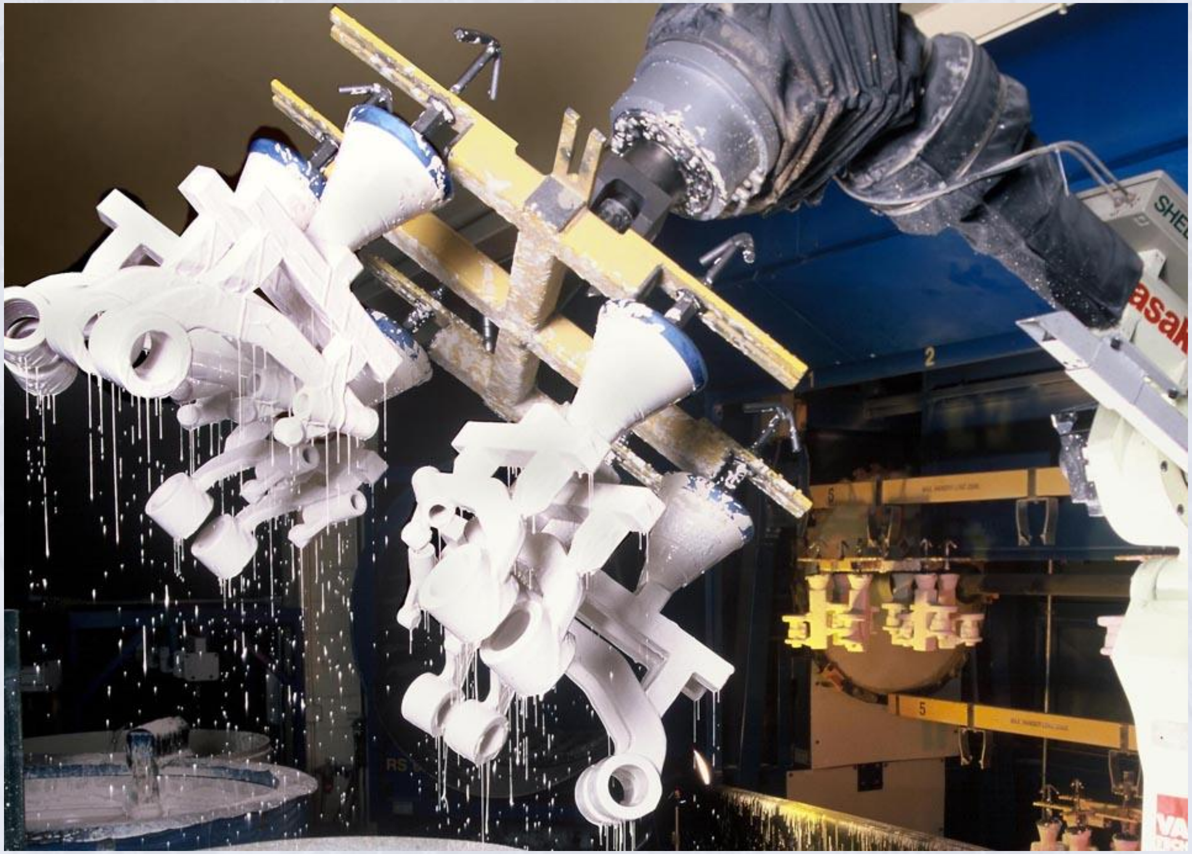
Chapter 12

Metal Casting: Design, Materials, and Economics



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Introduction

- Successful casting practice requires the proper control of a large number of variables: characteristics of the metals (or alloys) casts, method of casting, mold/die materials, mold/die design, and various process parameters.
- 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 and guidelines for metal casting and presents suggestions for avoiding defects.

Design Considerations in Casting

1. Design the part so that the shape is cast easily.
2. Select a casting process and material suitable for the part, size, mechanical properties, etc.
3. Locate the parting line of the mold in the part.
4. Locate and design 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 sprue, screens and risers, as appropriate.
7. Make sure proper controls and good practices are in place.

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Design Considerations in Casting - Design of cast parts

- **Corners, angles and section thickness**: avoid using sharp corners and angles (act as stress raisers) and may cause cracking and tearing during solidification. Use fillets with radii ranging from 3 to 25 mm

Design Considerations in Casting - Design of cast parts

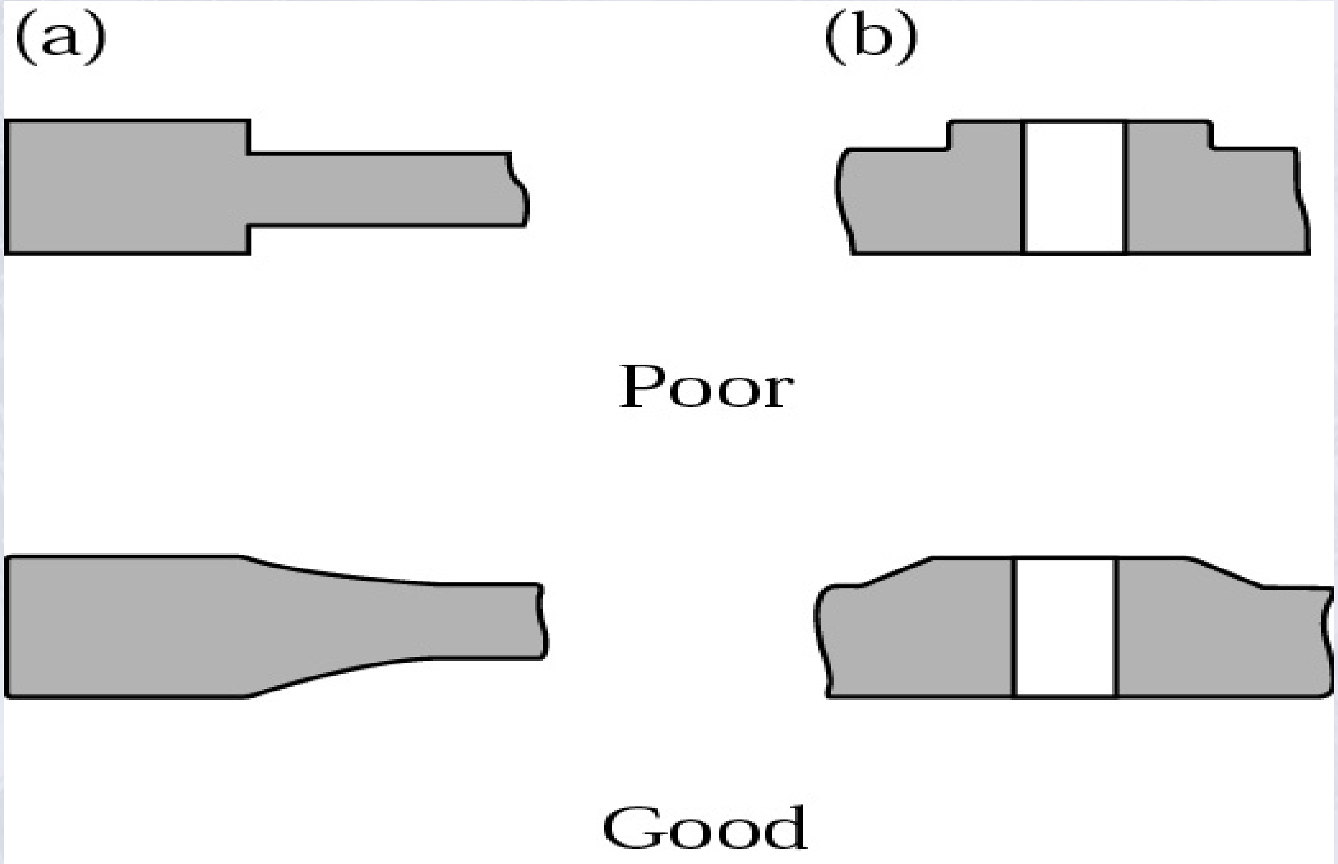

Figure 12.1 Suggested design modifications to avoid defects in castings. Note that sharp corners are avoided to reduce stress concentrations.

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Design Considerations in Casting - Design of cast parts

- Sections changes in castings should be blended smoothly into each other. Location of the largest circle that can be inscribed in a particular region is critical so far as shrinkage cavities are concerned (a & b). Because the cooling rate in regions with large circles is lower, they are **called hot spots**. These regions can develop shrinkage cavities and porosity (c & d).
- Cavities at hot spots can be eliminated by using small cores (e). It is important to maintain (as much as possible) uniform cross sections and wall thicknesses throughout the casting to avoid or minimize shrinkage cavities. Metal chills in the mold can eliminate or minimize hot spots.

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Design Considerations in Casting - Design of cast parts

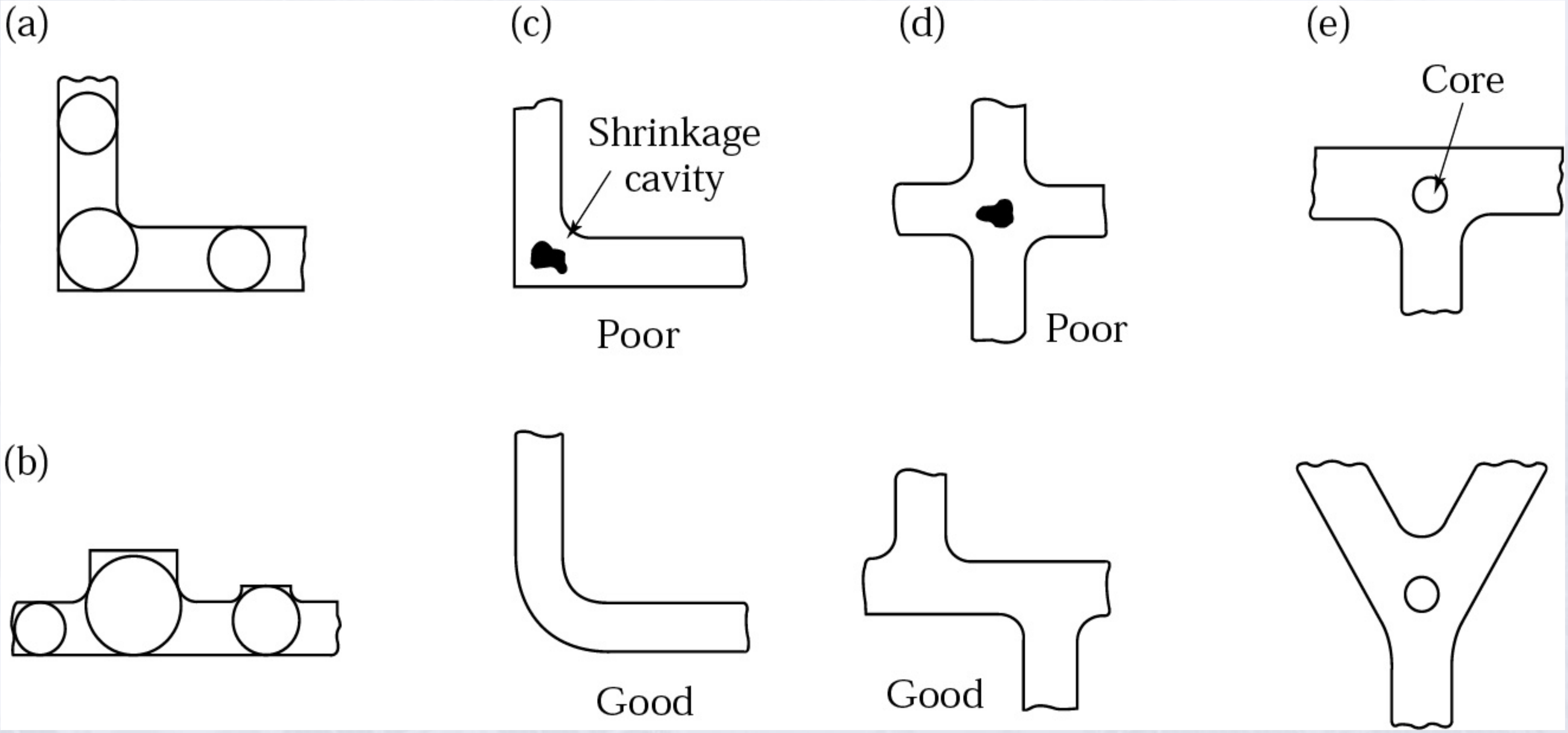

Figure 12.2 Examples of designs showing the importance of maintaining uniform cross-sections in castings to avoid hot spots and shrinkage cavities.

Elimination of Hot Spots

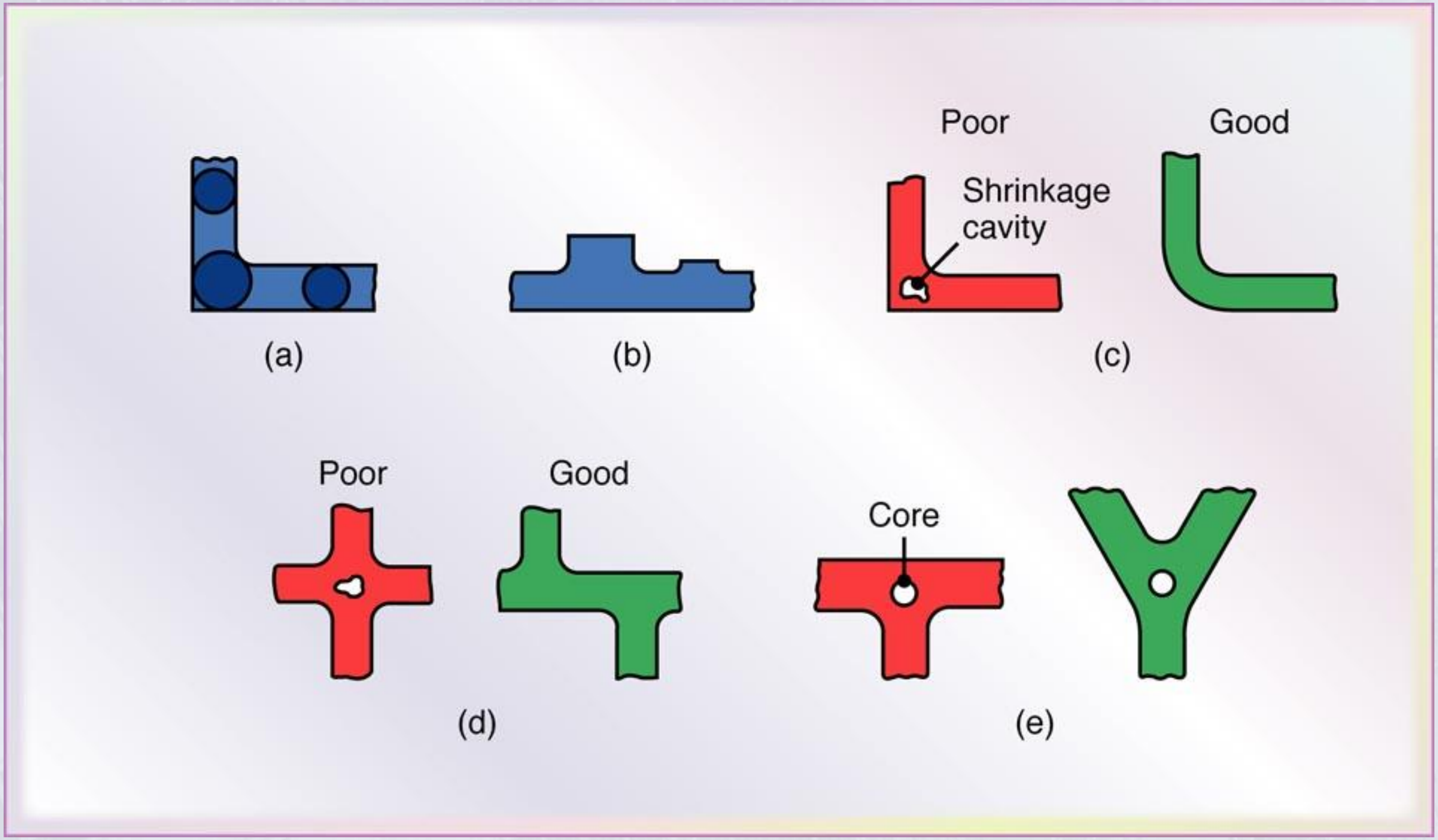

Figure 12.2 Examples of designs showing the importance of maintaining uniform cross-sections in castings to avoid hot spots and shrinkage cavities.

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Design Considerations in Casting - Design of cast parts

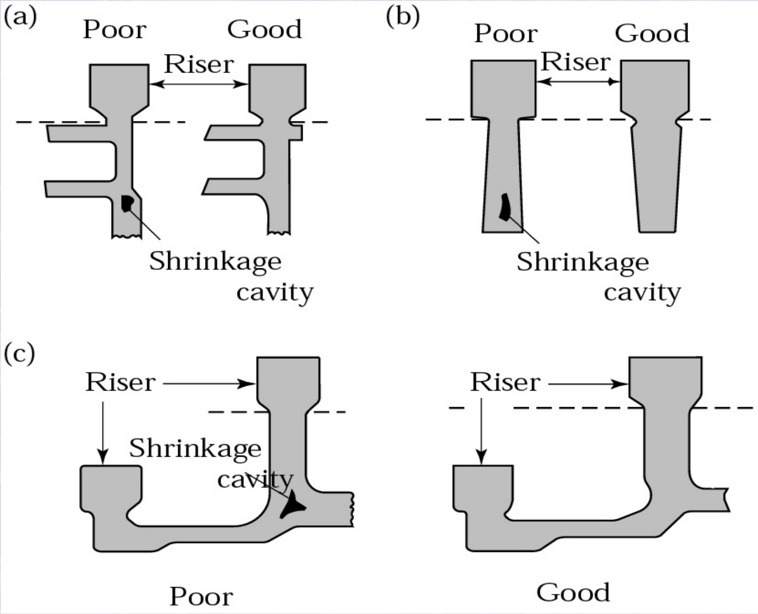


Figure 12.3 Examples of design modifications to avoid shrinkage cavities in castings.

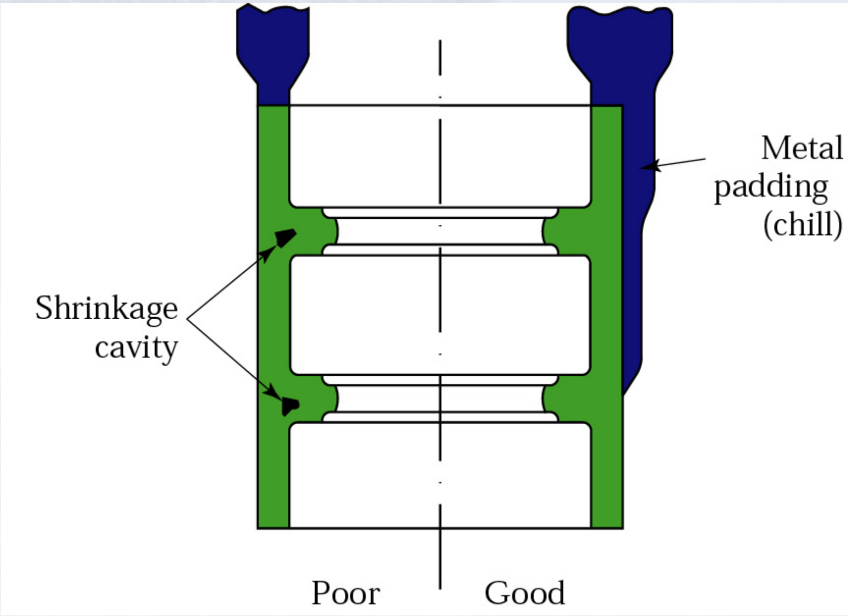
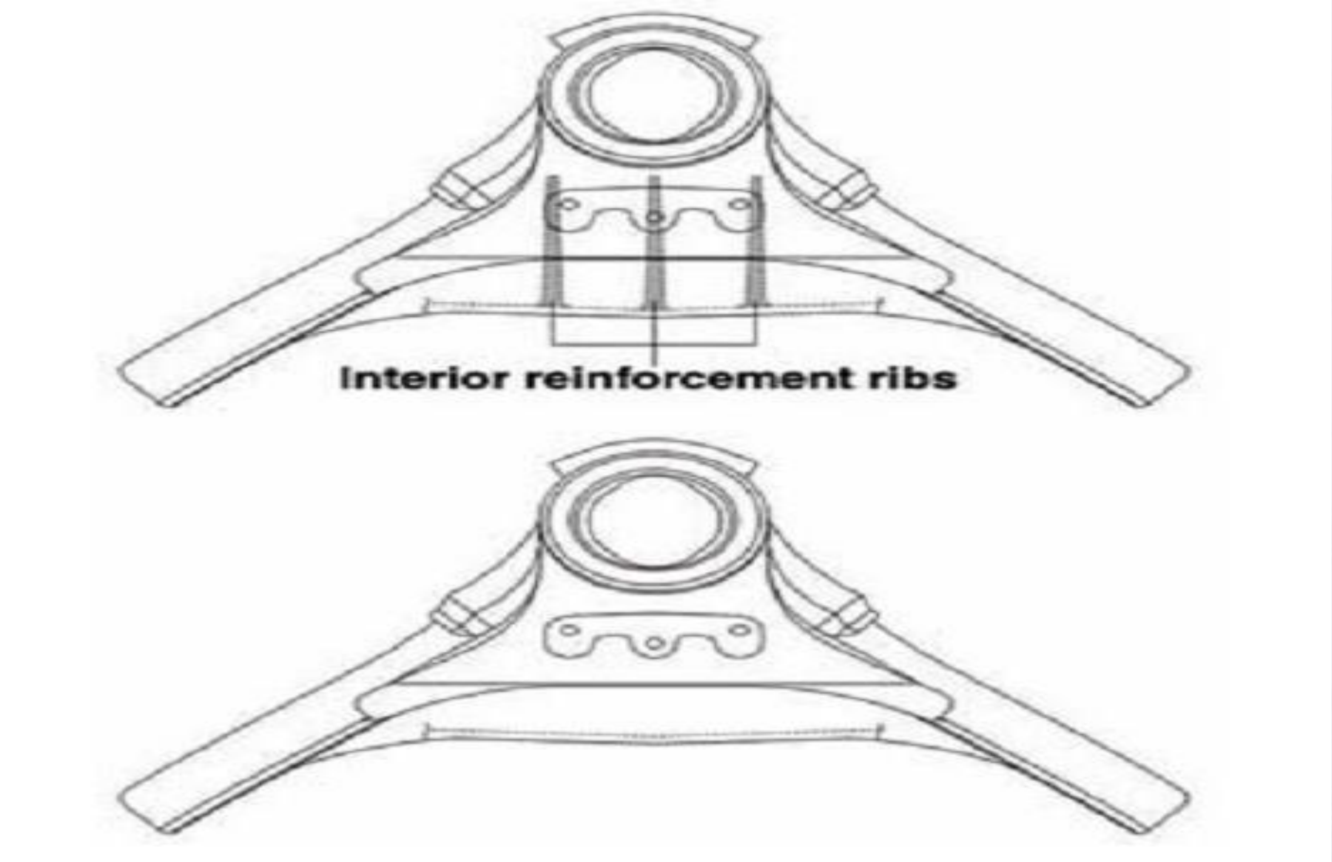


Figure 12.4 The use of metal padding (chills) to increase the rate of cooling in thick regions in a casting to avoid shrinkage cavities

Design Considerations in Casting - Design of cast parts

- **<u>Flat areas</u>:** large flat areas (plain surfaces) should be avoided, since they may warp during cooling because of temperature gradients, or they develop poor surface finish because of uneven flow of metal during pouring. To resolve this one can break up flat surfaces with staggered ribs.
- **<u>Shrinkage:</u>** 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 that are commonly sand cast.

Design Considerations in Casting - Design of cast parts



- Figure: Adding ribs to flat region decreases warping and increases stiffness against bending moments

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Shrinkage Allowance for Casting in Sand Molds

TABLE 12.1

Normal Shrinkage Allowance for Some Metals Cast in Sand Molds

Metal	%
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
Yellow brass	1.3–1.6
Phosphor bronze	1.0–1.6
Aluminum bronze	2.1
High-manganese steel	2.6

Typical patternmaker's shrinkage of various metals[23]		
Metal	Percentage	in/ft
Aluminum	1.0–1.3	1⁄8–5⁄32
Brass	1.5	3⁄16
Magnesium	1.0–1.3	1⁄8–5⁄32
Cast iron	0.8–1.0	1⁄10–1⁄8
Steel	1.5–2.0	3⁄16–1⁄4

Design Considerations in Casting - Design of cast parts

– **<u>Draft</u>:** a small draft (taper) typically is provided in sand mold pattern 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^o to 2^o.

– **<u>Dimensional tolerances</u>:** tolerances should be as wide as possible, within the limits of good part performance; otherwise, the cost of the casting increases. In commercial practices, tolerances are usually in the range of ± 0.8 mm for small castings. For large castings, tolerances may be as much as ± 6 mm.

Design Considerations in Casting - Design of cast parts

- **Lettering and markings:** it is common practice to include some form of part identification (such lettering or corporate logos) in castings. These features can be sunk into the casting or protrude from the surface.
- **Machining and finishing operations:** should be taken into account. For example, a hole to be drilled should be on a flat surface not a curved one. Better yet, should incorporate a small dimple as a starting point. Features to be used for clamping when machining.

Design Considerations in Casting - Selecting the casting process

- Casting process selection can not be separated from discussions of economics. However, Tables 11.1 and 11.2 provide a list of some of the advantages and limitations of casting processes that have and an impact on casting design.

Design Considerations in Casting - Locating the parting line

- A part 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.
- The parting line is line or plane separating the upper (cope) and lower (drag) halves of mold. In general, the parting line should **be along a flat plane** rather than be contoured.
- The parting line should be placed as low as possible relative to the casting for less dense metal (such as aluminum alloys) and located at around mid-height for denser metals (such as steels).

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Design Considerations in Casting - Locating the parting line

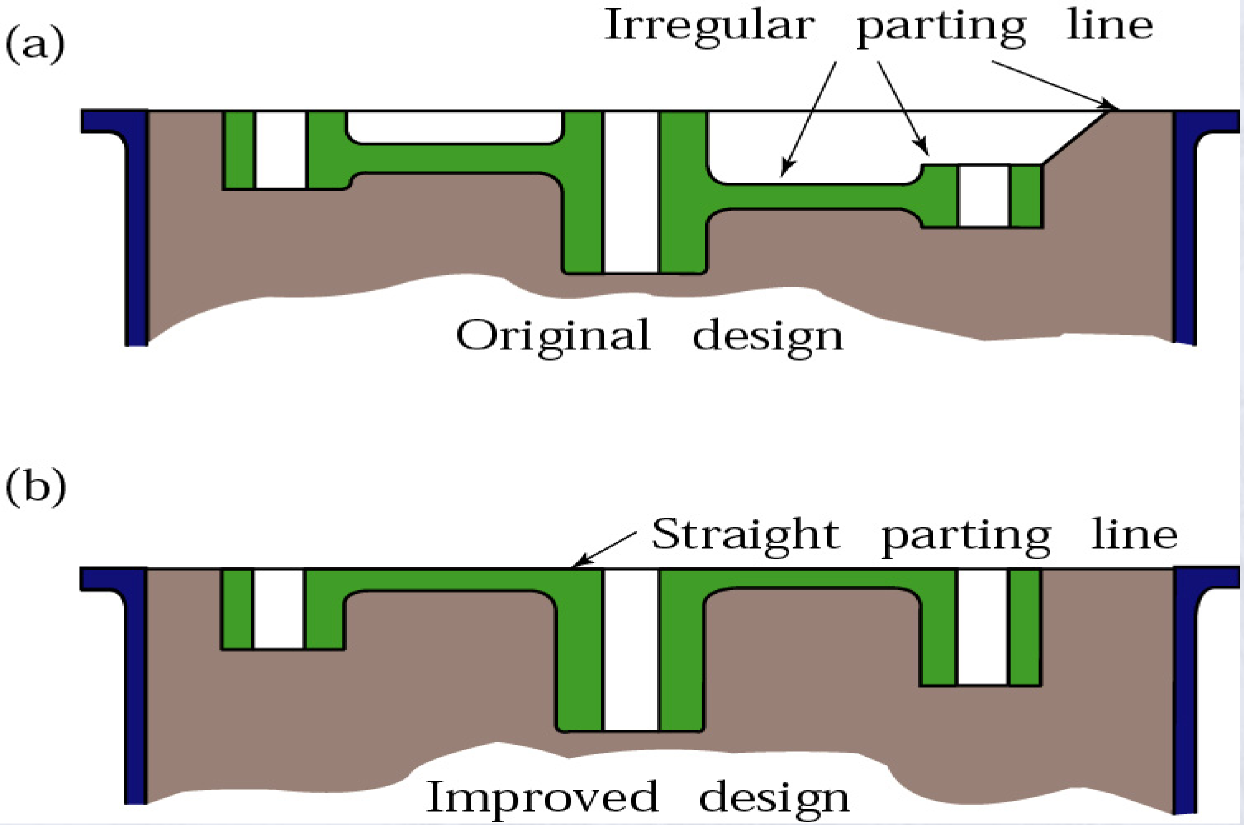

Figure 12.5 Redesign of a casting by making the parting line straight to avoid defects.

Design Considerations in Casting - Locating and designing gates

– The gates are connections between the runners and the part cavity. Some of the considerations in designing gating systems are:
– Multiple gates often are preferable and are necessary for large parts.
– Gates should feed into thick 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 far away so that the gate can be easily removed. This distance may be as small as a few mm for small casting and up to 500 mm for large parts.

Design Considerations in Casting - Locating and designing gates

- The minimum gate length should be three to five times the gate diameter, depending on the metal being cast. The 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, but when necessary, a straight section in the gate should be located immediately adjacent to the casting.

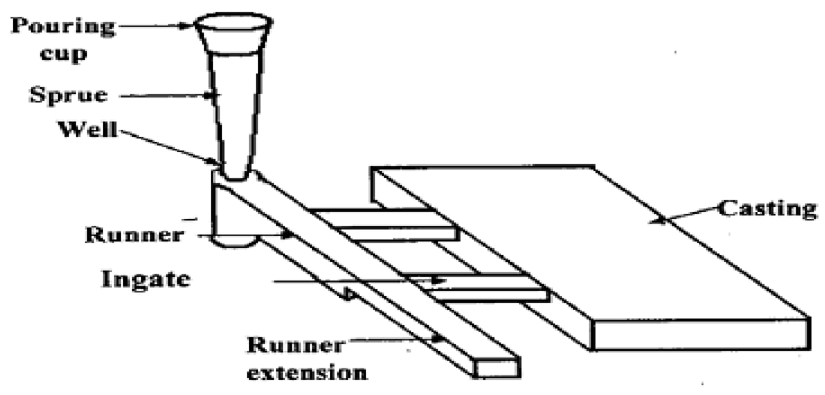

Figure 1: Gating system

Design Considerations in Casting - Runner design

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

Design Considerations in Casting - Designing other mold features

- The main goal in designing a sprue is to achieve the required metal flow rates while preventing excessive dross formation.
- Flow rates are determined such that ***turbulence is avoided***, but the ***mold is filled quickly 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 molten metal is maintained in the pouring basin during pouring, then the dross will float and will not enter the mold cavity.
- ***Filters*** are used to trap large contaminants and to slow 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.

Design Considerations in Casting - Establishing good practices

- Some ***quality control*** procedures are necessary:
  - 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 the metal being poured into a mold.
  - The pouring of the metal should ***not be <u>interrupted</u>***, since it can lead to dross entrainment and turbulence.
  - The <u>different cooling rates</u> within the body of a casting cause residual stresses. Stress relieving (section 4.11) thus may necessary to avoid distortions of castings in critical applications.

Design for expendable-mold casting

A.Mold layout.

- One of the most important goals in mold layout is to have solidification initiate at one end of the mold and progress in a uniform font a cross the casting with ***risers solidifying last***.
- Traditionally, this depends on experience and consideration of fluid flow and heat transfer.
- More recently, commercial computer programs based on finite-difference algorithms have become available.

Design for expendable-mold casting

B. Riser design.

- Risers (size and location) are extremely useful in affecting-front progression across a casting and are essential feature in the mold layout. ***Blind risers*** are good design features and maintain heat longer than open risers.
- **Risers are designed according to six basic rules:**

1. The riser ***must not*** solidify before the casting.
2. The riser volume must be large enough to provide a sufficient amount of liquid metal to ***compensate for shrinkage*** in the cavity.

Design for expendable-mold casting- Riser design

- **Risers are designed according to six basic rules:**

3. Junctions between casting and feeder should not develop a hot spot where shrinkage porosity can occur.
4. Risers must be placed so that the liquid metal can be delivered to locations where it is ***most needed.***
5. There must be ***sufficient pressure*** to drive the liquid metal into locations in the mold where it is most needed.
6. The pressure head from the riser should ***suppress*** cavity formation and encourage complete cavity filling.

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Design for expendable-mold casting

C. Machining allowance.

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

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Design for permanent-mold casting

- Example 12.3 shows several examples of poor and good designs in permanent-mold and die casting:

a. Lower portion of the design has a thin wall which may fracture under high forces. The good design eliminates this problem and also may simplify die and mold manufacturing.
b. Large flat surfaces may warp and develop uneven surfaces. We may break up the surfaces with ribs and serrations (dents) on the reverse side of the casting.
c. It is difficult to produce sharp internal radii or corners. Placement of a small radius at the corners at the bottom of the part
d. This part may represent a knob to be gripped and rotated. The casting die for the good design is easier to manufacture.
e. Poor design has sharp fillets. Good design prevents the die edges from chipping off.
f. The poor design has threads reaching the right face of the casting. The good design uses an offset on the threaded rod, eliminating this problem.

Examples of Good and Poor Designs

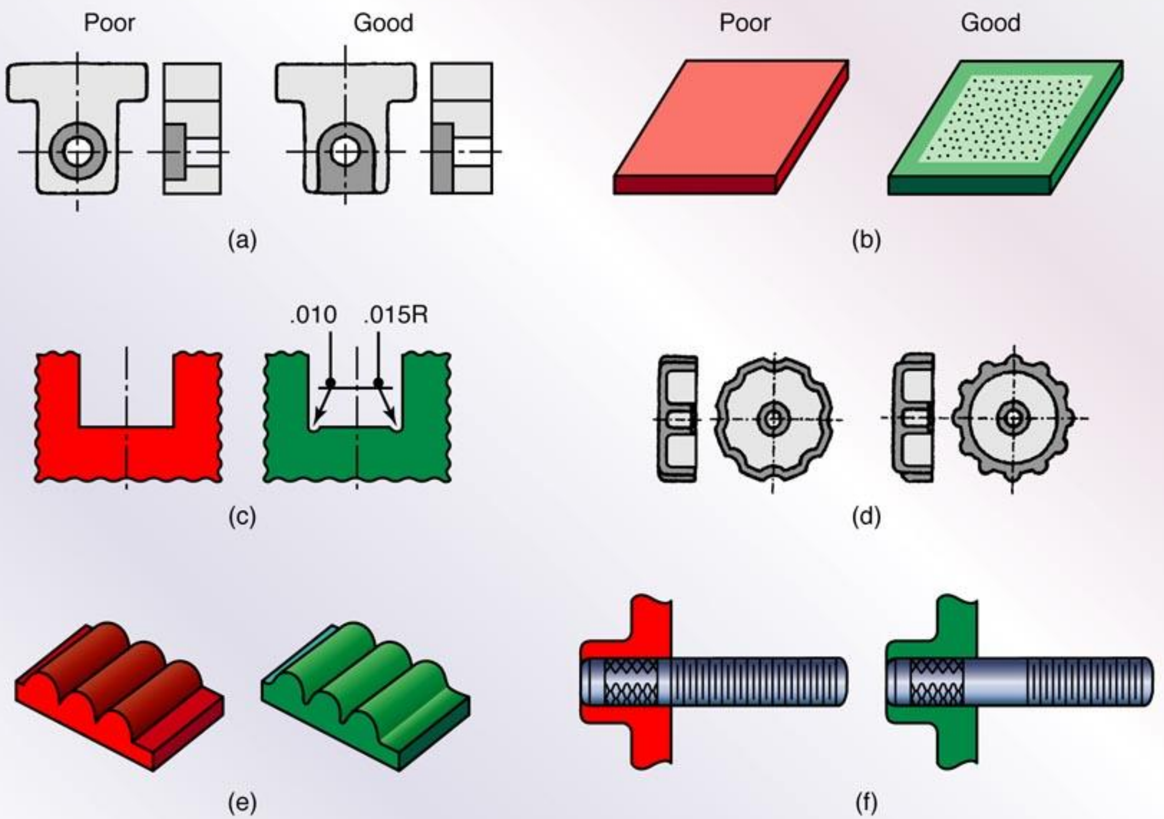

Figure 12.3 Examples of undesirable (poor) and desirable (good) casting designs. *Source:* Courtesy of American Die Casting Institute.

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Computer modeling of casting processes

- Rapid advances in computers and modeling analysis led innovations in **modeling** different aspects of casting including: fluid flow, heat transfer, and microstructures developed during solidification; under various casting-process conditions.
- **Specifically, software may provide:**
  - Modeling fluid flow in molds (Bernoulli's and continuity). Predict velocity and pressure of the molten metal in the gating system all the way into the mold cavity.
  - Modeling of heat transfer in casting.
  - Fluid flow and heat transfer (with surface conditions, thermal properties of materials) are coupled.
  - Modeling the development of microstructure in casting.

Computer modeling of casting processes

- The benefits of such user-friendly software are to increase productivity, improve quality, and easily plan and estimate cost. Also quicker response to design changes.
- Several commercial software programs now are available for modeling of casting processes:

1. Magmasoft,
2. ProCast,
3. Solidia, and
4. AFSsolid.

Mechanical Properties for Cast Alloys

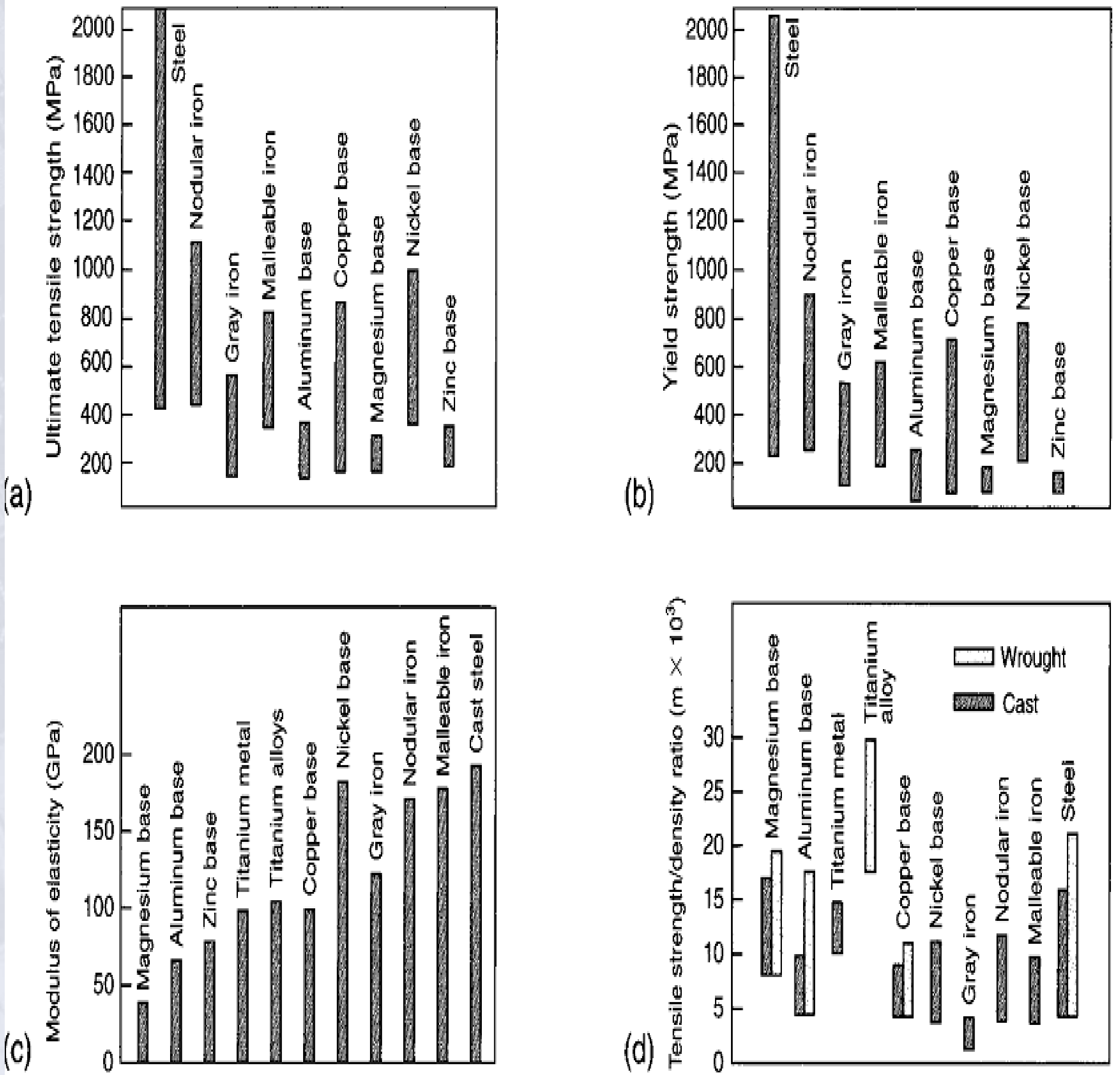

Figure 12.4 Mechanical properties for various groups of cast alloys. Note that even within the same group, the properties vary over a wide range, particularly for cast steels. *Source*: Courtesy of Steel Founders' Society of America.

Mechanical Properties for Cast Alloys

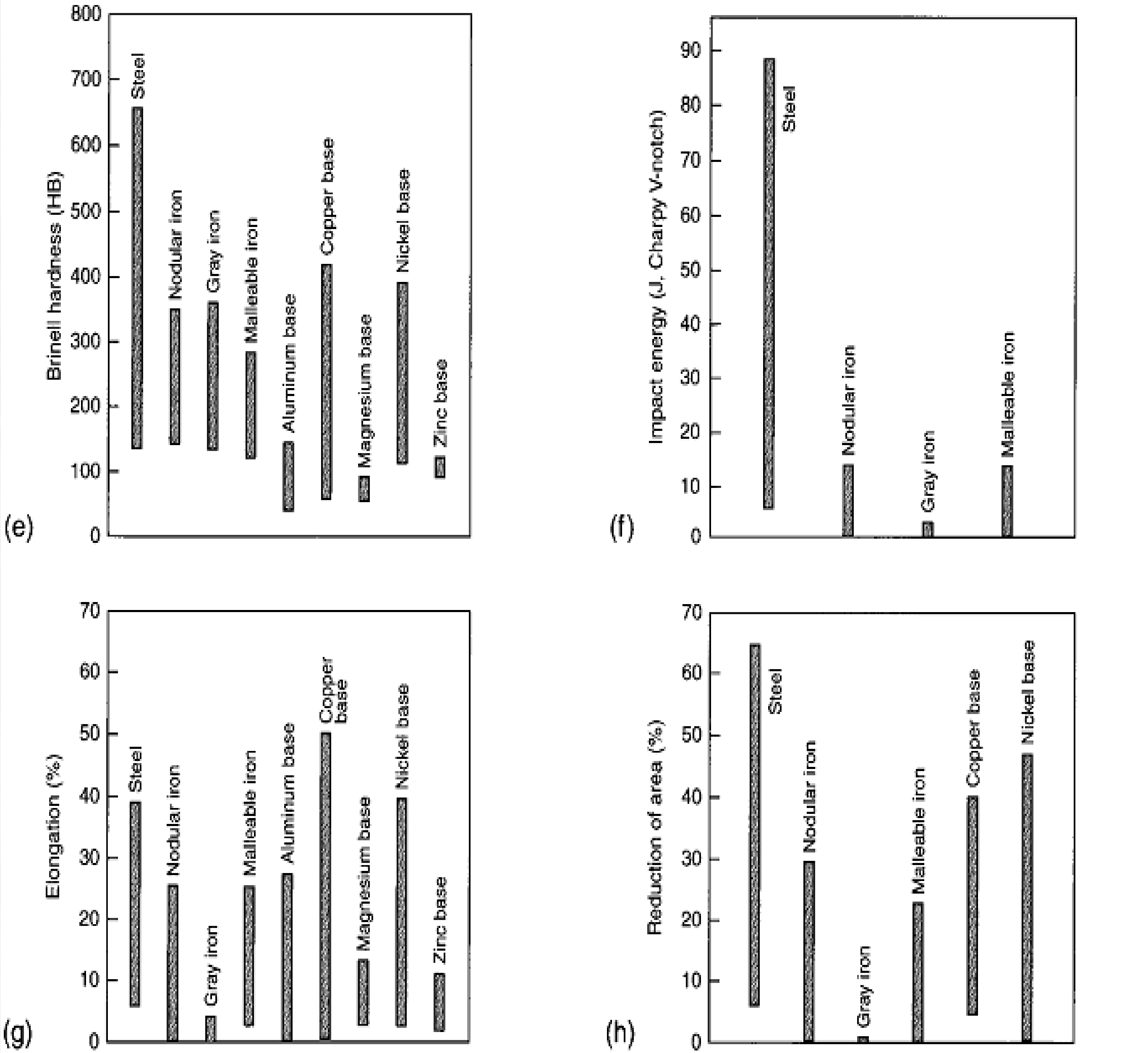

Figure 12.4 Mechanical properties for various groups of cast alloys. Note that even within the same group, the properties vary over a wide range, particularly for cast steels. *Source*: Courtesy of Steel Founders' Society of America.

Casting Applications and Characteristics

TABLE 12.2

Typical Applications for Castings and Casting Characteristics

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

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

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Nonferrous Casting Alloys -Aluminum-based alloys

- High electrical conductivity and generally good atmospheric corrosion resistance; except for some acids.
- Nontoxic, lightweight, and good machinability.
- Generally low resistance to wear except for alloys with silicon.
- Used in architectural and decorative applications. Used in automobiles for engine blocks, cylinder heads, transmission cases, wheels, and brakes.
- Parts made of Aluminum-based and magnesium-based alloys are known as light-metal castings.

Nonferrous Casting Alloys –Magnesium based alloys

- Lowest density of all commercial casting alloys.
- Good corrosion resistance and moderate strength.
- Used in automotive wheels, housings, and air-cooled engine blocks

Nonferrous Casting Alloys –Copper based alloys

- Somewhat expensive.
- Good electrical and thermal conductivity, corrosion resistance, and non toxicity.

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Nonferrous Casting Alloys –Zinc based alloys

- Low-melting point.
- Good corrosion resistance, good fluidity, and sufficient strength for structural applications.
- Used in die casting.

Nonferrous Casting Alloys –Tin based alloys

- Low in strength.
- Good corrosion resistance, and typically used for bearing surfaces.

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Nonferrous Casting Alloys –Lead based alloys

– Application similar to tin-based alloys.
– Toxicity is a major drawback of lead.

Nonferrous Casting Alloys –High temperature alloys

- Typically require temperature of up to 1650 for casting titanium and higher for refractory alloys (Molybdenum-2617^{o} C, Niobium-2468^{o} C, Tungsten-3410^{o} C).
- Special techniques are used to cast these alloys.

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Properties and Applications of Nonferrous Cast Alloys

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
Leaded tin bronze (C92500)	Annealed	260	105	35	Gears, bearings, valves
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

Ferrous Casting Alloys

1. **Cast Irons.** Represent the largest quantity of all metal cast. They process several desirable properties such as wear resistance, hardness, and good machinability. Represent a family of alloys (section 4.6) – see Tables 12.3 & 12.4:
    - **Gray cast iron.**
    - **Ductile (nodular) iron.**
    - **White cast iron.**
    - **Maleable iron.**
    - **Compacted graphite iron.**

Ferrous Casting Alloys

2. **Cast Steels.** Need high temperature to melt cast steels (up to 1650o). Casting requires considerable experience. If welded, need to be heat treated to restore mechanical properties. Used in equipment for railroads, mining, chemical plants, oil fields, and heavy constructions.
3. **Cast Stainless Steels.** Generally have long freezing ranges and high melting temperatures. Available in various compositions, and they can be heat treated and welded. Such products have high heat and corrosion resistance, specially in the chemical and food industry.

Properties and Applications of Cast Irons

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
	Pearilitic	275	240	0.4	Engine blocks, machine tools
	Martensitic	550	550	0	Wear surfaces
Ductile	Ferritic	415	275	18	Pipe, general service
(Nodular)	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

Mechanical Properties of Gray Cast Irons

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

Economics of Casting

- The cost of the cast part (unit cost) depends on several factors: including materials, tooling, equipment, and labor.
- Preparations for casting a product include the production of molds and dies that require raw materials, time, and effort – all of which also influence product cost.
- As shown in table 12.6, relatively little cost is involved in molds for sand casting. On the other hand, molds for various processes and die-casting dies require expensive materials and a great deal of preparation.

Cost Characteristics of Casting

TABLE 12.6

General Cost Characteristics of Casting Processes

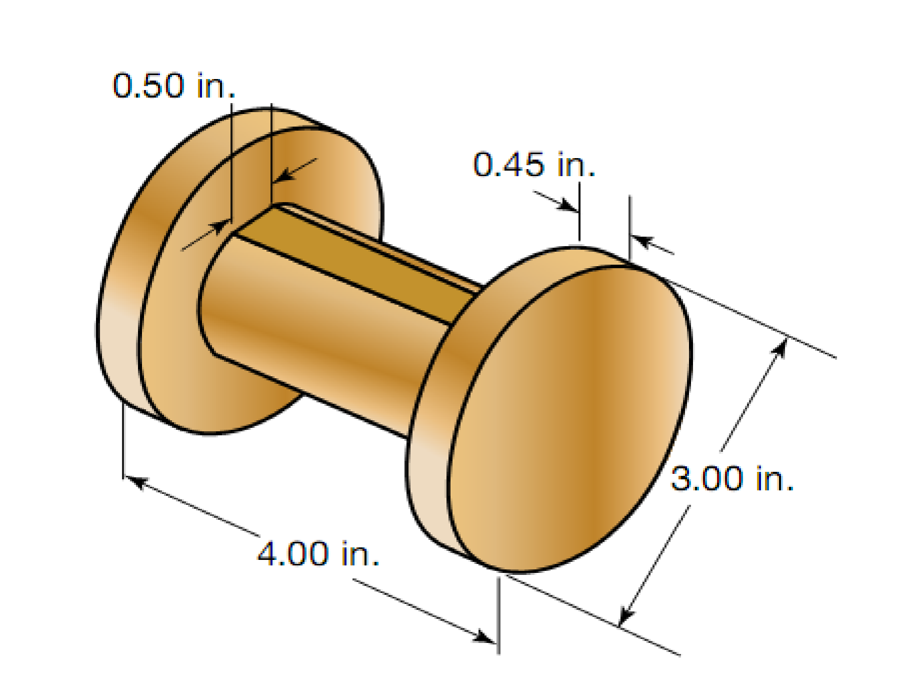
Casting process	Cost* Die	Equipment	Labor	Production rate (pieces/hr)
Sand	L	L	L–M	<20
Shell mold	L–M	M–H	L–M	<50
Plaster	L–M	M	M–H	<10
Investment	M–H	L–M	H	<1000
Permanent mold	M	M	L–M	<60
Die	H	H	L–M	<200
Centrifugal	M	H	L–M	<50

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

Economics of Casting

- There are also major costs involved in making patterns for casting.
- Costs also are involved in melting and pouring the molten metal into molds and in heat treating, cleaning, and inspecting the casting.
- Heat treatment in an important part of the production of many alloys groups (especially ferrous castings) and may be necessary to produce improved mechanical properties.
- The equipment cost per casting will decrease as the number of parts cast increase. Sustained high-production rates, therefore, can justify the high cost of dies and machinery.
- However, if the demand is relatively small, the cost-per-casting increases rapidly. It then becomes more economical to manufacture the parts by sand casting.

Home Work



- The part shown in the figure is to be sand cast out of an aluminum casting alloy. Make a sketch (design) of the wooden pattern for this part. Include all necessary allowances for shrinkage and machining. Use any design software for drawing

A. one piece pattern

B. Two piece pattern