Chapter 12

Metal Casting: Design, Materials, and Economics

- This final chapter on metal casting serves as a general guide to the interrelationships among product design, material and process selection, and economic considerations in casting.
- The chapter describes in detail the design considerations for casting operations, and discusses the general guidelines for successful casting practices.
- The characteristics and applications of the most common ferrous and nonferrous alloys are then described.
- The chapter ends with a brief review of casting economics.

12.1 Introduction

In the preceding two chapters, it was noted that successful casting practice requires the proper control of a large number of variables. These variables pertain to the particular characteristics of the metals and alloys cast, method of casting, mold and die materials, mold design, and processing parameters. Factors such as the flow of the molten metal in the mold cavities, the gating systems, the rate of cooling, and the gases evolved all influence the quality of a casting.

This chapter describes general design considerations for metal casting, and presents guidelines for avoiding defects. It then describes the characteristics of the metals and alloys that are commonly cast, together with their typical applications. Because the economics of casting operations are just as important as their technical aspects, the chapter also outlines the basic economic factors relevant to all casting operations.

12.2 Design Considerations in Casting

As in all manufacturing operations, certain **design principles** pertaining to casting have been developed over the years. Although these principles have been established primarily through experience, analytical methods, process simulation and modeling, and computer-aided design and manufacturing techniques have now all come into wide use as well, improving the quality of castings and productivity, resulting in significant cost savings.

All casting processes share several basic characteristics; consequently, a number of design considerations apply equally to, for example, sand casting and die casting. However, each process still has its own particular design considerations. Sand casting will require consideration of mold erosion and associated sand inclusions in the casting process, whereas die casting will not have this concern, but it has others, such as heat checking of dies, which significantly reduces die life.

Troubleshooting the causes of defects in cast products can be complicated; the considerations presented in this chapter are to serve only as guidelines. Moreover, defects frequently are random and can be difficult to reproduce, thus complicating the implementation of corrective measures. In most situations, a given mold design will produce mostly good parts as well as some defective parts. For these reasons, strict quality control procedures have to be implemented, especially for critical applications.

It should also be noted that many of the design rules developed over the years are now put in doubt or somewhat relaxed through the application of additive manufacturing (Chapter 20). For example, a sand mold produced through additive manufacturing need not be designed with certain accommodations, such as draft and corner radii, to allow for pattern removal. Additive manufacturing has its own design concerns, as described in Section 20.12, as well as its economic usefulness for short production runs.

12.2.1 General Design Considerations for Castings

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 needed to produce the desired casting. Robust design of castings usually involves the following steps:

1. Design the part so that the shape is cast as easily as possible. If secondary operations, such as machining, are required, include a machining allowance (that is, a slight oversize of the part), surfaces for fixturing, and reinforcement where necessary (to support the machining forces). Several design considerations are given in this chapter to assist in such efforts.

2. Select a casting process and a material suitable for the part, its size, the required production quantity, and mechanical properties. Often, the shape, the material, and the process(s) need to be specified simultaneously, which can be a demanding design challenge.

3. Locate the parting line of the mold in the part.

4. Design and locate the gates to allow uniform feeding of the mold cavity with molten metal.

5. Select an appropriate runner geometry for the system.

6. Locate mold features, such as sprues, screens, and risers, as appropriate.

7. Check that proper controls and good practices are in place.

Design of Parts to Be Cast. The following considerations are important in designing castings, as outlined in Fig. 12.1:

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

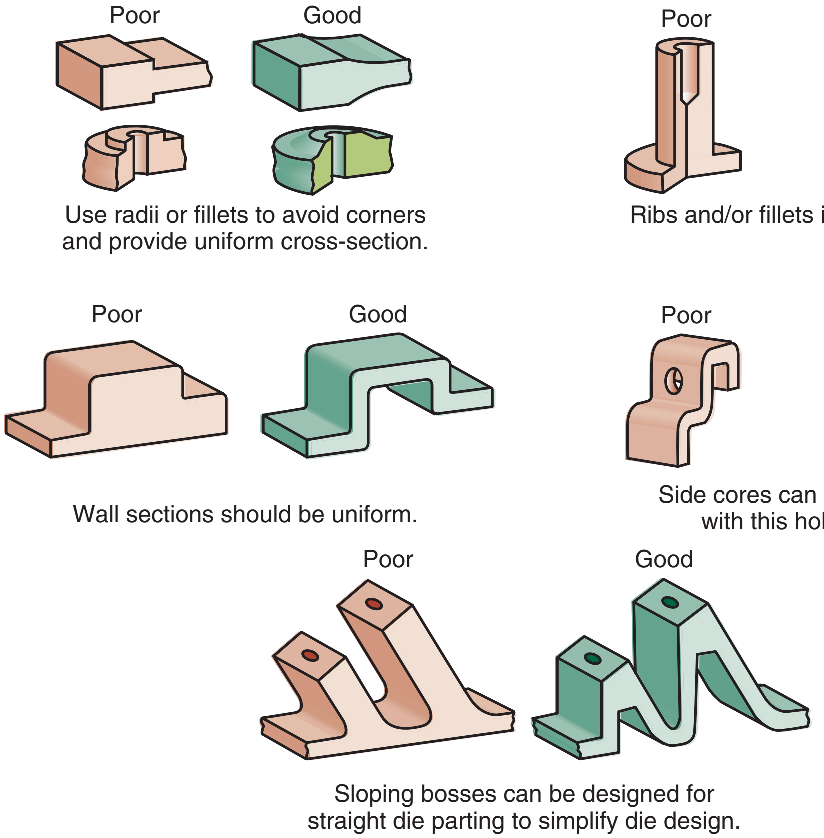

Figure 12.1: Suggested design modifications to avoid defects in castings. *Source:* Courtesy of the American Die Casting Institute.

well as of the dies) during solidification. Fillet radii should be selected so as to minimize stress concentrations and to ensure proper molten-metal flow during pouring. Fillet radii usually range from 3 to 25 mm, although smaller radii may be permissible in small castings and for specific applications. On the other hand, if the fillet radii are too large, the volume of the material in those regions also is large, and hence the cooling rate is lower.

Section changes should be blended smoothly into each other. The location of the largest circle that can be inscribed in a particular region (Figs. 12.2a and b) is critical so far as shrinkage cavities are concerned. Because the cooling rate in regions with larger circles is lower, these regions are called **hot spots**, and can cause **shrinkage cavities** and **porosity** (Figs. 12.2c and d). Cavities at hot spots can be eliminated by using small cores; although they produce cored holes in the casting (Fig. 12.2e), these holes do not significantly affect its strength. It is also important to maintain uniform cross sections and wall thicknesses throughout the casting, in order to avoid or minimize shrinkage cavities. Although they increase the production cost, *metal paddings* or *chills* in the mold can eliminate or minimize hot spots (see Fig. 10.14).

2. **Flat areas.** Large flat areas (plane surfaces) should be avoided, since (a) they may warp during cooling because of temperature gradients or (b) result in poor surface finish because of uneven flow of the metal during pouring. One of the common techniques for avoiding these problems is to break up flat surfaces with staggered ribs and serrations, as described below.

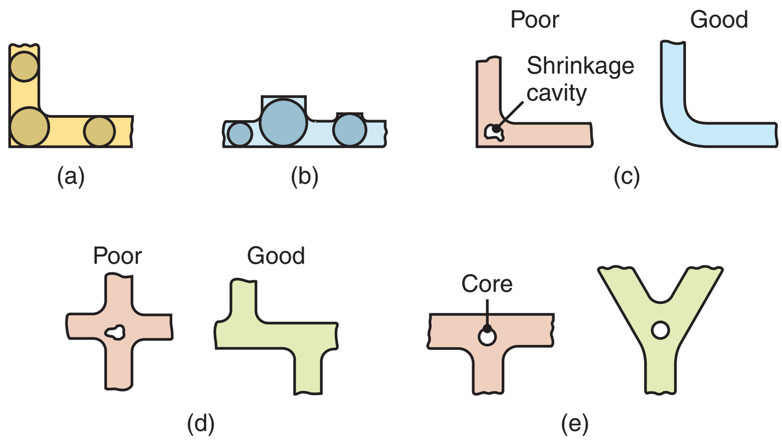

Figure 12.2: Examples of designs showing the importance of maintaining uniform cross sections in castings to avoid hot spots and shrinkage cavities. (a) Illustration of the method of inscribing the largest possible circle in a cross section; locations where abrupt changes in circle size occurs are concerns for hot spots and shrinkage pores. (b)–(e) Common geometries and strategies for reducing or eliminating pores.

3. **Ribs.** One method of producing parts with uniform thickness is to eliminate large, bulky volumes in the casting, as shown in Fig. 12.1; however, this can result in a loss in stiffness and, especially with flat regions, can lead to warping. One solution to these difficulties is to use ribs or a support structure on the casting, as shown in Fig. 12.3. They 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 should be deeper than their strut thickness. It is beneficial to have the ribs solidify before the members they adjoin. Ribs should not be placed on both sides of a casting, and should not meet at acute angles, because of complications to molding.

4. **Shrinkage.** To avoid cracking of the casting during cooling, allowance should be provided for shrinkage during solidification and/or cooling to room temperature. In castings with intersecting ribs, the tensile stresses developed can be reduced by staggering the ribs or by modifying the intersection

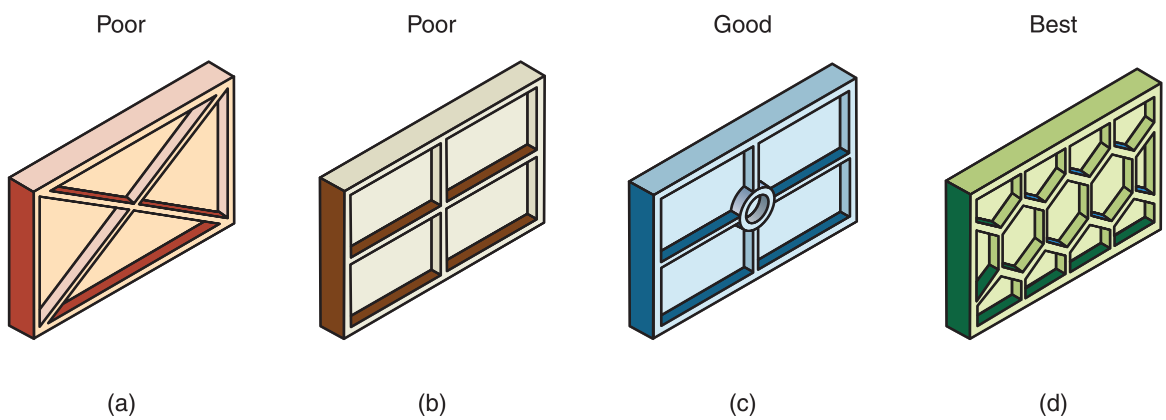

Figure 12.3: Rib designs for use on thin sections or flat surfaces to control or eliminate warping. Note the progression of designs: from left to right, the rib designs have improved castability and reliability.

Table 12.1: Normal Shrinkage Allowance for Some Metals Cast in Sand Molds.

Metal	Shrinkage allowance (%)
Cast Irons	
Gray cast iron	0.83–1.3
White cast iron	2.1
Malleable cast iron	0.78–1.0
Aluminum alloys	1.3
Magnesium alloys	1.3
Copper alloys	
Yellow brass	1.3–1.6
Phosphor bronze	1.0–1.6
Aluminum bronze	2.1
High-manganese steel	2.6

geometry. Pattern dimensions also should allow for shrinkage of the metal during solidification and cooling. Allowances for shrinkage, known as **patternmaker's shrinkage allowances**, usually range from about 10 to 20 mm/m. Table 12.1 gives the normal shrinkage allowance for metals commonly sand cast.

5. **Draft.** A small draft (taper) is typically provided in sand-mold patterns to enable the removal of the pattern without damaging the mold (see Fig. 11.5). 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 angles on inside surfaces typically are twice this range; they have to be higher than those for outer surfaces because the casting shrinks inward toward the core.

6. **Dimensional tolerances.** Dimensional tolerances depend on the particular casting process employed, size of the casting, and type of pattern used. Tolerances should be as wide as possible, within the limits of good part performance, as otherwise the cost of the casting increases. In commercial practice, tolerances are typically in the range of ± 0.8 mm for small castings, and increase with the size of the castings. For large castings, for instance, they may be as much as ± 6 mm.

7. **Lettering and markings.** It is common practice to include some form of part identification, such as lettering, numbers, or company logos. These features can be sunk into the casting or can protrude from the casting surface; the more desirable one depends on the method of producing the molds. For example, in sand casting, a pattern plate is produced by machining on a computer numerically controlled milling machine (Section 24.2), because it is simpler to machine letters into the pattern plate, they well be recessed in the part. In die casting, it is simpler to machine letters into the mold, leading to letters that protrude.

8. **Finishing operations.** In casting design, it is important to consider the subsequent machining and finishing operations that may be required. For example, if a hole is to be drilled in a casting, it is better to locate it on a flat surface rather than on a curved surface, in order to prevent the drill from wandering. An even better design would incorporate a small dimple on the curved surface as a starting point for the drilling operation. Castings should also include features that allow them to be clamped easily on to machine tools, if secondary machining operations are necessary.

9. **Integrated Computational Materials Engineering (ICME).** The use of modern computational tools allows identification of design and manufacturing issues and allows the prediction of material properties and microstructure that results from a particular mold cavity design. The time spent in process simulation actually saves time that normally would be expended in tooling rework and cost associated with defects.

Selecting a Casting Process. Casting processes cannot be selected separately from economic considerations, as described in Section 12.4. Table 11.2 lists some of the advantages and limitations of casting processes that have an impact on casting design.

Locating the Parting Line. A casting should be oriented in a mold so that the large portion of the casting is relatively low and the height of the casting is minimized. Part orientation also determines the distribution of porosity; for example, in casting aluminum, hydrogen is soluble in liquid metal but is not soluble as the aluminum solidifies (see Fig. 10.17). Hydrogen bubbles can form during the casting of aluminum, which float upwards due to buoyancy and causing a higher porosity in the top regions of castings. Thus, critical surfaces should be oriented so that they face downwards.

A properly oriented casting then can have the parting line determined; this is the line or plane separating the upper (cope) and lower (drag) halves of molds (see Fig. 11.3). In general, the parting line should be along a flat plane rather than be contoured. Whenever possible, the line should be at the corners or edges of castings rather than on flat surfaces in the middle of the casting, so that the **flash** (material squeezing out between the two halves of the mold) at the parting line will not be as visible. The location of the line is also important because it influences mold design, ease of molding, the number and shape of cores required, method of their support, and the gating system.

The parting line should be placed as low as possible (relative to the casting) for metals with lower density (such as aluminum alloys) and be located at around mid-height for denser metals (such as steels). However, the molten metal should not be allowed to flow vertically, especially when unconstrained by a sprue. The placement of the parting line has a large effect on the remainder of the mold design. For example, in sand casting, it is common practice that the runners, gates, and sprue well are all placed in the drag on the parting line. Also, the placement of the parting line and orientation of the part determine the number of cores required, especially when it is preferable to avoid the use of cores whenever practical.

Locating and Designing Gates. Gates are the connections between the runners and the part to be cast. Important considerations in gating system design are:

- Multiple gates often are preferable, and are necessary for large parts; they have the benefits of allowing lower pouring temperature and reducing temperature gradients in the casting.
- Gates should feed into thicker sections of castings.
- A fillet should be used where a gate meets a casting; this feature produces less turbulence than abrupt junctions.
- The gate closest to the sprue should be placed sufficiently away from the sprue, so that the gate can be easily removed. This distance may be as small as a few millimeters for small castings, and up to 500 mm for large ones.
- The minimum gate length should be three to five times the gate diameter, depending on the metal being cast. The gate cross section should be large enough to allow the filling of the mold cavity and should be smaller than the runner cross section.
- 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. They are used to trap *dross* (a mixture of oxide and metal that forms on the surface of metals) and keep it from entering the gates and 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. A single runner is used for simple parts, but two-runner systems may be necessary for more complicated castings.

Designing Various Mold Features. The main goal in designing a *sprue* (described in Section 10.3) is to achieve the required molten-metal flow rates, while preventing *aspiration* (entrainment of air) or excessive dross formation. Flow rates are determined such that turbulence is avoided, but also that 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 molten metal is maintained in the pouring basin during pouring, the dross will float and will not enter the mold cavity. *Filters* are used to trap large contaminants, also serving to reduce the metal velocity and make the flow more laminar. *Chills* can be used to speed solidification of the metal in a particular region of a casting.

Establishing Good Practices. It has been widely observed that a given mold design can produce acceptable castings as well as defective ones, and it rarely will produce only good or only defective castings. To check for defective ones, quality control procedures are necessary. Some common concerns are the following:

- Starting with a high-quality molten metal is essential for producing superior castings. Pouring temperature, metal chemistry, gas entrainment, and handling procedures all can affect the quality of metal being poured into a mold.
- The pouring of the molten metal should not be interrupted, because it can lead to dross entrainment and turbulence. The meniscus of the molten metal in the mold cavity should experience a continuous, uninterrupted, and upward advance.
- The different cooling rates within the body of a casting can cause residual stresses. Thus, stress relieving (Section 4.11) may be necessary to avoid distortions of castings in critical applications.

12.2.2 Design for Expendable-mold Casting

Expendable-mold processes have certain specific design requirements, mainly involving the mold material, part sizes, and the manufacturing method. Recall that a casting in an expendable-mold process, such investment casting, will cool much more slowly than it would in, say, die casting; this has important implications in the layout of molds. Important design considerations for expendable-mold casting are as follows.

Mold Layout. The various features in a mold must be placed logically and compactly, with gates as necessary. One of the most important goals in mold layout is to have solidification initiate at one end of the mold and progress across the casting in a uniform front, with the risers solidifying last. Traditionally, mold layout has been based on experience and on considerations of fluid flow and heat transfer. Commercial computer programs have now become widely available assisting in the analysis of fluid flow and heat transfer. These programs simulate mold filling and allow the rapid evaluation and design of mold layouts.

Riser Design. A major concern in the design of castings is the size of risers and their placement. Risers are very useful in affecting the solidification-front progression across a casting, and are an essential feature in mold layout described previously. Blind risers are good design features and maintain heat longer than open risers do.

Risers are designed according to the following basic rules:

1. The riser must not solidify before the casting does. This rule usually is satisfied by avoiding the use of small risers and by using cylindrical risers with small aspect ratios (i.e., small ratios of height to cross section). Spherical risers are the most efficient shape, but are difficult to work with.
2. The riser volume must be sufficiently large to provide enough molten metal to compensate for shrinkage in the casting.
3. Junctions between the casting and the riser should not develop hot spots, where shrinkage porosity can occur.
4. Risers must be placed such that the molten metal can reach locations where it is most needed.

5. There must be sufficient pressure to drive the molten metal into locations in the mold where it is needed. Risers are not as useful for metals with low density (such as aluminum alloys) as they are for those with higher density (such as steel and cast irons).

6. The pressure head from the riser should suppress cavity formation and encourage complete filling of the mold cavity.

Machining Allowance. Most expendable-mold castings require some additional finishing operations, such as machining and grinding; allowances have to be included in casting design for these operations. Machining allowances, which are included in pattern dimensions, depend on the type of casting operation, noting also that they increase with the size and section thickness of the casting. Allowances usually range from about 2 to 5 mm for small castings to more than 25 mm for large castings.

12.2.3 Design for Permanent-mold Casting

General design guidelines for permanent-mold casting are described in Example 12.1. 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; otherwise, galling (localized seizure or sticking of two surfaces, Section 33.5) may occur between the part and the dies, causing distortion of the casting. 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 11.3) and, in general, they do not require a machining allowance.

Case Study 12.1 Illustrations of Poor and Good Casting Designs

Several examples of poor and good designs in permanent-mold and die casting are illustrated in Fig. 12.4. The significant differences in design are outlined here for each example:

1. The lower portion of the design on the left has a thin wall, with no apparent specific function; at this location, the part may fracture if subjected to high forces or to impact. The good design eliminates this possibility, and also may simplify die and mold making.

2. Large flat surfaces always present difficulties, as they tend to warp and develop uneven surfaces. A common practice to avoid this situation is to break up the surface with *ribs* (see Fig. 12.3) and serrations on the reverse side of the casting. This approach greatly reduces part distortion, while not adversely affecting the appearance and function of the flat surface. In addition to ribs, it is beneficial to use a *textured* surface, as shown in Fig. 12.4b, since very smooth surfaces are difficult to cast without objectionable aesthetic features.

3. This example of poor and good design is relevant not only to castings, but also to parts that are subsequently machined or ground. It is difficult to produce sharp internal radii or corners that may be required for functional purposes, such as inserts designed to reach the bottom of the part cavity. Also, in the case of lubricated cavities, the lubricant can accumulate at the bottom and, because it is incompressible, prevent full insertion of an insert. The placement of a small radius at the corners or periphery at the bottom of the part eliminates this problem.

4. A cast part could function, for instance, as a knob to be gripped and rotated, hence the outer features along its periphery. Note in the design on the left that the inner periphery of the knob also has features which are not functional but help save material; the die for the good design is easier to manufacture.

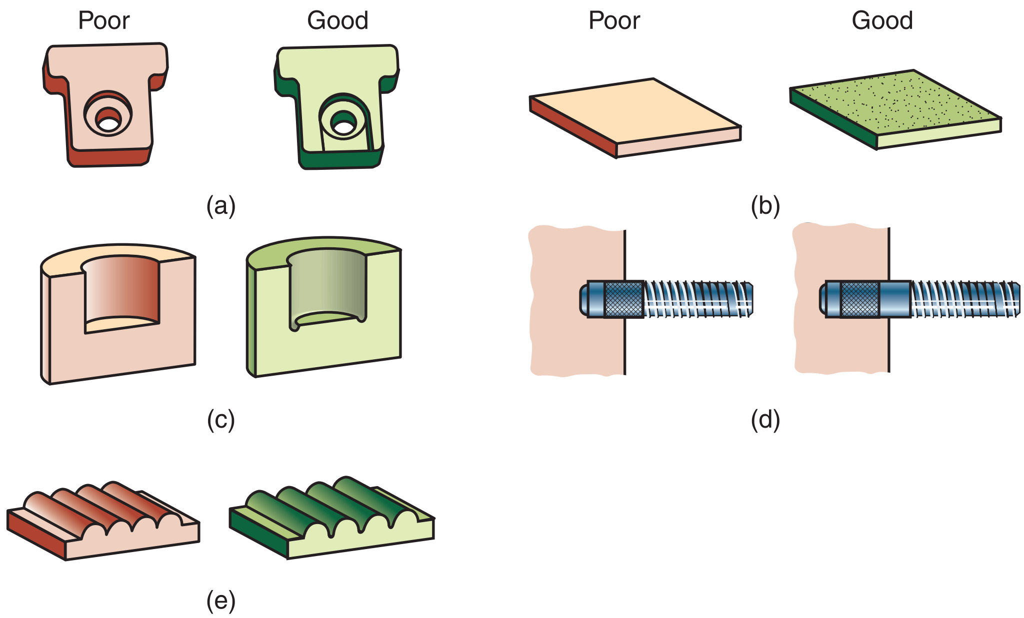

Figure 12.4: Examples of undesirable (poor) and desirable (good) casting designs.

5. Note that the poor design has sharp fillets at the base of the longitudinal grooves, indicating that the die has sharp (knife-edge) protrusions. It is thus possible that, with overextended use of the die, these edges may chip off.

12.2.4 Computer Modeling of Casting Processes

Because casting involves complex interactions among several material and process variables, a quantitative study of these interactions is essential to the proper design and production of high-quality castings. Rapid advances in modeling techniques have led to important innovations in modeling casting processes. These include fluid flow, heat transfer, and the microstructures developed during solidification under various casting conditions, as described in Section 10.3.

Simulations are capable of predicting, for example, the width of the mushy zone (see Fig. 10.4) during solidification and the grain size in castings. Similarly, the capability to calculate *isotherms* (lines of equal temperature) give insight into possible hot spots and the subsequent development of shrinkage cavities. With the availability of user-friendly software and advances in computer-aided design and manufacturing (Chapter 38), modeling techniques have become easier to implement. The benefits of this approach are improved quality, easier planning and cost estimating, increased productivity, and faster response to design changes.

12.3 Casting Alloys

The general properties and typical applications of ferrous and nonferrous metals and alloys were presented in Chapters 5 and 6, respectively. This section describes the properties and applications of cast metals and alloys; their properties and casting and manufacturing characteristics are summarized in Fig. 12.5 and Tables 12.2 through 12.5. In addition to their casting characteristics, other important considerations in casting alloys include their machinability and weldability, since they are assembled with other components to produce the entire assembly.

The most commonly used casting alloy (in tonnage) is gray iron, followed by ductile iron, malleable iron, steel, copper, aluminum, magnesium, and zinc. Shipments of castings in the United States alone are around 9.07 million metric tons per year.

12.3.1 Nonferrous Casting Alloys

Common nonferrous casting alloys are as follows:

Aluminum-based Alloys. Aluminum alloys have a wide range of mechanical properties, mainly because of various hardening mechanisms and heat treatments that can be used (Section 4.9). Parts made of aluminum and magnesium alloys are known as **light-metal** castings. They have high electrical conductivity and generally good atmospheric corrosion resistance; however, their resistance to all alkalines and some acids is poor, and care must be taken to prevent galvanic corrosion.

Aluminum alloys are lightweight, nontoxic, and have good machinability. Except for alloys containing silicon, they generally have low resistance to wear and abrasion. They have numerous applications, including architectural and decorative purposes. An increasing trend is their use in automobiles, for components such as engine blocks, cylinder heads, intake manifolds, transmission cases, suspension components, wheels and brakes.

Magnesium-based Alloys. These alloys have the lowest density of all commercial casting alloys. They have good corrosion resistance and moderate strength, depending on the particular heat treatment used. Typical applications include automotive wheels, housings, and air-cooled engine blocks. Because of their light weight, magnesium castings are being increasingly used in automobiles to increase fuel economy.

Copper-based Alloys. These alloys have the advantages of good electrical and thermal conductivity, corrosion resistance, and nontoxicity, as well as wear properties suitable as bearing materials. A wide variety of copper-based alloys is available, including brasses, aluminum bronzes, phosphor bronzes, and tin bronzes.

Zinc-based Alloys. A low-melting-point alloy group, zinc-based alloys have good corrosion resistance, good fluidity, and sufficient strength for structural applications. These alloys are commonly used in die casting, particularly for parts with thin walls and complex shapes.

Tin-based Alloys. Although low in strength, these alloys have good corrosion resistance and are typically used for linings or bearing surfaces.

High-temperature Alloys. These alloys have a wide range of properties, and typically require temperatures of up to 1650°C for casting titanium and superalloys, and even higher for refractory alloys (Mo, Nb, W, and Ta). Special techniques are used to cast these alloys for nozzles and various jet- and rocket-engine components. Some high-temperature alloys are more suitable and economical for casting than for shaping by other manufacturing methods, such as forging and powder metallurgy techniques.

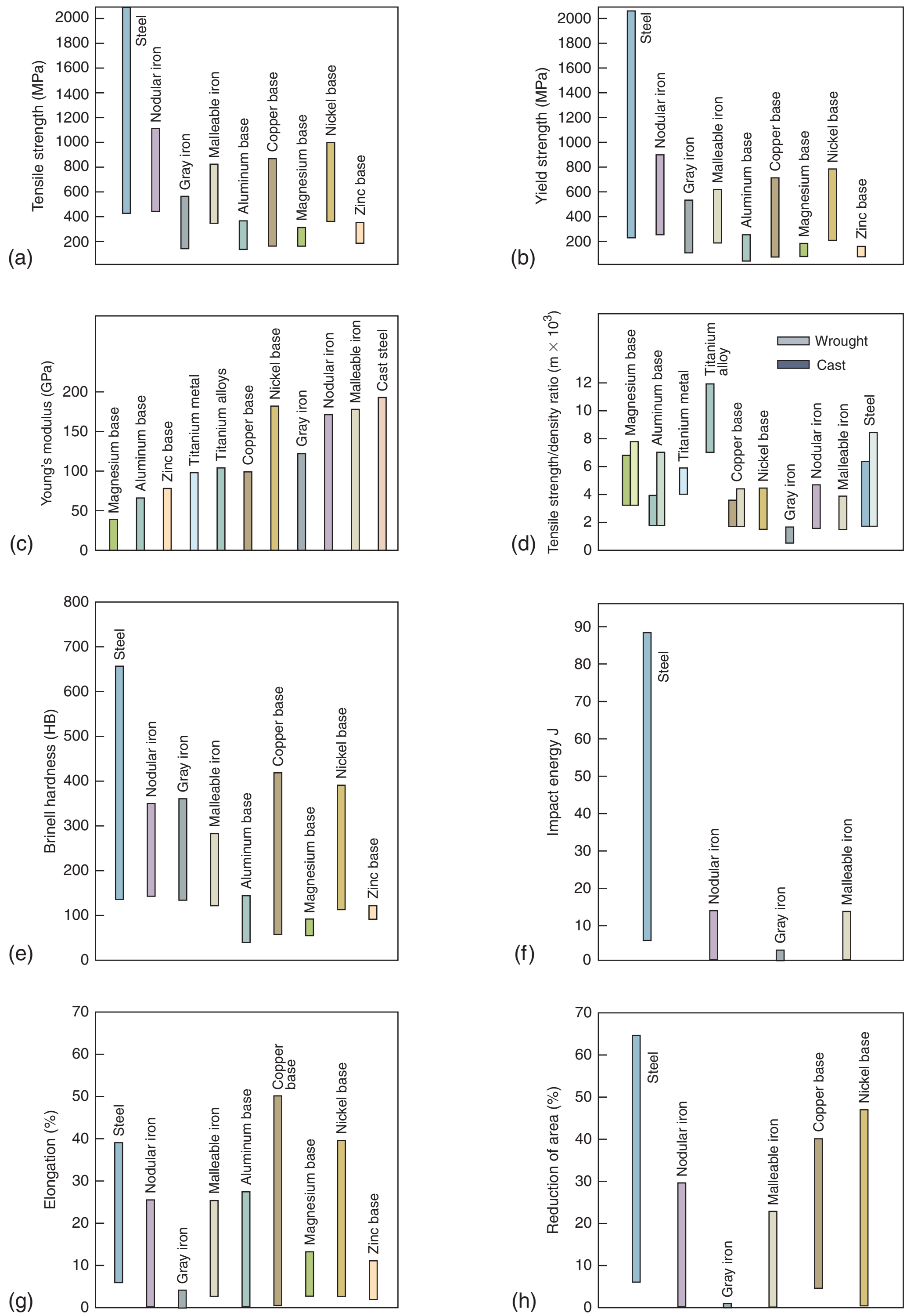

Figure 12.5: Mechanical properties for various groups of cast alloys. Note that even within the same group, the properties vary over a wide range, particularly for cast steels. *Source:* Courtesy of Steel Founders' Society of America.

Table 12.2: Typical Applications for Castings and Casting Characteristics.

Type of alloy	Castability*	Weldability*	Machinability*	Typical applications
Aluminum	E	F	G–E	Pistons, clutch housings, intake manifolds
Copper	F–G	F	F–G	Pumps, valves, gear blanks, marine propellers
Iron				
Ductile	G	D	G	Crankshafts, heavy-duty gears
Gray	E	D	G	Engine blocks, gears, brake disks and drums, machine bases
Malleable iron	G	D	G	Farm and construction machinery, heavy-duty bearings, railroad rolling stock
White iron	G	VP	VP	Mill liners, shot-blasting nozzles, railroad brake shoes, crushers, and pulverizers
Magnesium	G–E	G	E	Crankcase, transmission housings
Nickel	F	F	F	Gas turbine blades, pump and valve components for chemical plants
Steel				
Carbon and low-alloy	F	E	F	Die blocks, heavy-duty gear blanks, aircraft undercarriage members, railroad wheels
High-alloy	F	E	F	Gas-turbine housings, pump and valve components, rock-crusher jaws
Zinc	E	D	E	Door handles, radiator grills

Note: * E = excellent; G = good; F = fair; VP = very poor; D = difficult

Table 12.3: Properties and Typical Applications of Cast Irons.

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

Table 12.4: Mechanical Properties of Gray Cast Irons.

ASTM class	Ultimate tensile strength (MPa)	Compressive strength (MPa)	Elastic modulus (GPa)	Hardness (HB)
20	152	572	66–97	156
25	179	669	79–102	174
30	214	752	90–113	210
35	252	855	100–119	212
40	293	965	110–138	235
50	362	1130	130–157	262
60	431	1293	141–162	302

Table 12.5: Properties and Typical Applications of Nonferrous Cast Alloys.

Alloys (UNS)	Condition	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Aluminum alloys					
195 (AO1950)	Heat treated	220–280	110–220	8.5–2	Sand castings
319 (AO3190)	Heat treated	185–250	125–180	2–1.5	Sand castings
356 (AO3560)	Heat treated	260	185	5	Permanent mold castings
Copper alloys					
Red brass (C83600)	Annealed	235	115	25	Pipe fittings, gears
Yellow brass (C86400)	Annealed	275	95	25	Hardware, ornamental
Manganese bronze (C86100)	Annealed	480	195	30	Propeller hubs, blades
Sulfur tin bronze (C83470)	As cast	190	95	15	Water supply piping and fittings, valves
Copper Bismuth (C89836)	As cast	230	95	20	Antimicrobial; water supply and fittings
Gun metal (C90500)	Annealed	275	105	30	Pump parts, fittings
Nickel silver (C97600)	Annealed	275	175	15	Marine parts, valves
Magnesium alloys					
AZ91A	F	230	150	3	Die castings
AZ63A	T4	275	95	12	Sand and permanent mold castings
AZ91C	T6	275	130	5	High-strength parts
EZ33A	T5	160	110	3	Elevated-temperature parts
HK31A	T6	210	105	8	Elevated-temperature parts
QE22A	T6	275	205	4	Highest-strength parts

12.3.2 Ferrous Casting Alloys

Commonly cast ferrous alloys are as follows:

Cast Irons. Cast irons represent the largest quantity of all metals cast. They can easily be cast into intricate shapes, and generally possess several desirable properties, such as high hardness, wear resistance, and good machinability. The term *cast iron* refers to a family of alloys, and as described in Section 4.6, they are classified as gray cast iron (gray iron), ductile (nodular or spheroidal) iron, white cast iron, malleable iron, and compacted-graphite iron. Their general properties and typical applications are given in Tables 12.3 and 12.4.

1. **Gray cast iron.** Gray iron castings have relatively few shrinkage cavities and low porosity. Various forms of gray cast iron are *ferritic*, *pearlitic*, and *martensitic*, and because of differences in their structures, each type has different properties (Table 12.4). Gray cast irons are specified by a two-digit ASTM designation; thus, for example, class 20 specifies that the material must have a minimum tensile strength of 140 MPa. Typical uses of gray cast iron are in engine blocks, electric-motor housings, pipes, and wear surfaces for machines. Also, because of its high damping capacity, gray iron is used widely for machine-tool bases (Section 25.3).

2. **Ductile (nodular) iron.** Typically used for machine parts, housings, gears, pipe, rolls for rolling mills, and automotive crankshafts, ductile irons are specified by a set of two-digit numbers. For example, class or grade 80-55-06 indicates that it has a minimum tensile strength of 550 MPa, a minimum yield strength of 380 MPa, and 6% elongation in 50 mm.

3. **White cast iron.** Because of its very high hardness and wear resistance, white cast iron is used typically for rolls for rolling mills, railroad-car brake shoes, and liners in machinery for processing abrasive materials.

4. **Malleable iron.** The principal use of malleable iron is for railroad equipment and various types of hardware, fittings, and components for electrical applications. Malleable irons are specified by a five-digit designation. For example, 35018 indicates that the yield strength is 240 MPa and its elongation is 18% in 50 mm.

5. **Compacted-graphite iron.** First produced commercially in 1976, compacted-graphite iron (CGI) has properties that are between those of gray irons and ductile irons. Gray iron has good damping and thermal conductivity, but low ductility, whereas ductile iron has poor damping and thermal conductivity, but high tensile strength and fatigue resistance. Compacted-graphite iron has damping and thermal properties similar to gray iron and strength and stiffness that are comparable to those of ductile iron. Because of its strength, castings made of CGI can be smaller, thus lighter. This iron is easy to cast and has properties that are consistent throughout the casting. Moreover, its machinability is better than that of ductile iron (an important consideration since compacted-graphite iron is used for automotive engine blocks and cylinder heads, which require extensive machining).

Cast Steels. Because of the high temperatures required to melt steels (up to about 1650°C), casting steels requires special considerations. The high temperatures involved present difficulties in the selection of mold materials, particularly in view of the high reactivity of steels with oxygen during the melting and pouring of the metal. Steel castings possess properties that are more uniform (isotropic) than those made by mechanical working processes (Part III). Although they can be welded, welding alters the cast microstructure in the heat-affected zone (see Fig. 30.15), thus influencing the strength, ductility, and toughness of the base metal. Subsequent heat treatment would be required to restore the mechanical properties of the casting. Cast weldments have gained importance for assembling large machines and structures. Cast steels have important applications in mining, chemical plants, oil fields, heavy construction, and equipment for railroads.

Cast Stainless Steels. Casting of stainless steels involves considerations similar to those for steels. Stainless steels generally have long freezing ranges (see Section 10.2.2) and high melting temperatures. They can develop several structures, depending on their composition and processing parameters. Cast stainless steels are available in various compositions, and they can be heat treated and welded. Cast stainless-steel parts have high heat and corrosion resistance, especially useful in the chemical and food industries. Nickel-based casting alloys are used for very corrosive environments and for very high temperature service.

Table 12.6: General Cost Characteristics of Casting Processes.

Casting process	Cost*			Production rate (pieces/hr)
	Die	Equipment	Labor	
Sand	L	L	L–M	< 20
Shell mold	L–M	M–H	L–M	< 10
Plaster	L–M	M	M–H	< 10
Investment	M–H	L–M	H	< 1000
Permanent mold	M	M	L–M	< 60
Die	H	H	L–M	< 200
Centrifugal	M	H	L–M	< 50

* L = low; M = medium; H = high.

12.4 Economics of Casting

As in all manufacturing processes, the cost of each cast part (**unit cost**) depends on several factors, including materials, equipment, and labor. Recall that among various casting processes described in Chapter 11, some require more labor than others, some require expensive dies and machinery, and some require a long production times to produce the castings (Table 12.6). Each of these individual factors affects the overall cost of a casting operation and to varying degrees.

As can be noted in Table 12.6, relatively little cost is involved in making molds for sand casting, whereas molds for other casting processes and especially dies for die-casting require expensive materials and manufacturing operations. There are also major costs involved in making patterns for casting, although much progress continues to be made in utilizing additive manufacturing techniques (Section 20.10) to reduce costs and production time.

Costs are also incurred in melting and pouring the molten metal into molds, and in heat treating, cleaning, and inspecting the castings. Heat treating is an important part of the production of many alloy groups (especially ferrous castings), and may be necessary for improving the mechanical properties. However, heat treating may also introduce another set of production problems, such as scale formation on casting surfaces and warpage of the part, that can be a significant aspect of production costs.

The labor and the skills required can vary considerably, depending on the particular casting operation and level of automation in the foundry. Investment casting, for example, requires much labor because of the several steps involved in the operation, although some automation in a plant can be implemented, such as using robots (Fig. 11.13a). On the other hand, operations such as in highly automated die-casting maintain high production rates, with little labor involved.

Note also that the equipment cost per casting decreases as the number of parts cast increases. Sustained high production rates can justify the high cost of dies and machinery. However, if demand is relatively small, the cost per casting increases rapidly. It then becomes more economical to manufacture the parts either by other casting processes described in this chapter or by considering other manufacturing processes, described in detail in Parts III and IV, singly or in combination.

Summary

- General guidelines have been established to aid in the production of castings without defects, and to meet dimensional tolerances, surface finish, service requirements, and various specifications and standards. The guidelines concern the shape of the casting and the various techniques to minimize hot spots that could lead to shrinkage cavities. 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 molds and dies, and the rate of cooling in different regions of the mold.

- Numerous nonferrous and ferrous casting alloys are available, with a wide range of properties, casting characteristics, and applications. Because many castings are designed and produced to be assembled with other mechanical components and structures (subassemblies), several other considerations, such as weldability, machinability, and surface characteristics, also are important.
- Within the limits of good performance, the economics of casting is just as important as the technical considerations. Factors affecting the overall cost are the cost of materials, molds, dies, equipment, and labor, each of which varies with the particular casting operation.

Key Terms

Cast iron
Compacted-graphite iron
Design principles
Draft
Flash
Hot spots
Machining allowance
Parting line
Patternmaker's shrinkage allowance
Porosity
Shrinkage cavities
Unit cost

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Review Questions

12.1. Why are steels more difficult to cast than cast irons?

12.2. What is the significance of hot spots in metal casting?

12.3. What is shrinkage allowance? Machining allowance?

12.4. Explain the reason for drafts in molds.

12.5. Why are ribs useful for flat surfaces?

12.6. What are light castings and where are they used most commonly?

12.7. Name the types of cast irons generally available, and list their major characteristics and applications.

12.8. Comment on your observations regarding Fig. 12.5.

12.9. Describe the difference between a runner and a gate.

12.10. What is the difference between machining allowance and dimensional tolerance?

12.11. What is dross? Can it be eliminated?

Qualitative Problems

12.12. Describe your observation concerning the design changes shown in Fig. 12.1.

12.13. If you need only a few castings of the same design, which three processes would be the most expensive per piece cast?

12.14. Do you generally agree with the cost ratings in Table 12.6? If so, why?

12.15. Describe the nature of the design differences shown in Fig. 12.4. What general principles do you observe in this figure?

12.16. Note in Fig. 12.5 that the ductility of some cast alloys is very low. Do you think that this should be a significant concern in engineering applications of castings? Explain.

12.17. Do you think that there will be fewer defects in a casting made by gravity pouring versus one made by pouring under pressure? Explain.

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

12.19. What type of cast iron would be suitable for heavy-machine bases, such as presses and machine tools? Why?

12.20. Explain the advantages and limitations of sharp and rounded fillets, respectively, in casting design.

12.21. Explain why the elastic modulus, E, of gray cast iron varies so widely, as shown in Table 12.4.

12.22. If you were to incorporate lettering or numbers on a sand-cast part, would you make them protrude from the surface or recess them into the surface? What if the part were to be made by investment casting? Explain your answer.

12.23. The general design recommendations for a well in sand casting (see Fig. 11.3) are that (a) its diameter should be at least twice the exit diameter of the sprue and (b) its depth should be approximately twice the depth of the runner. Explain the consequences of deviating from these guidelines.

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

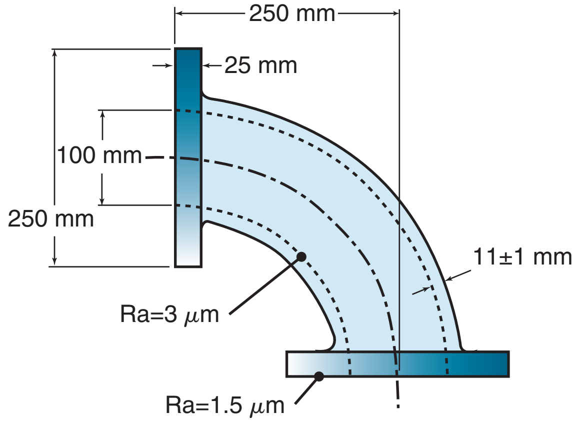
12.25. What are the benefits and drawbacks to having a pouring temperature that is much higher than the metal's melting temperature? What are the advantages and disadvantages in having the pouring temperature remain close to the melting temperature?

Quantitative Problems

12.26. When designing patterns for casting, patternmakers use special rulers that automatically incorporate solid shrinkage allowances into their designs. For example, a 300 mm patternmaker's ruler is longer than 300 mm. How long should a patternmaker's ruler be for making patterns for (a) aluminum castings and (b) high-manganese steel?

12.27. Using the data given in Table 12.2, develop approximate plots of (a) castability versus weldability and (b) castability versus machinability, for at least five of the materials listed in the table.

12.28. The part in the figure below is to be cast of 10% Sn bronze at the rate of 100 parts per month. To find an appropriate casting process, consider all casting processes, 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.



Synthesis, Design, and Projects

12.29. Describe the general design considerations pertaining to metal casting.

12.30. Add more examples to those shown in Fig. 12.2.

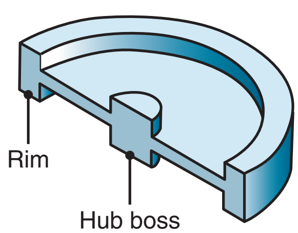
12.31. Explain how ribs and serrations are helpful in casting flat surfaces that otherwise may warp. Give a specific illustration.

12.32. List casting processes that are suitable for making hollow parts with (a) complex external features, (b) complex internal features, and (c) both complex external and complex internal features. Explain your choices.

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

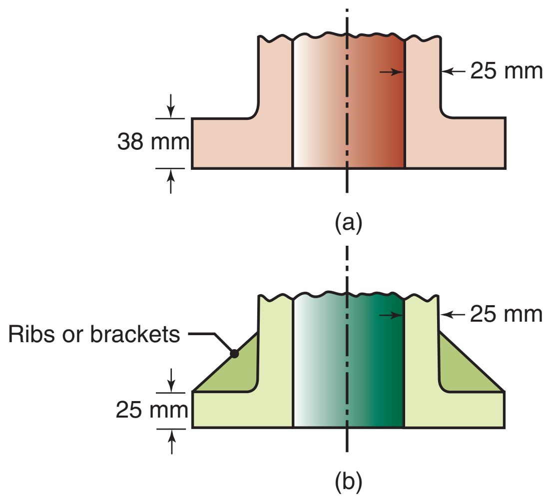
12.34. If you need only a few units of a particular casting, which process(es) would you use? Why?

12.35. For the cast metal wheel illustrated 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 hub boss.

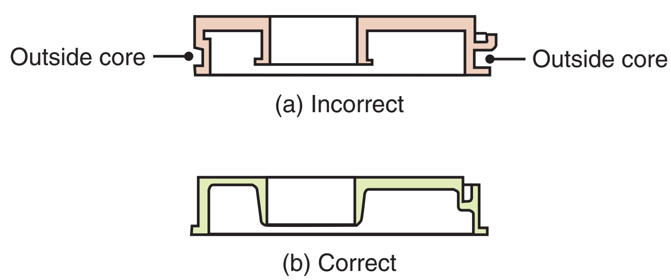


12.36. Assume that the introduction to this chapter is missing. Write a brief introduction to highlight the importance of the topics covered in it.

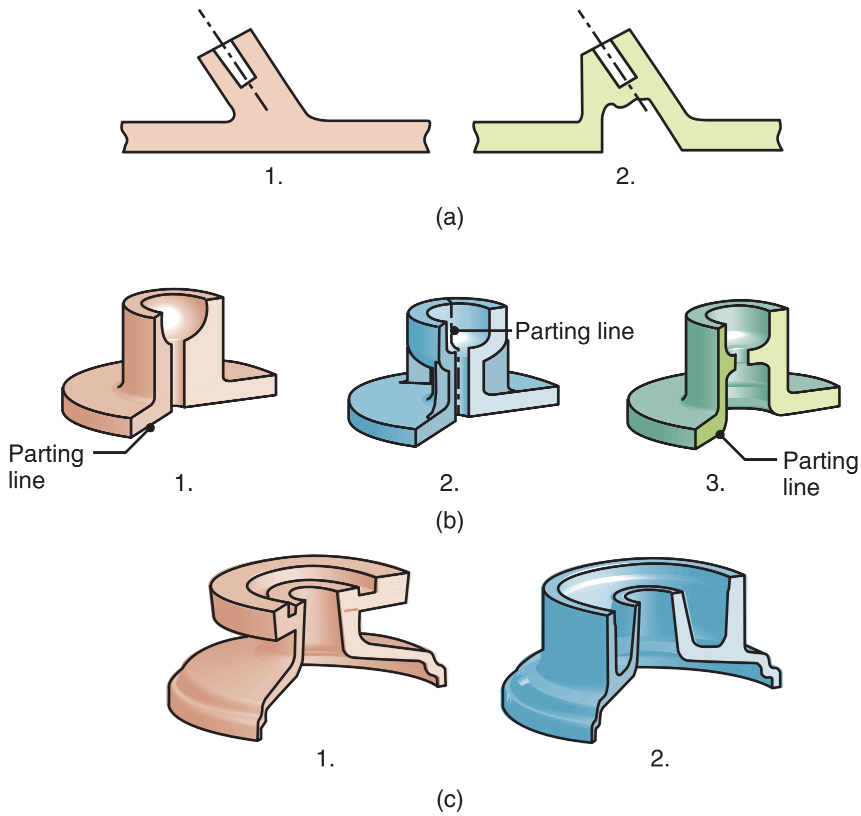
12.37. In the figure below, the original casting design shown in (a) was resized and modified to incorporate ribs in the design shown in (b). The casting is round and has a vertical axis of symmetry. What advantages do you think the new design has as a functional part over the old one?



12.38. An incorrect and a correct design for casting are shown below. Review the changes made and comment on their advantages.



12.39. Three sets of designs for die casting are shown below. Note the changes made to design 1 and comment on the reasons for then or them.



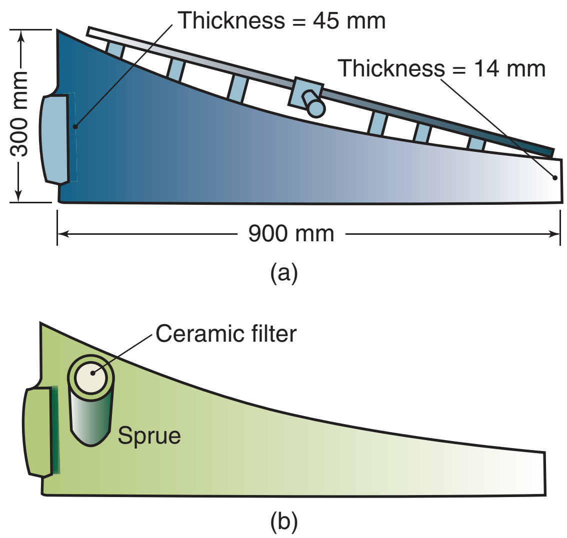
12.40. Using the method of inscribed circles shown in Fig. 12.2, justify the trend shown in Fig. 12.3.

12.41. A growing trend is the production of patterns and molds through rapid prototyping approaches described in Chapter 20. 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?

12.42. Repeat Problem 12.41 for the case where (a) a pattern for sand casting is produced by rapid prototyping; (b) a sand mold for sand casting is produced.

12.43. 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.

12.44. 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.



12.45. 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?