally classified as either expendable-mold or permanent-mold casting. The most common expendable-mold methods are sand, shell-mold, plaster, ceramic-mold, and investment casting. Permanent-mold methods include slush casting, pressure casting, and die casting. Compared to permanent-mold casting, expendable-mold casting usually involves lower mold and equipment costs, but with lower dimensional accuracy. (Sections 5.8–5.10)
- Castings, as well as wrought parts made by other manufacturing processes, may be subjected to subsequent heat-treatment operations, to enhance various properties and service life. Several transformations take place in microstructures that have widely varying characteristics and properties. Important mechanisms of hardening and strengthening involve thermal treatments, including quenching and precipitation hardening. (Section 5.11)
- General principles have been established to aid designers to produce castings that are free from defects and meet dimensional tolerance and service requirements. Because of the large number of variables involved, close control of all parameters is essential, particularly those related to the nature of liquid metal flow into the molds and dies and the rate of cooling in different regions of castings. (Section 5.12)
- Within limits of good performance, the economic aspects of casting are as important as the technical considerations. Factors affecting the overall cost include the cost of materials, molds, dies, equipment, and labor, each of which varies with the particular casting operation. An important parameter is the cost per casting, which, for large production runs, can justify major expenditures typical of automated machinery and operations. (Section 5.13)

SUMMARY OF EQUATIONS

Bernoulli's theorem, $b + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{Constant}$ Sprue contour, $\frac{A_1}{A_2} = \sqrt{\frac{h_2}{h_1}}$ Reynolds number, $\text{Re} = \frac{vD\rho}{\eta}$ Chvorinov's rule, Solidification time = $C\left(\frac{\text{Volume}}{\text{Surface area}}\right)^n$ Continuity equation, $Q = A_1v_1 = A_2v_2$

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QUESTIONS

5.1 Describe the characteristics of (a) an alloy; (b) pearlite; (c) austenite; (d) martensite; and (e) cementite.

5.2 What are the effects of mold materials on fluid flow and heat transfer?

5.3 How can you tell whether cavities in a casting are due to porosity or to shrinkage?

5.4 How does the shape of graphite in cast iron affect its properties?

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5.5 Explain the difference between short and long freezing ranges. How are they determined? Why are they important?

5.6 It is known that pouring molten metal at a high rate into a mold has certain disadvantages. Are there any disadvantages to pouring it very slowly? Explain.

5.7 Why does porosity have detrimental effects on the mechanical properties of castings? Which physical properties are also affected adversely by porosity?

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

5.9 Which of the following considerations are important for a riser to function properly? (a) Have a surface area larger than the part being cast; (b) be kept open to atmospheric pressure; (c) solidify first. Why?

5.10 Explain why the constant c in Eq. (5.9) depends on mold material, metal properties, and temperature.

5.11 Explain why gray iron undergoes expansion, rather than contraction, during solidification.

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

5.13 Explain the reasons for hot tearing in castings.

5.14 Review Fig. 5.10 and make a summary, explaining the purpose of each feature shown and the consequences of omitting the feature from the mold design.

5.15 Would you be concerned about the fact that parts of internal chills are left within the casting? What materials do you think chills should be made of, and why?

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

5.17 Do you think early formation of dendrites in a mold can impede the free flow of molten metal into the mold? Explain.

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

5.19 It has long been observed by foundry-men that low pouring temperatures, i.e., low superheat, promote equiaxed grains over columnar grains. Also, equiaxed grains become finer as the pouring temperature decreases. Explain these phenomena.

5.20 What are the reasons for the large variety of casting processes that have been developed over the years?

5.21 Why can blind risers be smaller than open-top risers?

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

5.23 Would you recommend preheating the molds in permanent-mold casting? Also, would you remove the casting soon after it has solidified? Explain.

5.24 In a sand-casting operation, what factors determine the time at which you would remove the casting from the mold?

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

5.26 Explain why the strength-to-weight ratio of diecast parts increases with decreasing wall thickness.

5.27 We note that the ductility of some cast alloys is essentially zero (See Fig. 5.12). Do you think this should be a significant concern in engineering applications of castings? Explain.

5.28 The modulus of elasticity of gray iron varies significantly with its type, such as the ASTM class. Explain why.

5.29 List and explain the considerations for selecting pattern materials.

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

5.31 Explain why a casting may have a slightly different shape than the pattern used to make the mold.

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

5.33 Why are steels more difficult to cast than cast irons?

5.34 What would you do to improve the surface finish in expendable-mold casting processes?

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

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

5.37 Which of the casting processes would be suitable for making small toys in large numbers? Why?

5.38 Why are allowances provided for in making patterns? What do they depend on?

5.39 Explain the difference in the importance of drafts in green-sand casting versus permanent-mold casting.

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

5.41 Explain why carbon is so effective in imparting strength to iron in the form of steel.

5.42 Describe the engineering significance of the existence of a eutectic point in phase diagrams.

5.43 Explain the difference between hardness and hardenability.

5.44 Explain why it may be desirable for castings to be subjected to various heat treatments.

5.45 Describe the differences between case hardening and through hardening insofar as engineering applications are concerned.

5.46 *Type metal* is a bismuth alloy used to cast type for printing. Explain why bismuth is ideal for this process.

5.47 Do you expect to see larger solidification shrinkage for a material with a bcc crystal structure or fcc? Explain.

5.48 Describe the drawbacks to having a riser that is (a) too large; or (b) too small.

5.49 If you were to incorporate lettering on a sand casting, would you make the letters protrude from the surface or recess into the surface? What if the part were to be made by investment casting?

5.50 List and briefly explain the three mechanisms by which metals shrink during casting.

5.51 Explain the significance of the "tree" in investment casting.

5.52 Sketch the microstructure you would expect for a slab cast through (a) continuous casting; (b) strip casting; and (c) melt spinning.

5.53 The general design recommendations for a well in sand casting are that (a) its diameter should be twice the sprue exit diameter; and (b) the depth should be

approximately twice the depth of the runner. Explain the consequences of deviating from these rules.

5.54 Describe thixocasting and rheocasting.

5.55 Sketch the temperature profile you would expect for (a) continuous casting of a billet; (b) sand casting of a cube; and (c) centrifugal casting of a pipe.

5.56 What are the benefits and drawbacks to having a pouring temperature that is much higher than the metal's melting temperature? What are the advantages and disadvantages in having the pouring temperature remain close to the melting temperature?

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

5.58 Can a chaplet also be a chill? Explain.

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

5.60 The heavy regions of parts typically are placed in the drag in sand casting and not in the cope. Explain why.

PROBLEMS

5.61 Using Fig. 5.3, estimate the following quantities for a 60% Cu-40% Ni alloy: (a) liquidus temperature; (b) solidus temperature; (c) percentage of nickel in the liquid at 1250°C; (d) the major phase at 1250°C; and (e) the ratio of solid to liquid at 1250°C.

5.62 Determine the amount of gamma and alpha phases (Fig. 5.4b) in a 10-kg, 1060 steel casting as it is being cooled to the following temperatures: (a) 750°C; (b) 728°C; and (c) 726°C.

5.63 Derive Eq. (5.7).

5.64 A round casting is 0.5 m in diameter and 0.8 m in length. Another casting of the same metal is elliptical in cross section, with a major-to-minor axis ratio of 3, and has the same length and cross-sectional area as the round casting. Both pieces are cast under the same conditions. What is the ratio of the solidification times of the two castings?

5.65 Two halves of a mold (cope and drag) are weighted down to keep them from separating under the pressure exerted by the molten metal (buoyancy). Consider a solid, spherical steel casting, 250 mm in diameter, that is being produced by sand casting. Each

flask (See Fig. 5.10) is 0.6 m by 0.6 m and 400 mm deep. The parting line is at the middle of the part. Estimate the clamping force required if the molten metal has a density of 8.96 g/cm^3 and the sand has a density of 1.2 g/cm^3 .

5.66 Would the position of the parting line in Problem 5.65 influence your answer? Explain.

5.67 Plot the clamping force in Problem 5.65 as a function of increasing diameter of the casting, from 0.3 m to 0.6 m.

5.68 A cylindrical casting has a diameter of 350 mm and a length of 1.25 m. Another casting of the same metal is rectangular in cross section, with a width-to-thickness ratio of 4, and has the same length and cross-sectional area as the round casting. Both pieces are cast under the same conditions. The cylindrical casting solidifies in four minutes. How long does the rectangular cross section casting take to solidify?

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

5.70 A 75-mm thick square plate and a right circular cylinder with a radius of 100 mm and height of 50 mm each have the same volume. If each is to be cast using a cylindrical riser, will each part require the same size riser to ensure proper feeding? Explain.

5.71 Assume that the top of a round sprue has a diameter of 150 mm and has a height of 350 mm. At the bottom, the sprue has a diameter of 30 mm. Based on Eq. (5.7), plot the profile of the sprue diameter as a function of its height.

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



5.73 Repeat Problem 5.72, but assume that the aluminum spool is to be cast using expendable-pattern casting. Explain the important differences between the two patterns.

5.74 The optimum shape of a riser is spherical to ensure that it cools more slowly than the casting it feeds. Spherically shaped risers, however, are difficult to cast. (a) Sketch the shape of a blind riser that is easy to mold, but also has the smallest possible surface areato-volume ratio. (b) Compare the solidification time of the riser in part (a) to that of a riser shaped like a right circular cylinder. Assume that the volume of each riser is the same, and that for each the height is equal to the diameter (see Example 5.2).

5.75 A cylinder with a diameter-to-height ratio of 1 solidifies in four minutes in a sand casting operation. What is the solidification time if the cylinder height is tripled? What is the time if the diameter is tripled?

5.76 Estimate the clamping force for a diecasting machine in which the casting is rectangular, with projected dimensions of $100 \text{ mm} \times 200 \text{ mm}$. Would your answer depend on whether or not it is a hot-chamber or cold-chamber process? Explain.

5.77 When designing patterns for casting, patternmakers use special rulers that automatically incorporate solid shrinkage allowances into their designs. Therefore, a 300 mm patternmaker's ruler is longer than 300 mm. How long is a patternmaker's ruler designed for the making of patterns for (a) aluminum castings; (b) pure silicon; and (c) high-manganese steel? 5.78 In sand casting, it is important that the cope mold half be held down with enough force to keep it from floating when the molten metal is poured in. For the casting shown in the figure below, calculate the minimum amount of weight necessary to keep the cope from floating up as the molten metal is poured in. (Hint: The buoyancy force exerted by the molten metal on the cope is related to the effective height of the metal head above the cope.)



Density: 7600 kg/m³ All dimensions in mm **5.79** The part shown below is a hemispherical shell used as an acetabular (mushroom shaped) cup in a total hip replacement. Select a casting process for this part and provide a sketch of all patterns or tooling needed if it is to be produced from cobalt-chrome alloy.



5.80 A sprue is 250 mm long and has a diameter of 150 mm at the top, where the metal is poured. If a flow rate of 70,000 mm³/s is to be achieved, what should be the diameter of the bottom of the sprue?

5.81 Steel piping is to be produced by centrifugal casting. The length is 5 m, the diameter is 1.5 m, and the thickness is 20 mm. Using basic equations from dynamics and statics, determine the rotational speed needed to have the centripetal force be 60 times its weight.

5.82 A sphere with a diameter of 75 mm solidifies in three minutes in a sand-casting operation. Using the same equipment and metal, estimate the time required to produce the part considered in Problem 5.72.

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

5.84 Pure aluminum is poured into a sand mold. The metal level in the pouring basin is 250 mm above the metal level in the mold, and the runner is circular with a 10 mm diameter. What is the velocity and rate of the flow of the metal into the mold? Is the flow turbulent or laminar? Use a viscosity of $\eta = 0.0015 \text{ Ns/m}^2$.

5.85 For the sprue described in Problem 5.84, what runner diameter is needed to ensure a Reynolds number of 2000? How long will a 300,000 mm³ casting take to fill with such a runner?

5.86 How long would it take for the sprue in Problem 5.84 to feed a casting with a square cross section of 50 mm per side and a height of 100 mm? Assume the sprue is frictionless

5.87 A rectangular mold with dimensions 100 mm \times 200 mm \times 400 mm is filled with aluminum with no superheat. Determine the final dimensions of the part as it cools to room temperature. Repeat the analysis for gray cast iron.

5.88 The constant *C* in Chvorinov's rule is given as 3 s/mm^2 and is used to produce a cylindrical casting with a diameter of 75 mm and a height of 125 mm. Estimate the time for the casting to fully solidify. The mold can be broken safely when the solidified shell is at least 20 mm. Assuming the cylinder cools evenly, how much time must transpire after pouring the molten metal before the mold can be broken?

5.89 A jeweler wishes to produce twenty-five gold rings in one investment-casting operation. The wax parts are attached to a wax central sprue with a 25 mm diameter. The rings are located in five rows, each 20 mm from the other on the sprue. The rings require a 4 mm diameter, 15 mm long runner to the sprue. Estimate the weight of gold needed to completely fill the rings, runners, and sprues. Assume a typical ring has a 30 mm outer diameter, 22 mm inner diameter and 6 mm width. The specific gravity of gold is 19.3.

5.90 Plot the solidification time of a cylinder with a volume of $15,000 \text{ mm}^3$ as a function of its diameter-to-length ratio. Assume that the solidification time for a 25-mm diameter sphere is three minutes.

5.91 If an acceleration of 150 g is necessary to produce a part in true centrifugal casting and the part has an inner diameter of 300 mm, a mean outer diameter of 450 mm, and a length of 8 m, what rotational speed is needed?

5.92 Assume that you are asked to give a quiz to students on the contents of this chapter. Prepare three quantitative problems and three qualitative questions, and supply the answers.

DESIGN

5.93 The figures below indicate various defects and discontinuities in cast products. Review each one and offer design solutions to avoid them.



5.94 Porosity developed in the boss of a casting is illustrated in the figure below. Show that by simply repositioning the parting line of this casting, this problem can be eliminated.

(d)

(c)



5.95 Design test methods to determine the fluidity of metals in casting (see Section 5.4.2). Make appropriate sketches and explain the important features of each design.

5.96 Design an experiment to measure the constants C and n from Chvorinov's Rule [Eq. (5.11)]. Describe the features of your design, and comment on any difficulties that might be encountered in running such an experiment.

5.97 For the wheel illustrated in the figure below, show how (a) riser placement; (b) core placement;

(c) padding; and (d) chills may be used to help feed molten metal and eliminate porosity in the isolated hob boss.



5.98 In the figure below, the original casting design shown in (a) was changed to the design shown in (b). The casting is round, with a vertical axis of symmetry. As a functional part, what advantages do you think the new design has over the old one?



5.99 An incorrect and a correct design for casting are shown, respectively, in the figure below. Review the changes made and comment on their advantages.



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

5.101 Utilizing the equipment and materials available in a typical kitchen, design an experiment to reproduce results similar to those shown in Fig. 5.11.

5.102 Design a test method to measure the permeability of sand for sand casting.

5.103 Reproduce Fig. 5.5 for a casting that is spherical in shape.

5.104 Explain how ribs and serrations are helpful in casting flat surfaces that otherwise may warp. How would you go about designing the geometry (thickness, depth, etc.) of a reinforcing rib?

5.105 A growing trend is the production of patterns and molds through rapid-prototyping approaches, described in Chapter 10. Consider the case of an injection molding operation, where the patterns are produced by rapid prototyping, and then hand assembled onto trees and processed in traditional fashion. What design rules discussed in this chapter would still be valid, and which would not be as important in this case?

5.106 Repeat Problem 5.105 for the case where (a) a pattern for sand casting is produced by rapid prototyping and (b) a sand mold for sand casting is produced.

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

5.108 Describe the procedures that would be involved in making a bronze statue. Which casting process or processes would be suitable? Why?

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

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

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

5.112 Three sets of designs for die casting are shown below. Note the changes made to original die design (1) and comment on the reasons.



5.113 Note that in cast jewelry, gemstones are usually cast in place; that is, they are not attached after the ring is cast, but are incorporated into the ring. Design a ring with a means of securing a gemstone in the wax pattern, such that it will remain in the mold as the wax is being melted. Could such an approach be used in lost foam casting?

5.114 The following part is to be cast of 10% Sn bronze at the rate of 100 parts per month. To find an appropriate casting process, consider all the processes in this chapter, then reject those that are (a) technically inadmissible; (b) technically feasible but too expensive for the purpose; and (c) identify the most economical one. Write a rationale using common-sense assumptions about cost.



5.115 The two illustrations shown are proposed designs of a gating system for an aluminum low-power water turbine blade. The first uses a conventional

sprue-runner-gate system, while the second uses a ceramic filter underneath a pouring cup, but without gates (direct pour method). Evaluate the two designs, and list their advantages and disadvantages. Based on your analysis, select a preferred approach.

