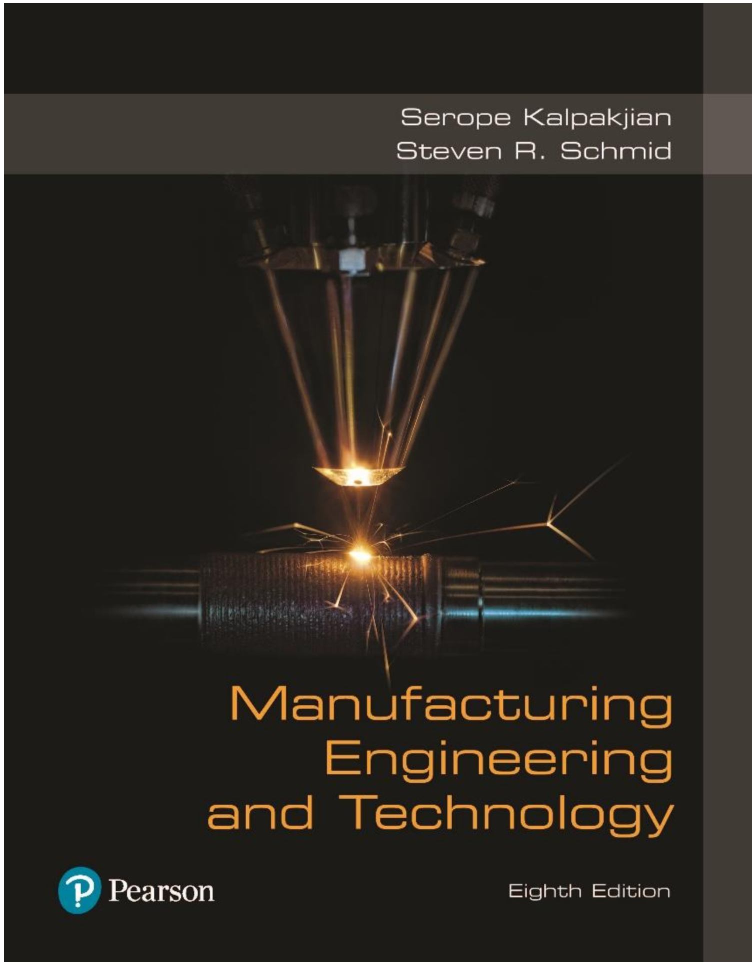
Manufacturing Engineering and Technology

Eighth Edition



Chapter 10-12

Fundamentals of Metal Casting

Pearson

Figure II.1

(a) Examples of cast parts. (b) A tree of rings produced through investment casting.

(a)

(b)

Source: (a) Shutterstock/Mr.1 (b) Courtesy of Romanoff, Inc.

Figure II.2

Cast parts in a typical automobile.

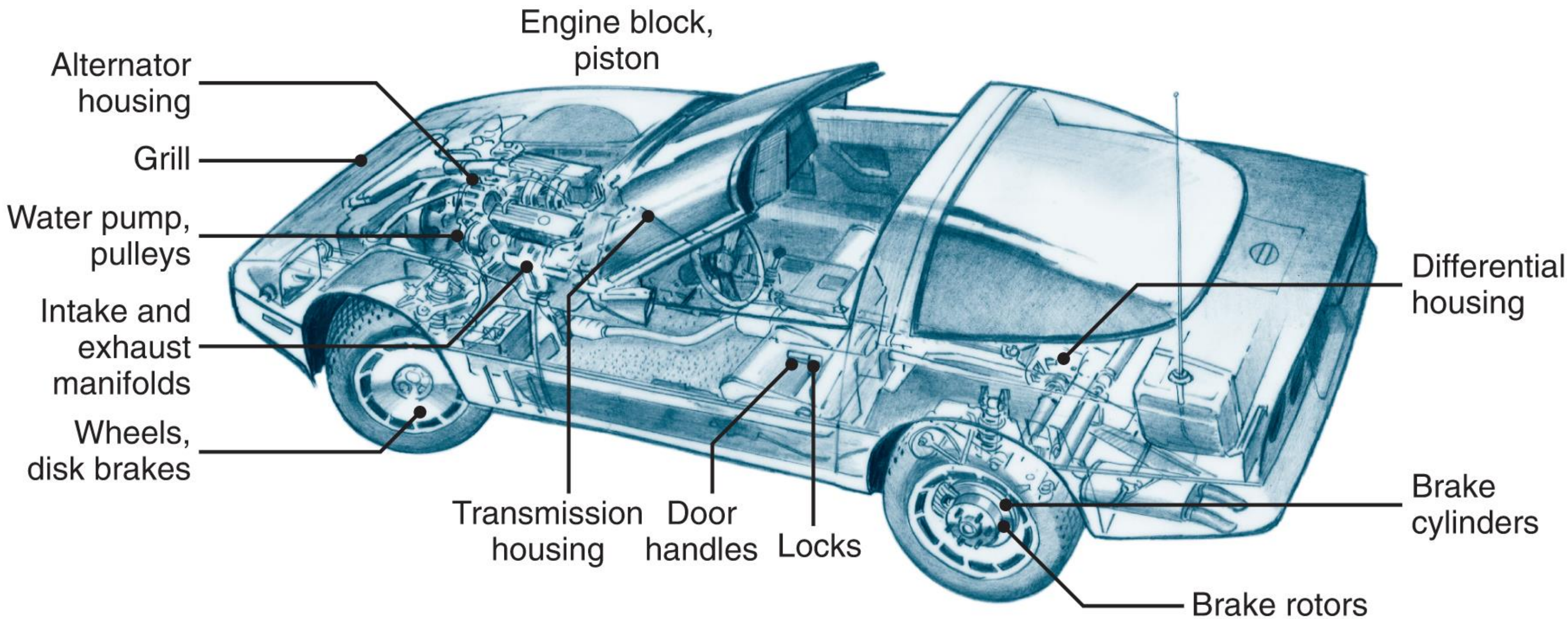


Figure II.3

Outline of metal-casting processes described in Part II.

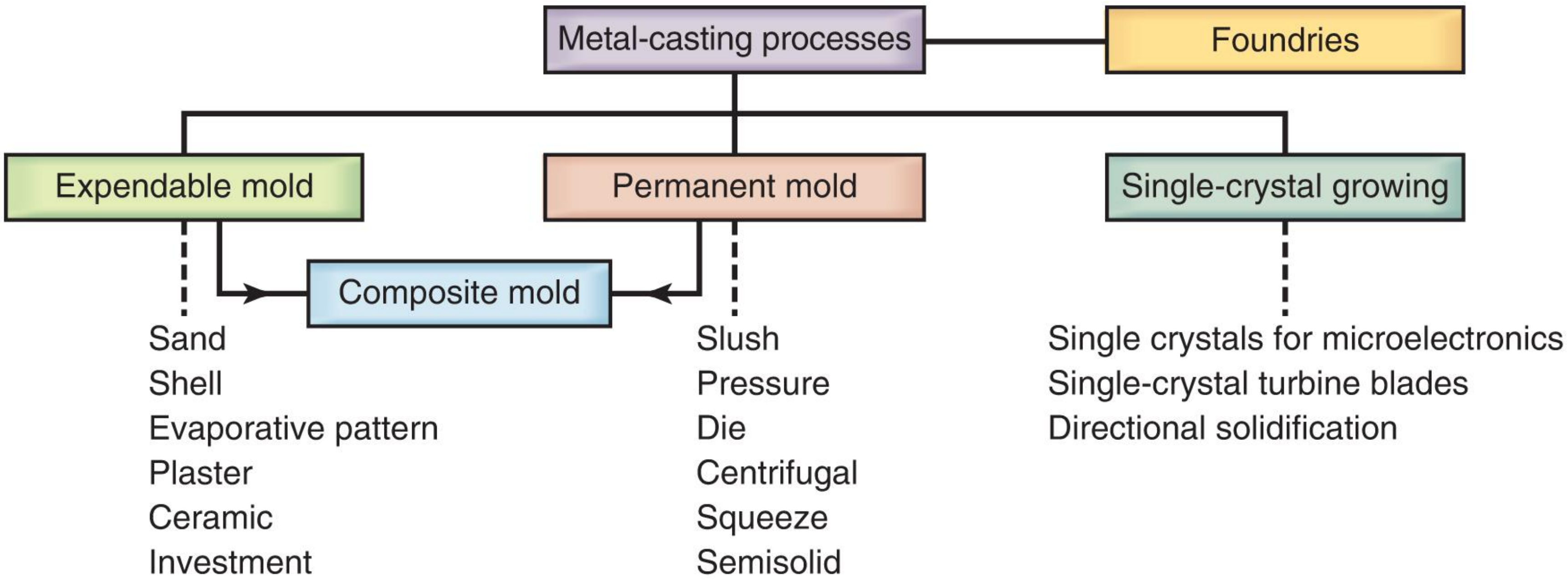


Figure 10.1

(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.

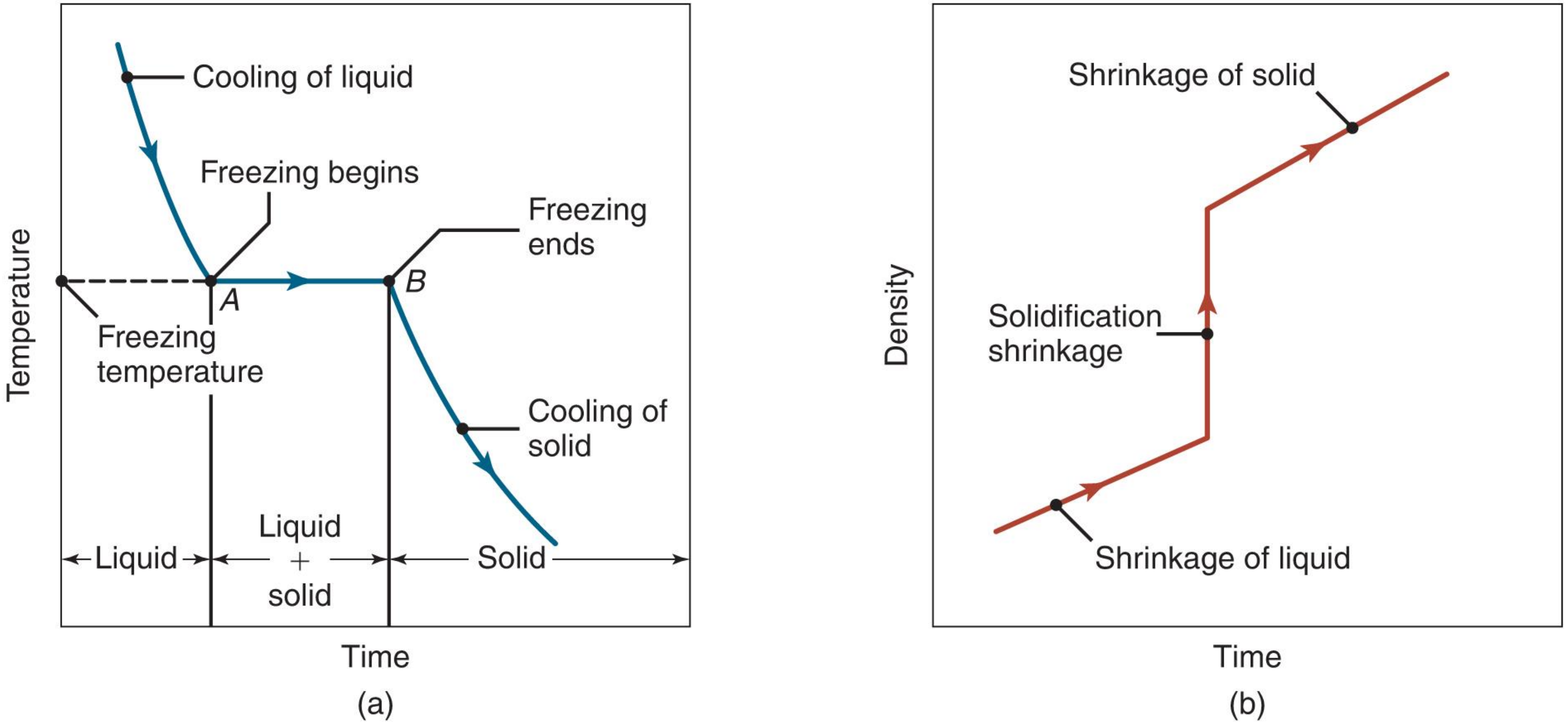


Figure 10.2

Schematic illustration of three cast structures of metals solidified in a square mold: (a) pure metals. (b) solid–solution alloys. (c) structure obtained by using nucleating agents.

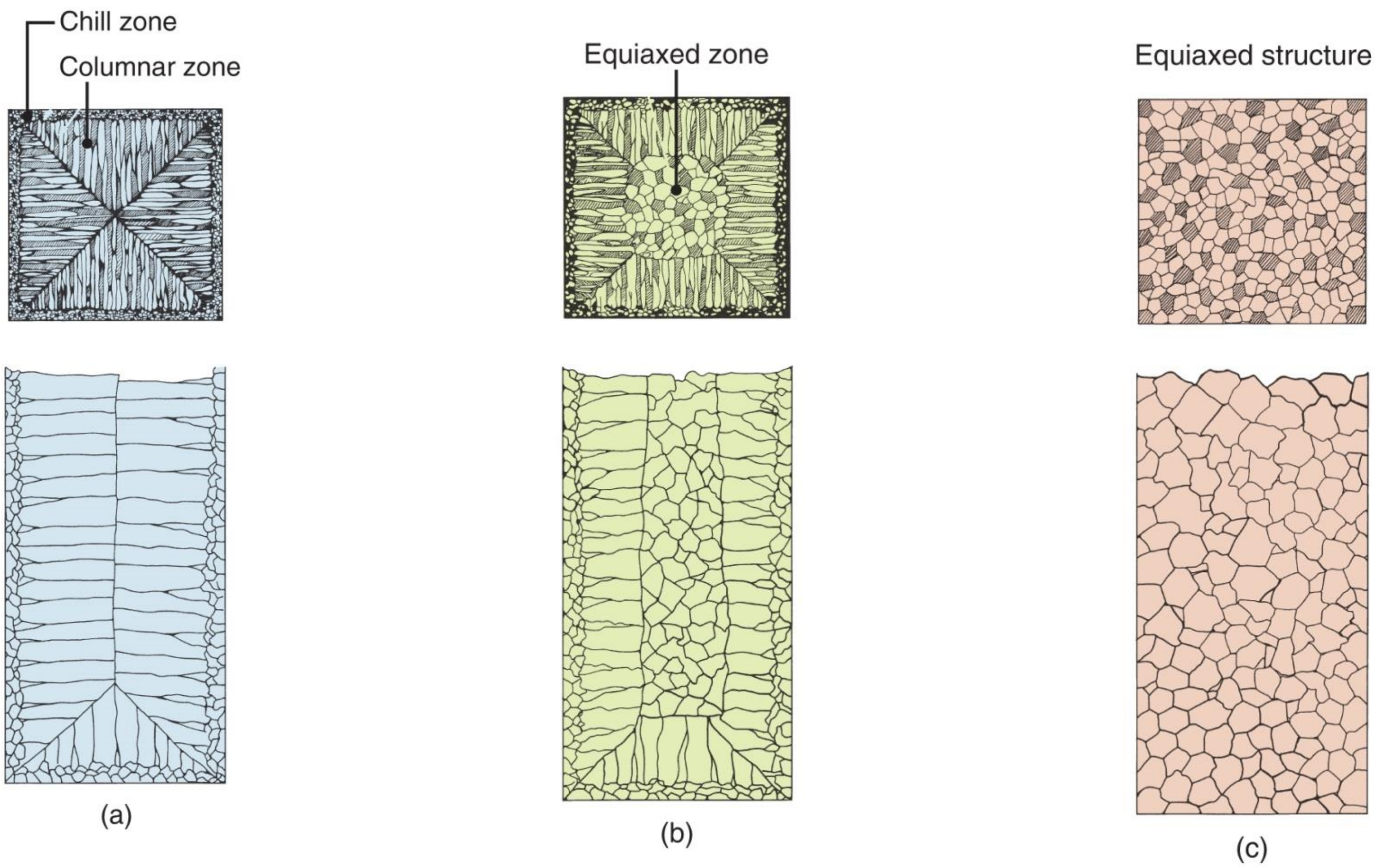


Figure 10.3

Development of a preferred texture at a cool mold wall; note that only favorably oriented grains grow away from the surface of the mold.

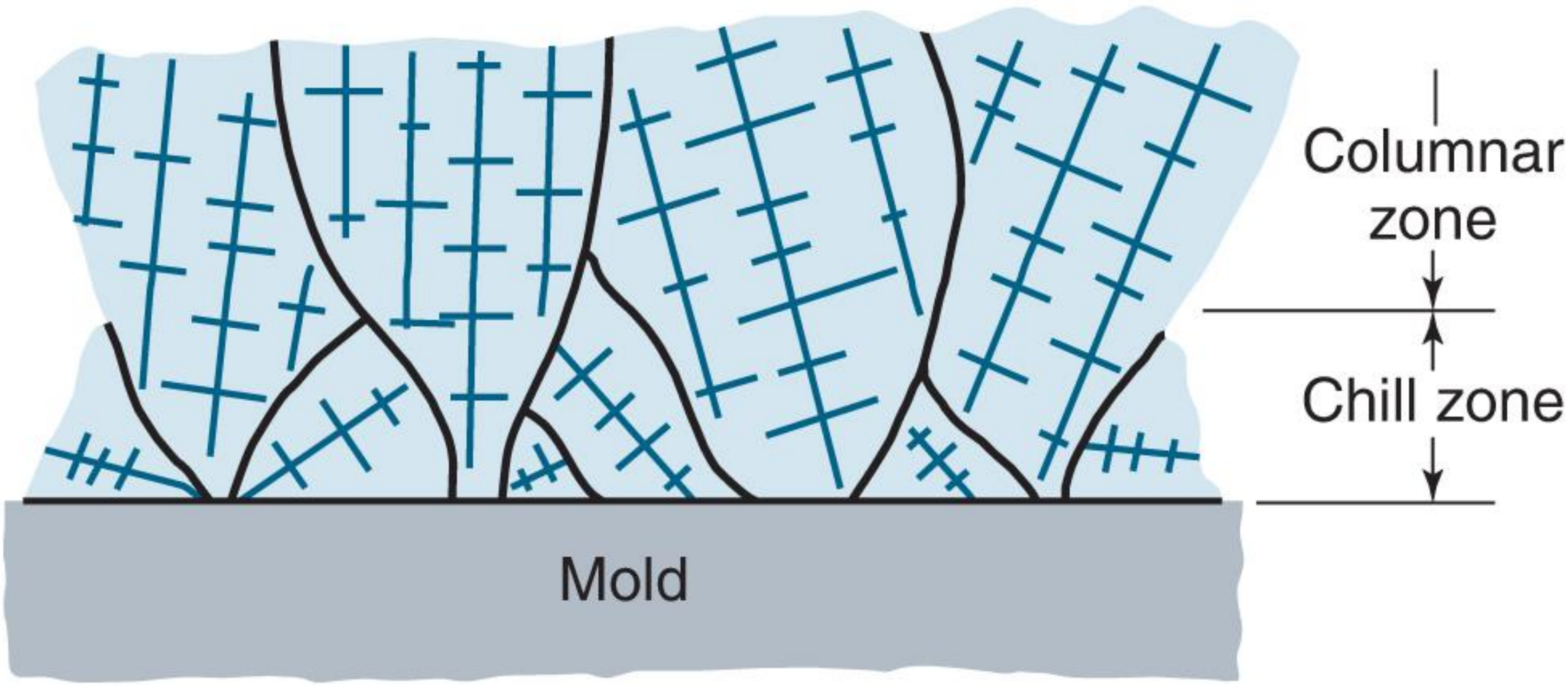


Figure 10.4

Schematic illustration of alloy solidification and temperature distribution in the solidifying metal. Note the formation of dendrites in the mushy zone.

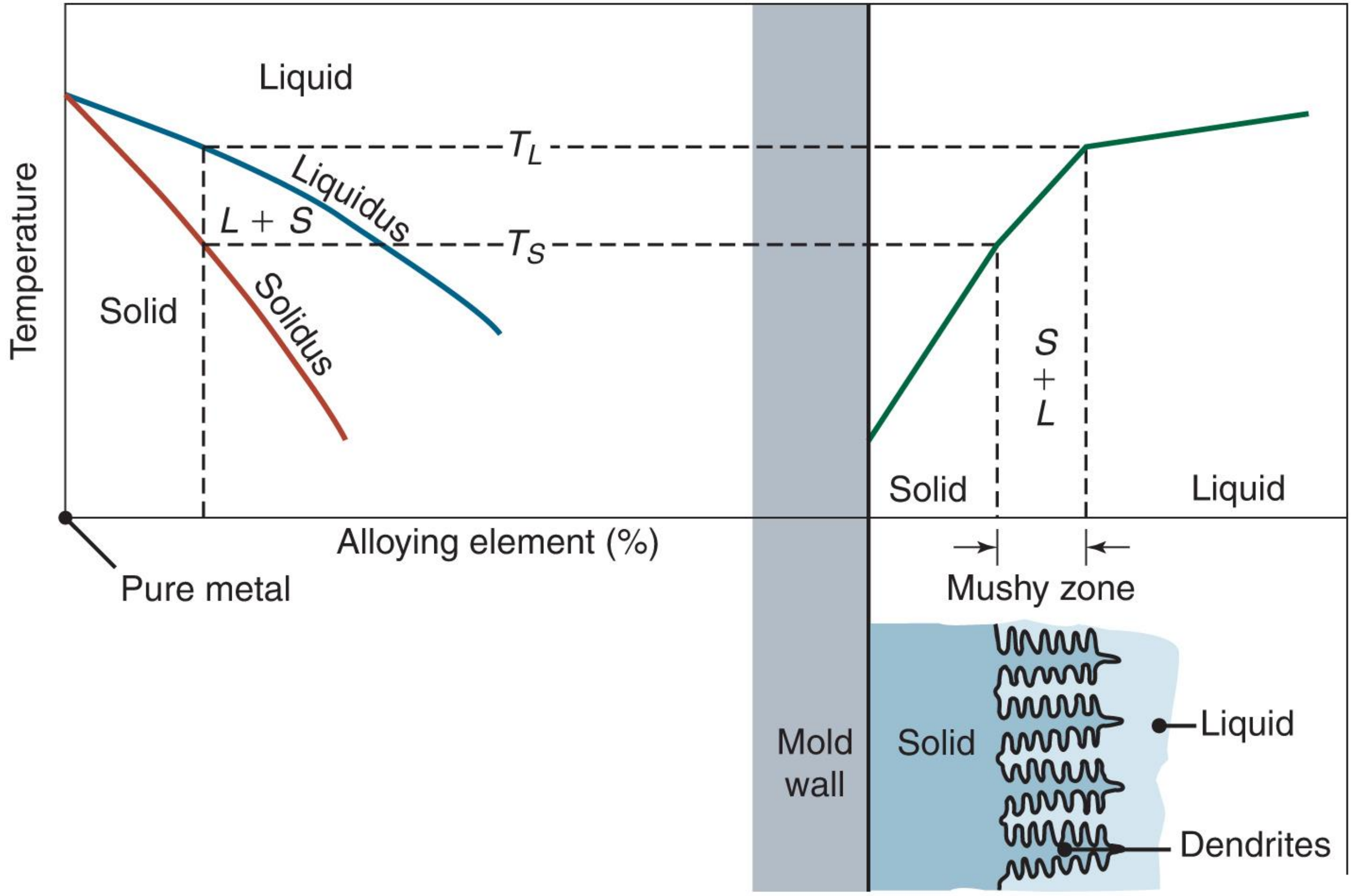


Figure 10.5

(a) Solidification patterns for gray cast iron in a 180-mm (7-in.) square casting. Note that after 11 minutes of cooling, dendrites begin to reach each other, but the casting is still mushy throughout. It takes about 2 hours more 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 of the metal increases.

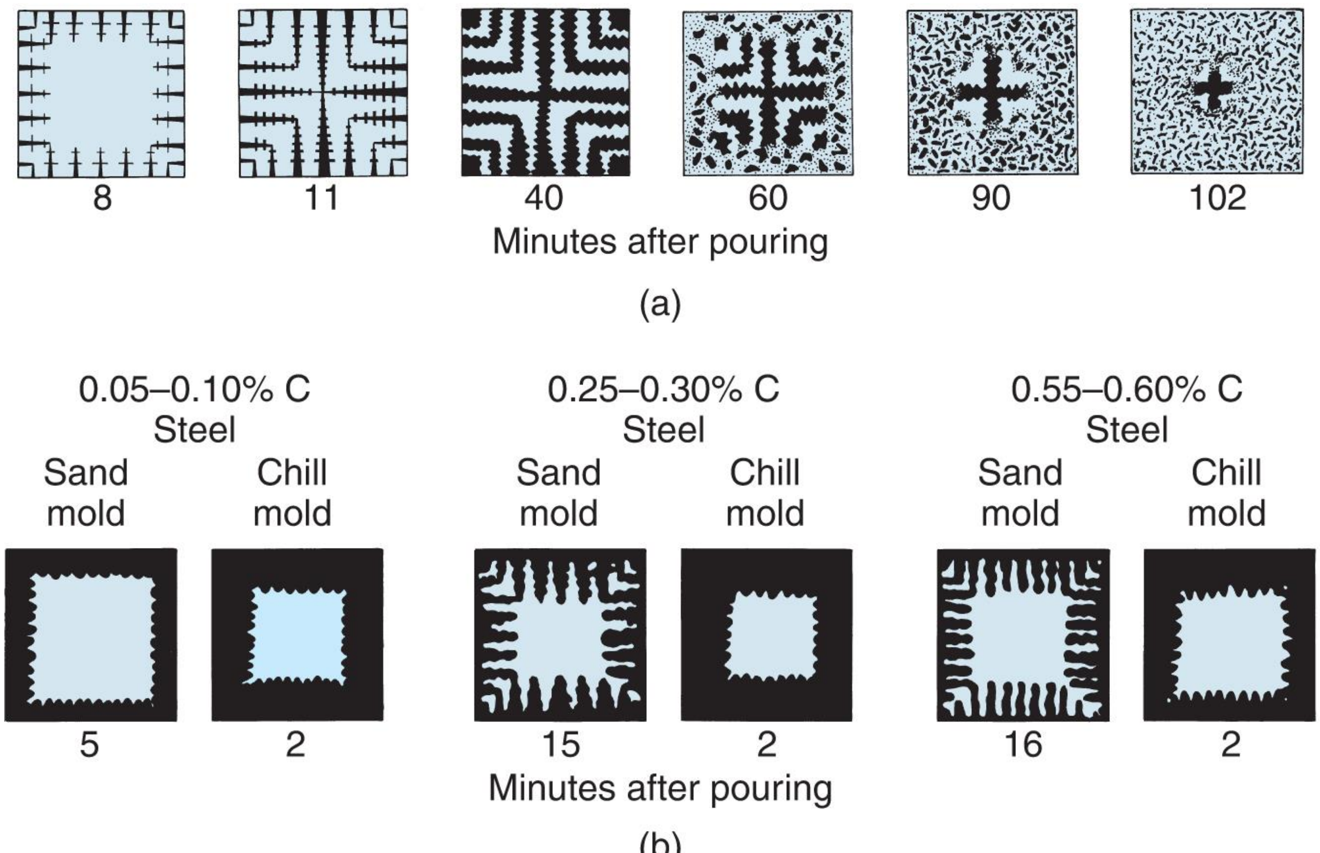


Figure 10.6

Schematic illustration of three basic types of cast structures: (a) columnar dendritic. (b) equiaxed dendritic. (c) equiaxed nondendritic.

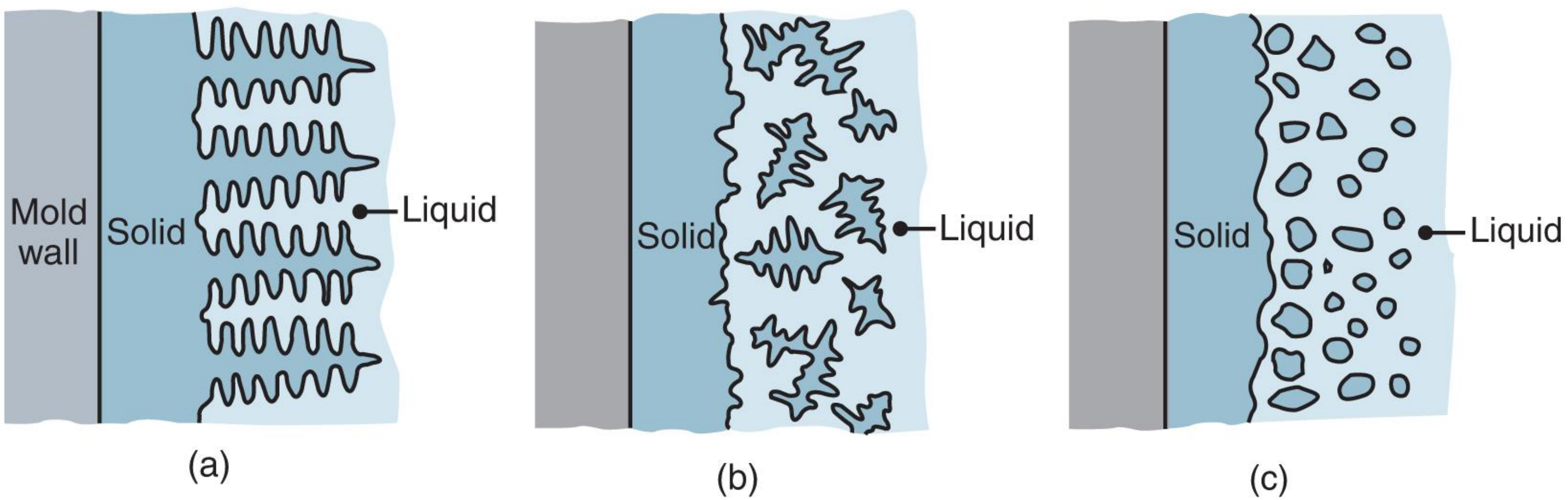


Figure 10.7

Schematic illustration of cast structures in (a) plane front, single phase. (b) plane front, two phase.

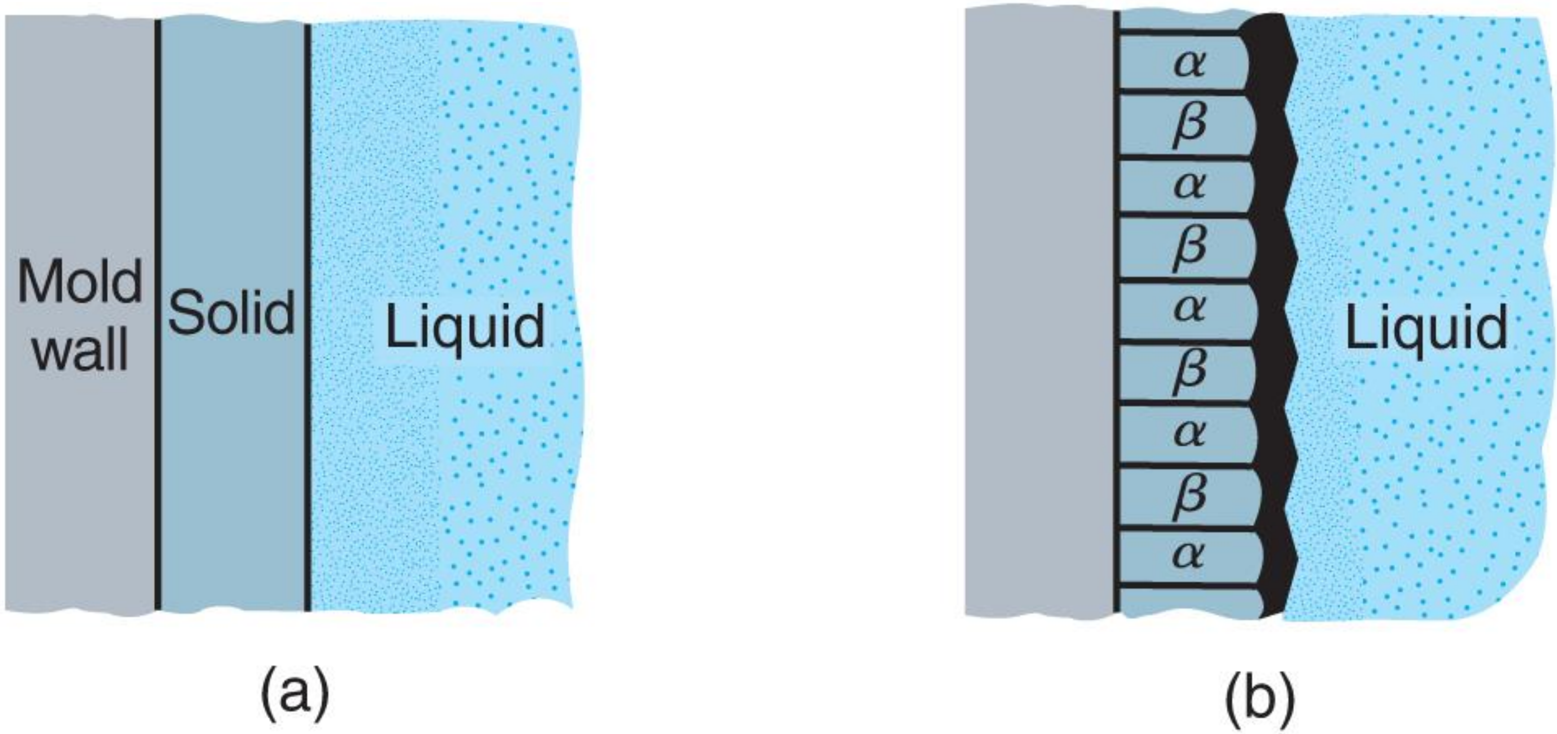


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Figure 10.10

Schematic illustration of a typical riser-gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification.

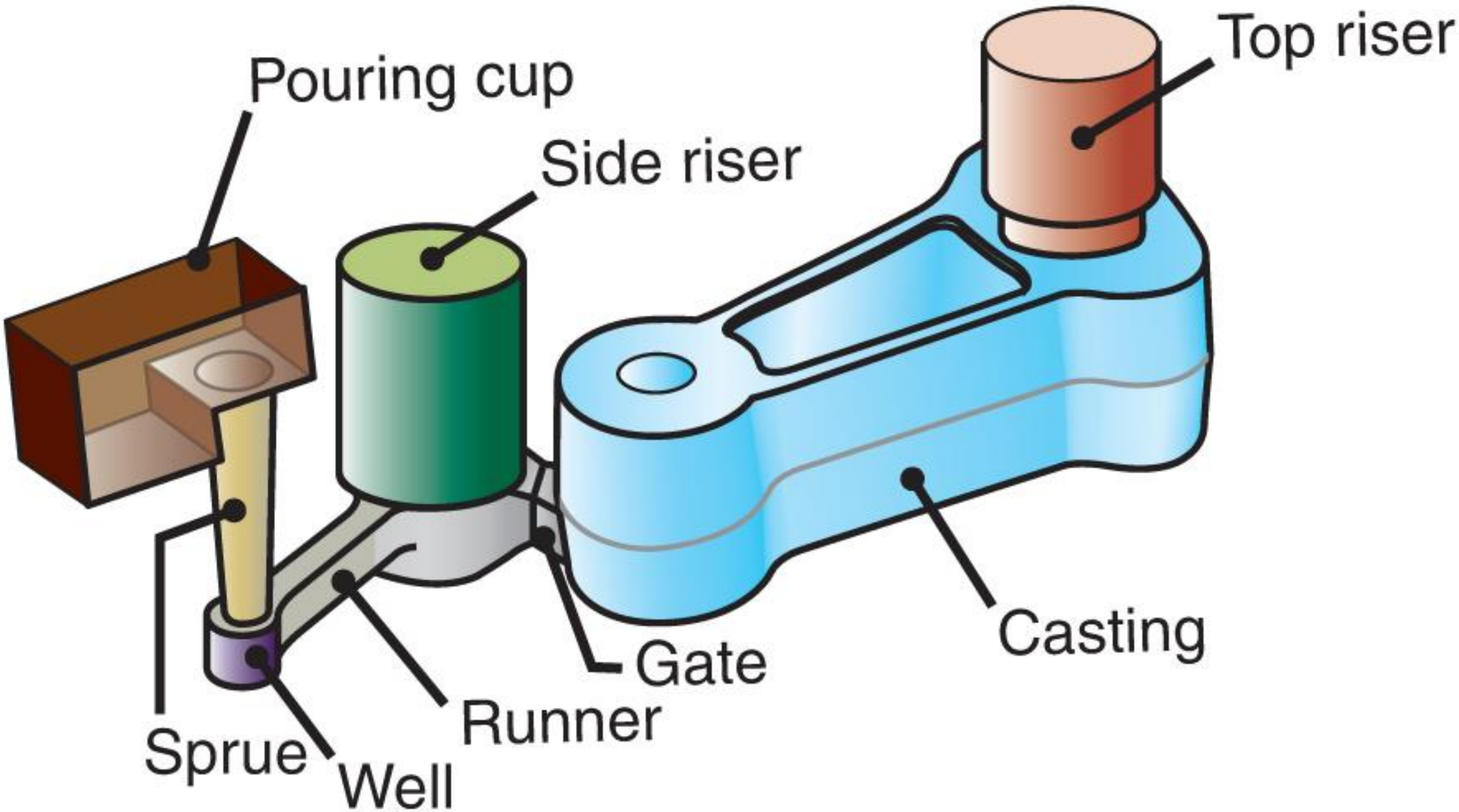


Figure 10.11

A test method for fluidity using a spiral mold. The fluidity index is the length of the solidified metal in the spiral passage. The greater the length of the solidified metal, the greater is the metal's fluidity.

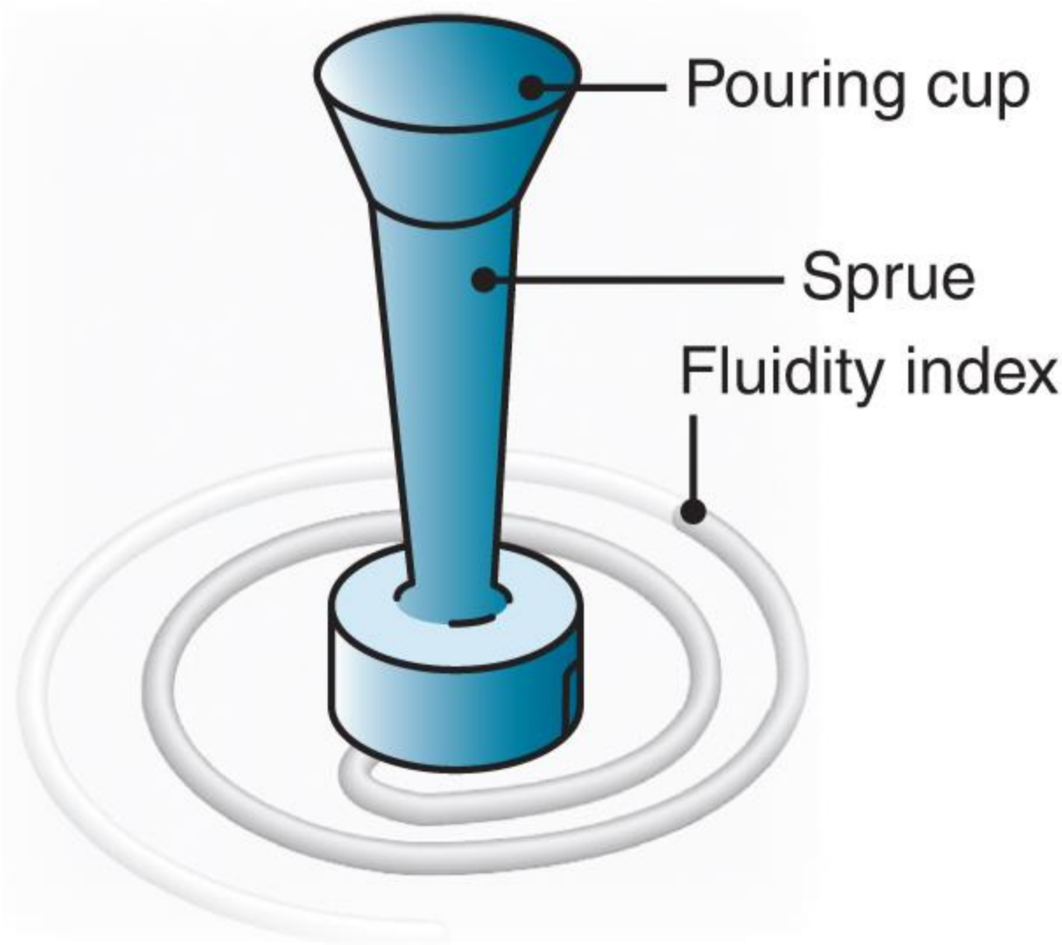


Figure 10.12

Temperature distribution at the interface of the mold wall and the liquid metal during the solidification of metals in casting.

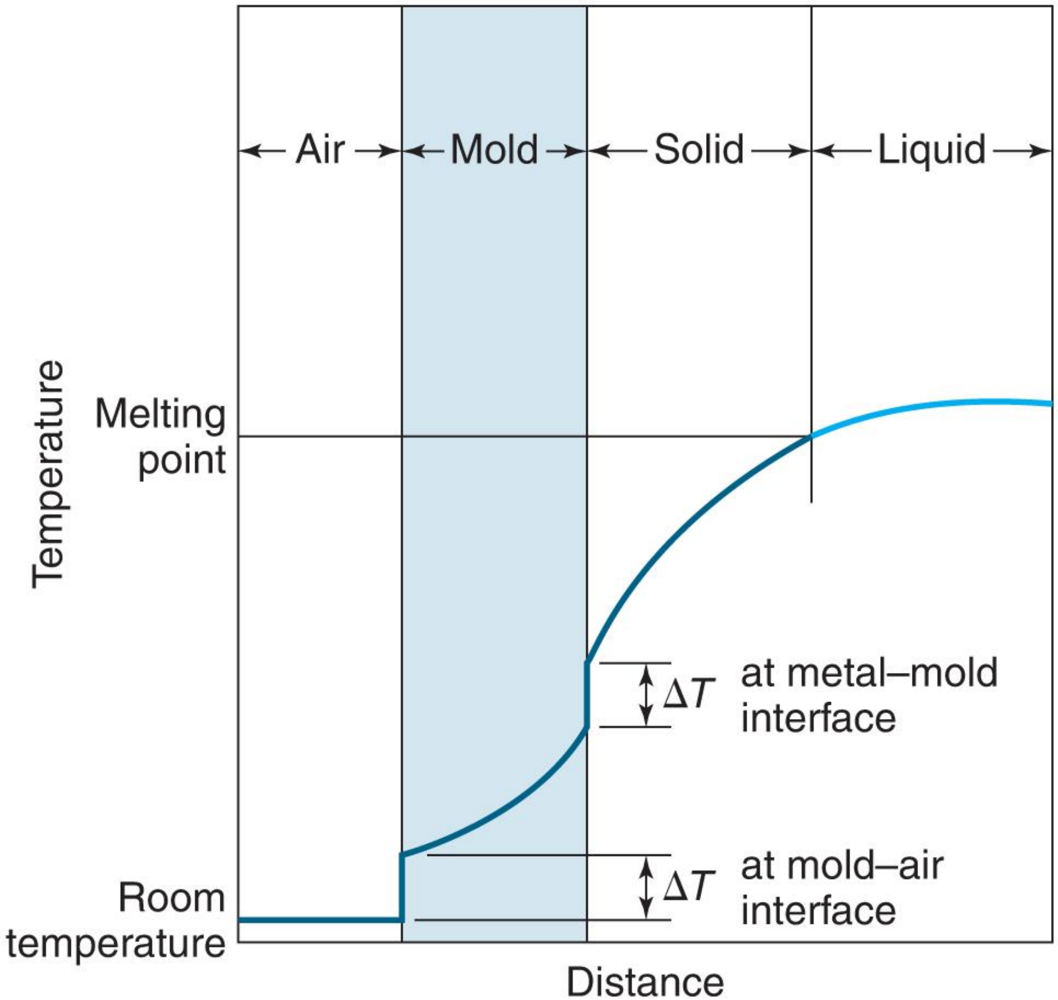
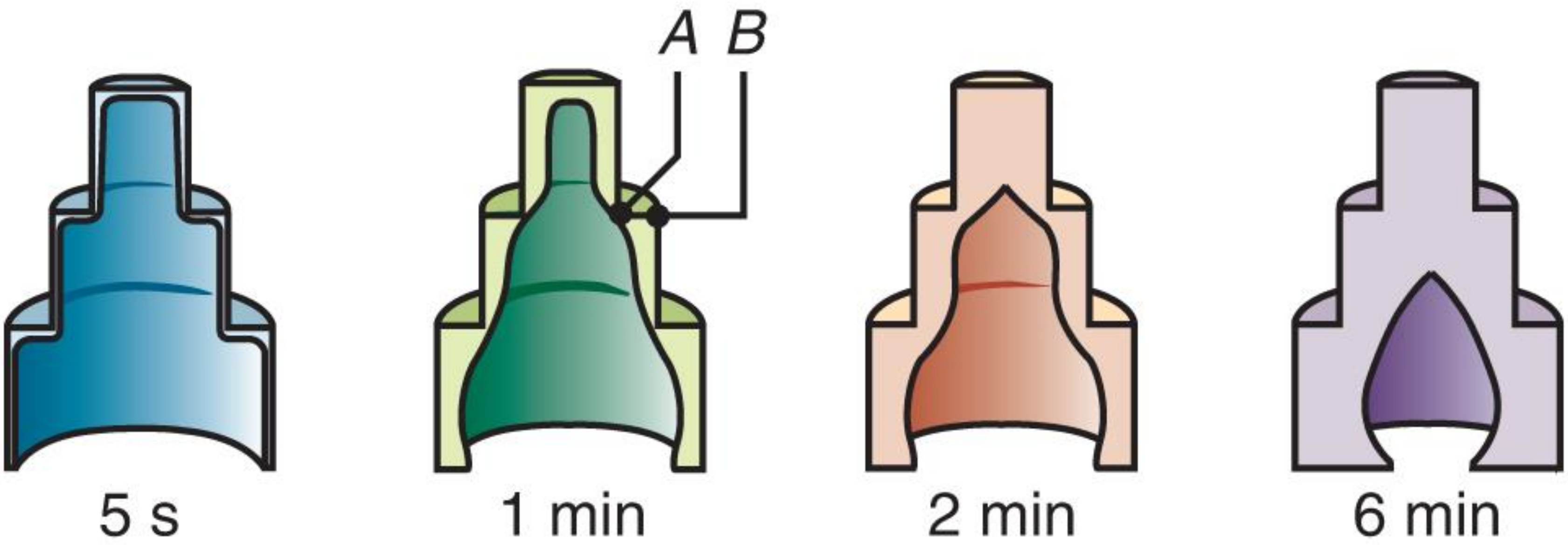


Figure 10.13

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.

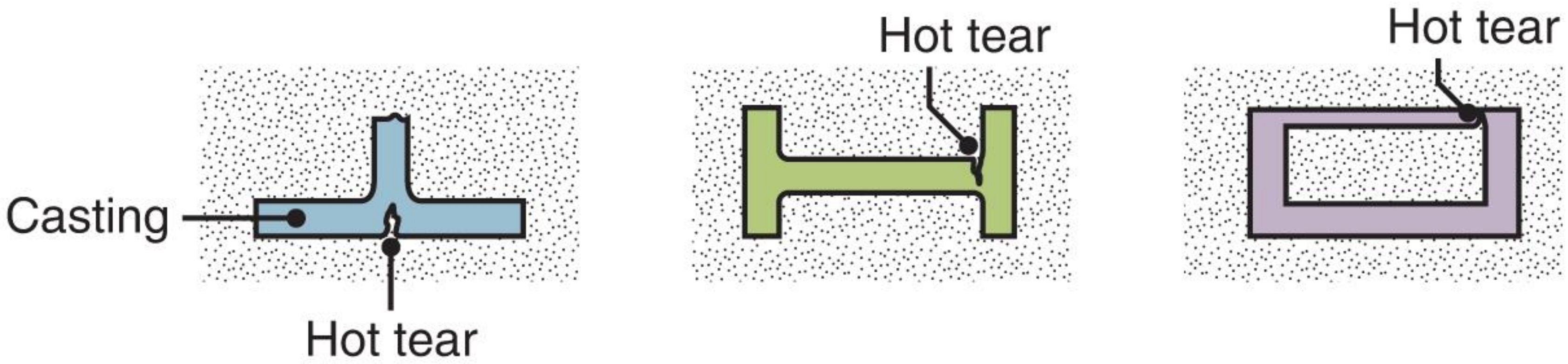
Table 10.1

Volumetric Solidification Contraction or Expansion for Various Cast Metals.

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		

Figure 10.14

Examples of hot tears in castings. These defects occur because the casting cannot shrink freely during cooling, owing to constraints in various portions of the molds and cores. Exothermic (heat producing) compounds may be used as *exothermic padding* to control cooling at critical regions to avoid hot tearing.



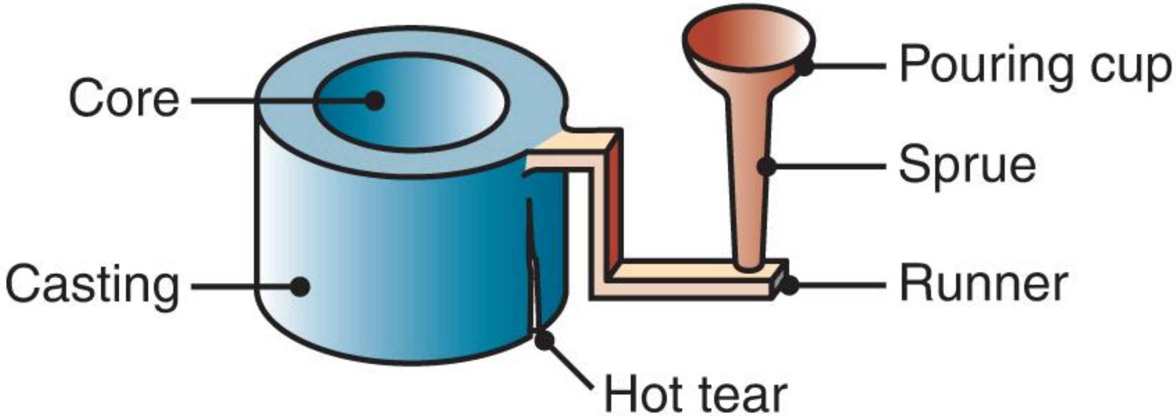


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Figure 10.15

Examples of common defects in castings. These defects can be minimized or eliminated by proper design and preparation of molds and control of pouring procedures.

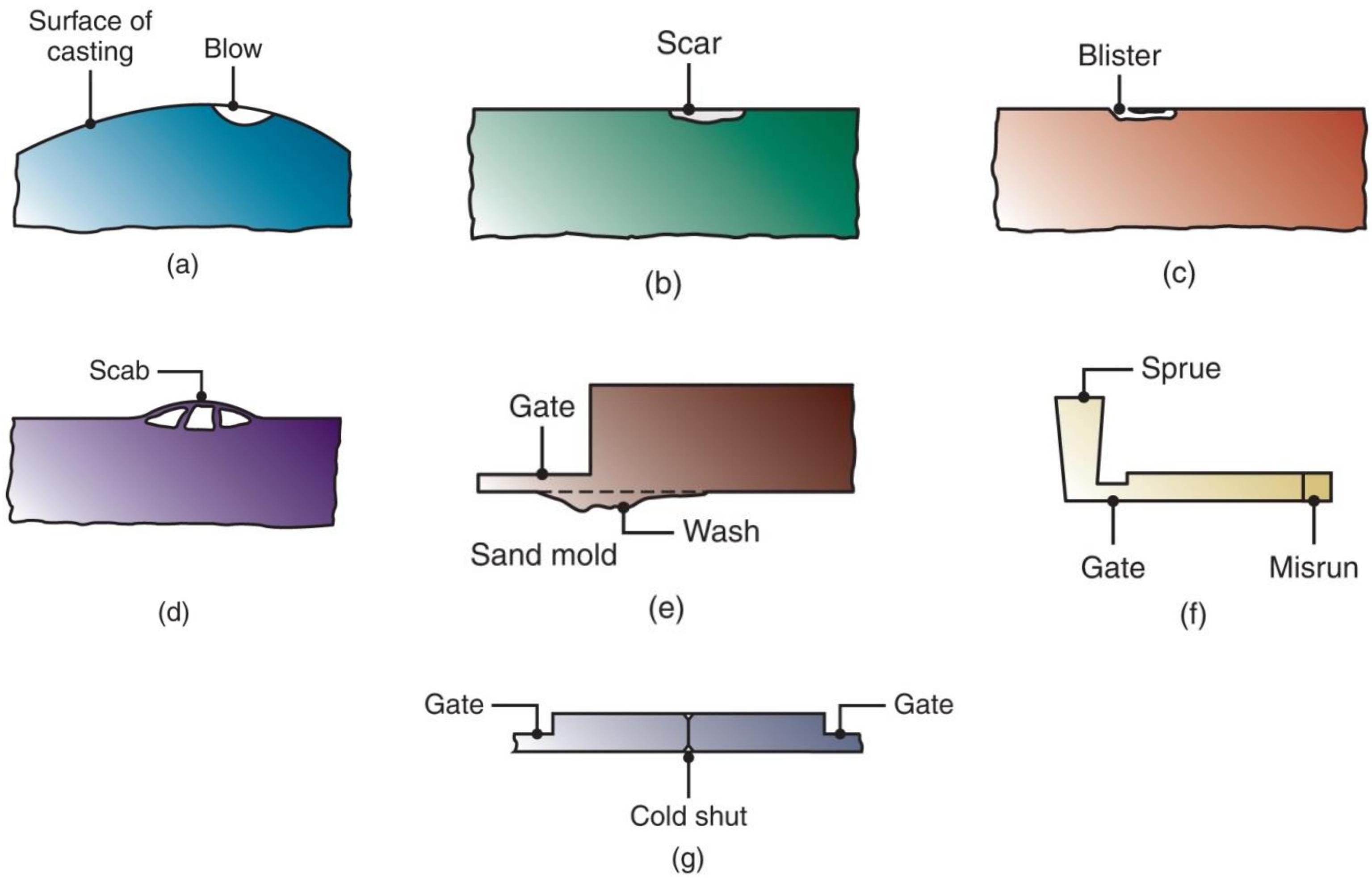

Figure 10.16 (1 of 3)

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).

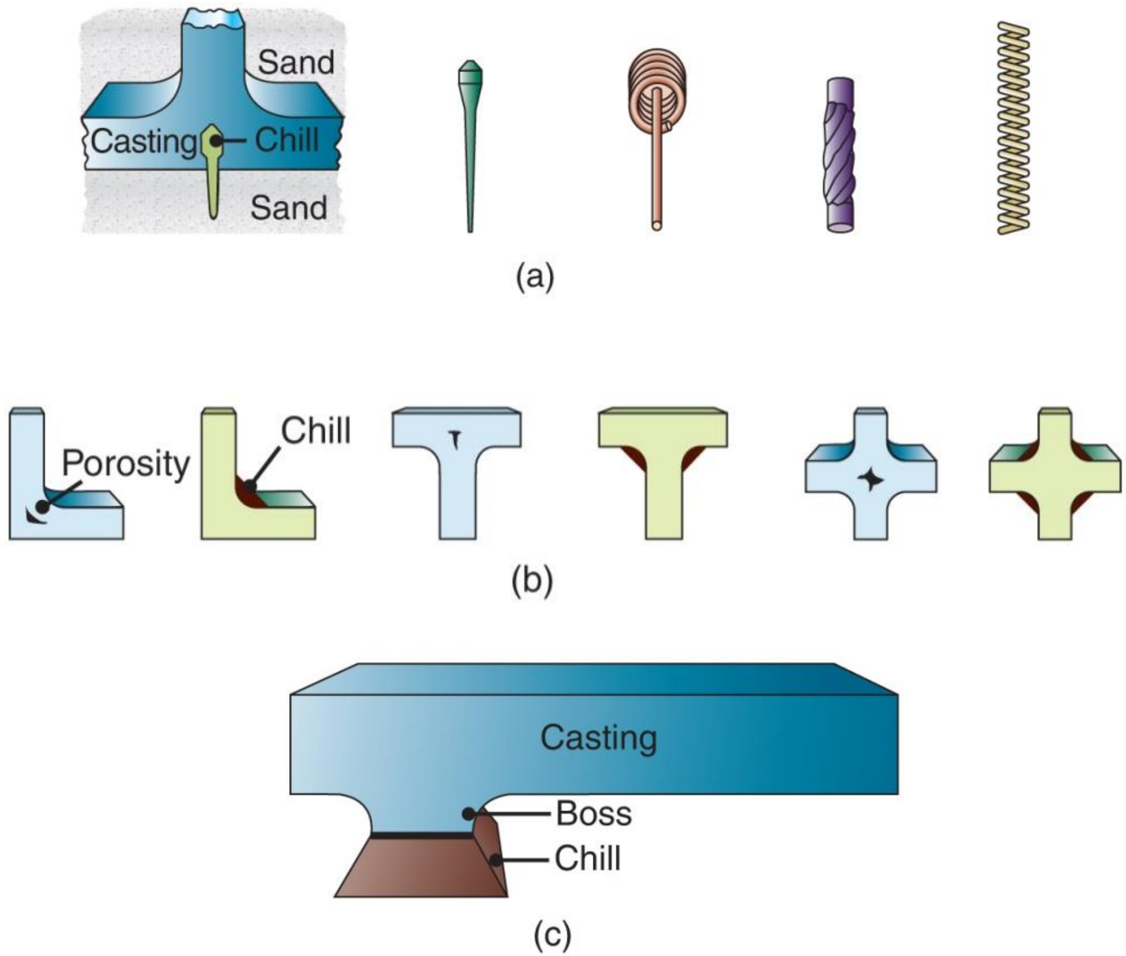

Table 11.1

Summary of Casting Processes.

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

Figure 11.1 (1 of 2)

(a) Examples of stainless steel castings. Note the intricate part shapes. (b) Die-cast magnesium automobile wheels

(a)

(b)

Source: (a) Shutterstock/Mr.1

Table 11.2

General Characteristics of Casting Processes.

	Sand	Shell	Evaporative pattern	Plaster	Investment	Permanent mold	Die	Centrifugal
Typical materials cast	All	All	All	Nonferrous (Al, Mg, Zn, Cu)	All	All	Nonferrous (Al, Mg, Zn, Cu)	All
Weight (kg):								
Minimum	0.01	0.01	0.01	0.01	0.001	0.1	¡0.01	0.01
Maximum	No limit	100+	100+	50+	100+	300	50	5000+
Typical surface finish (R_a in μm)	5–25	1–3	5–25	1–2	0.3–2	2–6	1–2	2–10
Porosity[1]	3–5	4–5	3–5	4–5	5	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]	3	2	3	2	1	1	1	3
Section thickness (mm):								
Minimum	3	2	2	1	1	2	0.5	2
Maximum	No limit	—	—	—	75	50	12	100
Typical dimensional tolerance (mm)	1.6–4 mm (0.25 mm for small parts)	±0.003		±0.005 – 0.010	±0.005	±0.015	±0.001 – 0.005	0.015
Equipment	3–5	3	2–3	3–5	3–5	2	1	1
Pattern/die	3–5	2–3	2–3	3–5	2–3	2	1	1
Labor	1–3	3	3	1–2	1–2	3	5	5
Typical lead time[2]	Days	Weeks	Weeks	Days	Weeks	Weeks	Weeks to months	Months
Typical production rate[2] (parts/mold-hour)	1–20	5–50	1–20	1–10	1–1000	5–50	2–200	1–1000
Minimum quantity[2]	1	100	500	10	10	1000	10,000	10–10,000

Notes: 1. Relative rating, from 1 (best) to 5 (worst). Note that, for example, a die casting has relatively low porosity, mid-to-low shape complexity, high dimensional accuracy, high equipment and die costs, and low labor costs. These ratings are general, as significant variations can occur, depending on the particular production method.

2. Approximate values, without using rapid prototyping technologies. Minimum quantity is 1 when applying rapid prototyping.

Source: Data taken from J.A. Schey, *Introduction to Manufacturing Processes*, 3rd ed., McGraw-Hill, 2000.

Figure 11.2

Outline of production steps in a typical sand-casting operation.

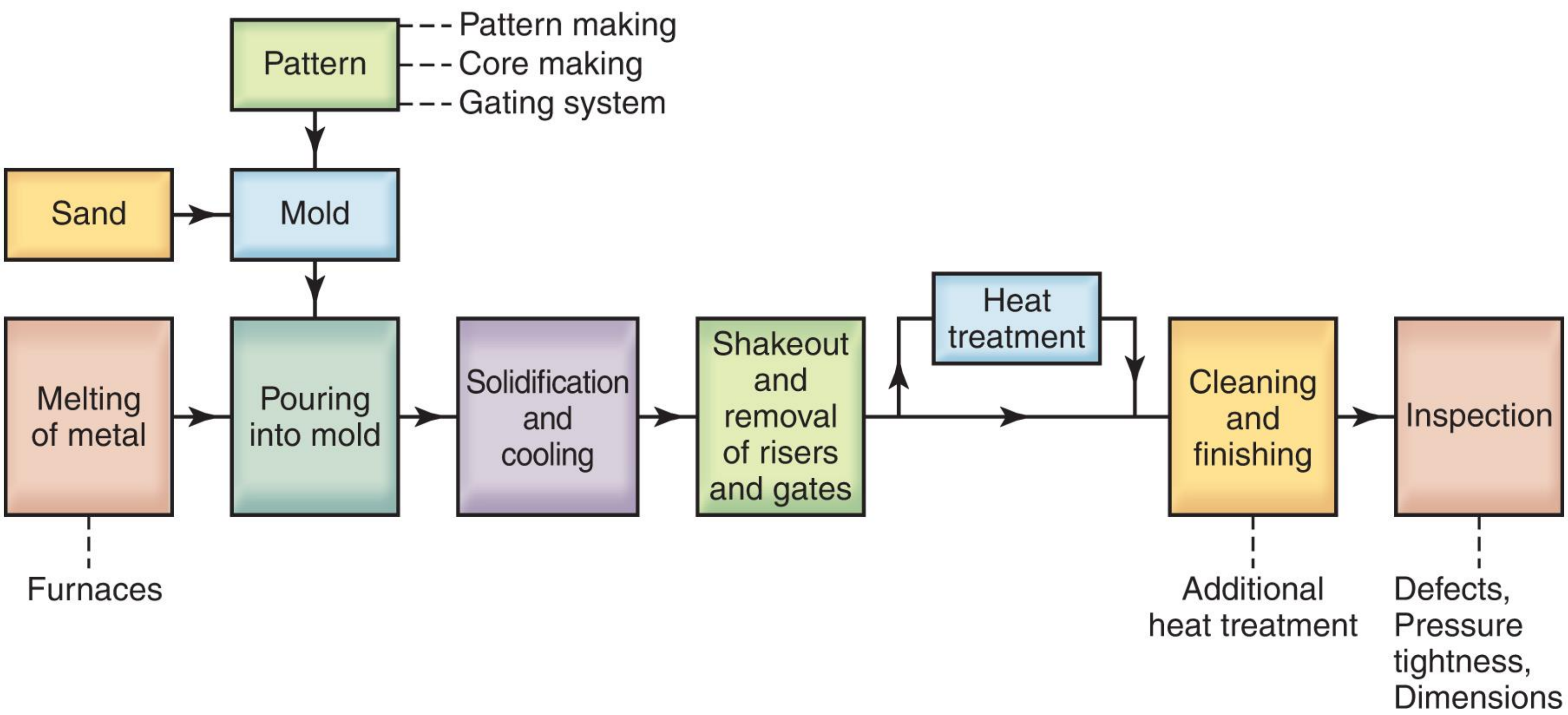

Figure 11.3

Schematic illustration of a sand mold, showing various features.

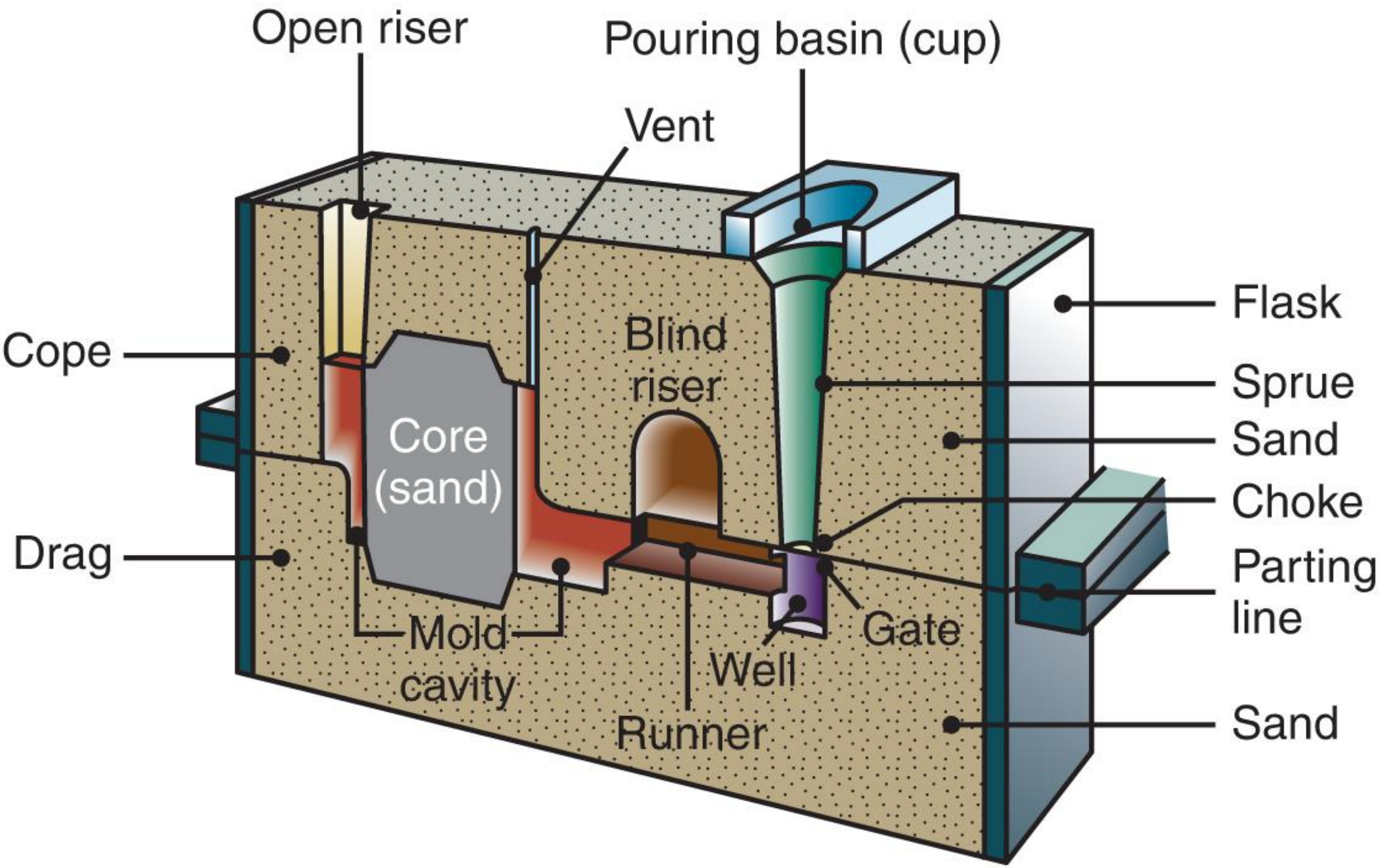

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Figure 11.4

A typical metal match-plate pattern used in sand casting.

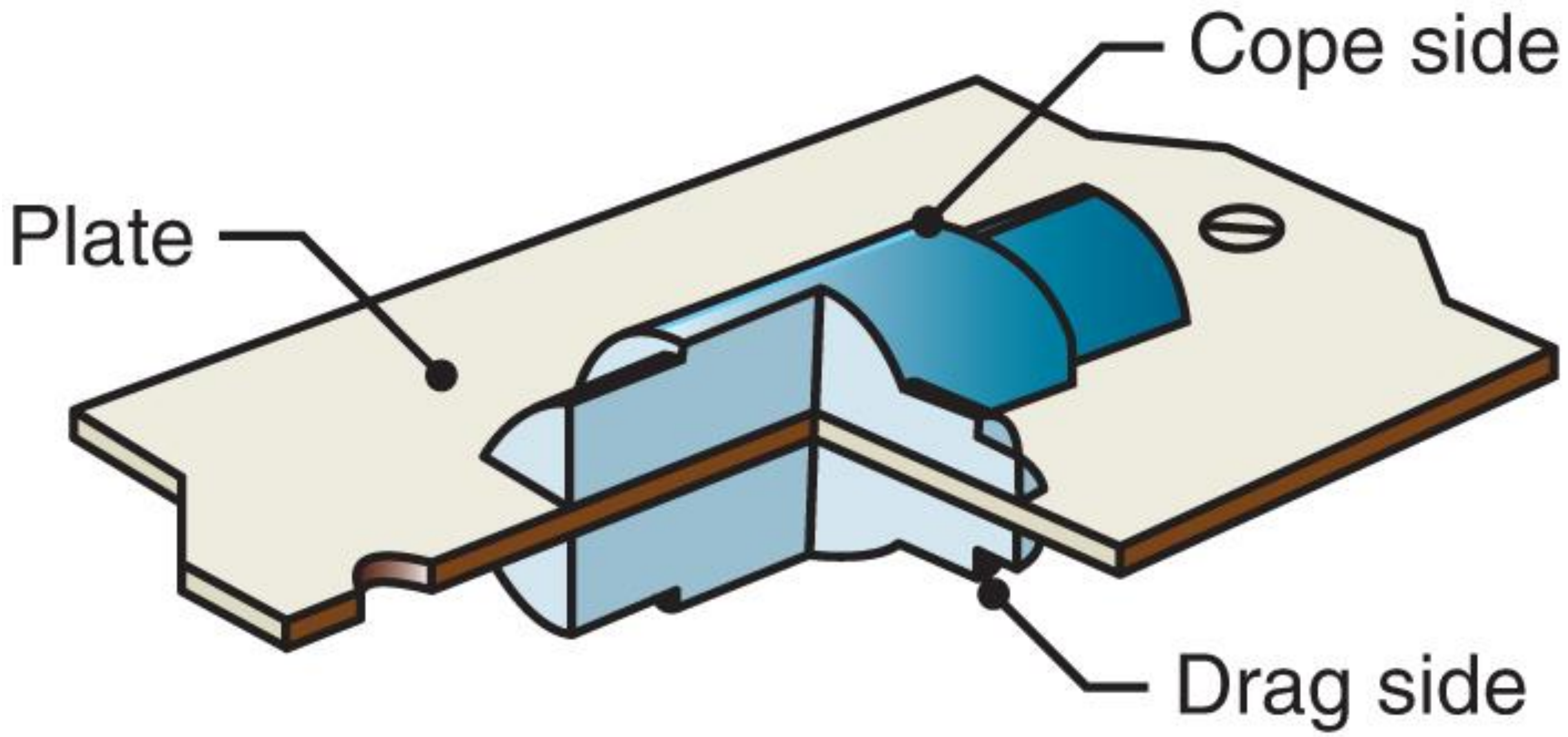


Figure 11.5

Taper on patterns for ease of removal from the sand mold.

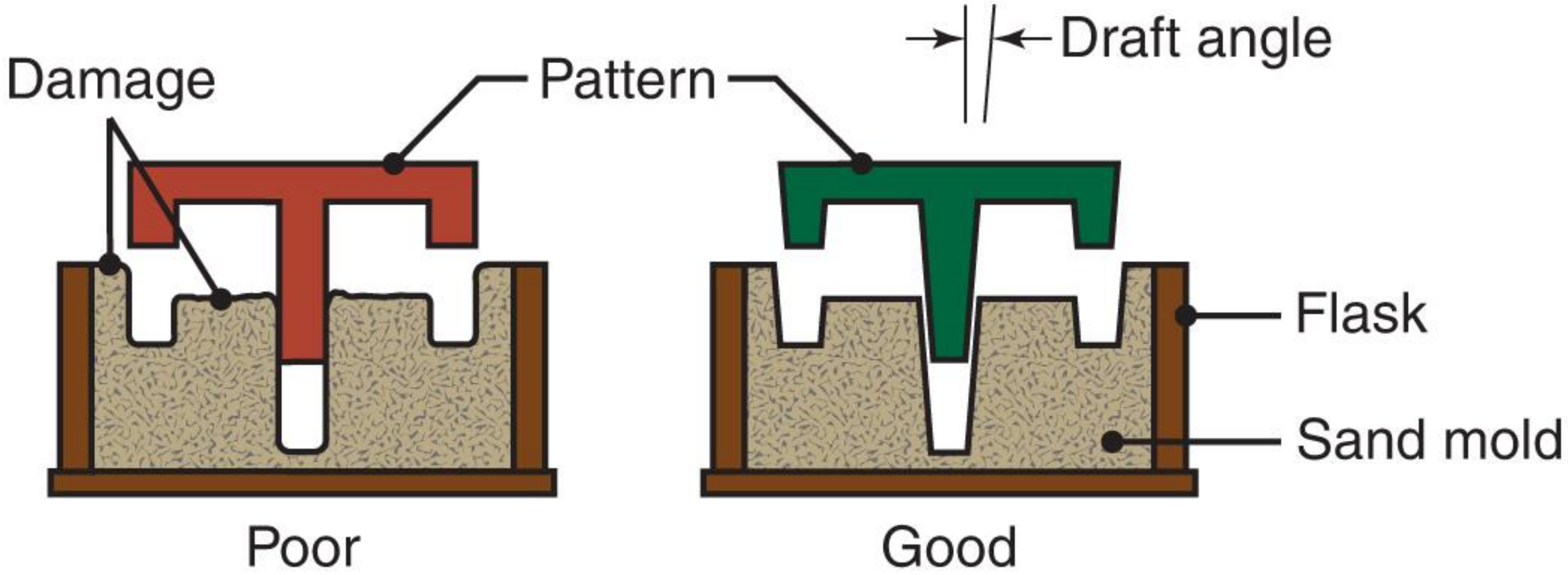


Figure 11.6

Examples of sand cores, showing core prints and chaplets to support the cores.

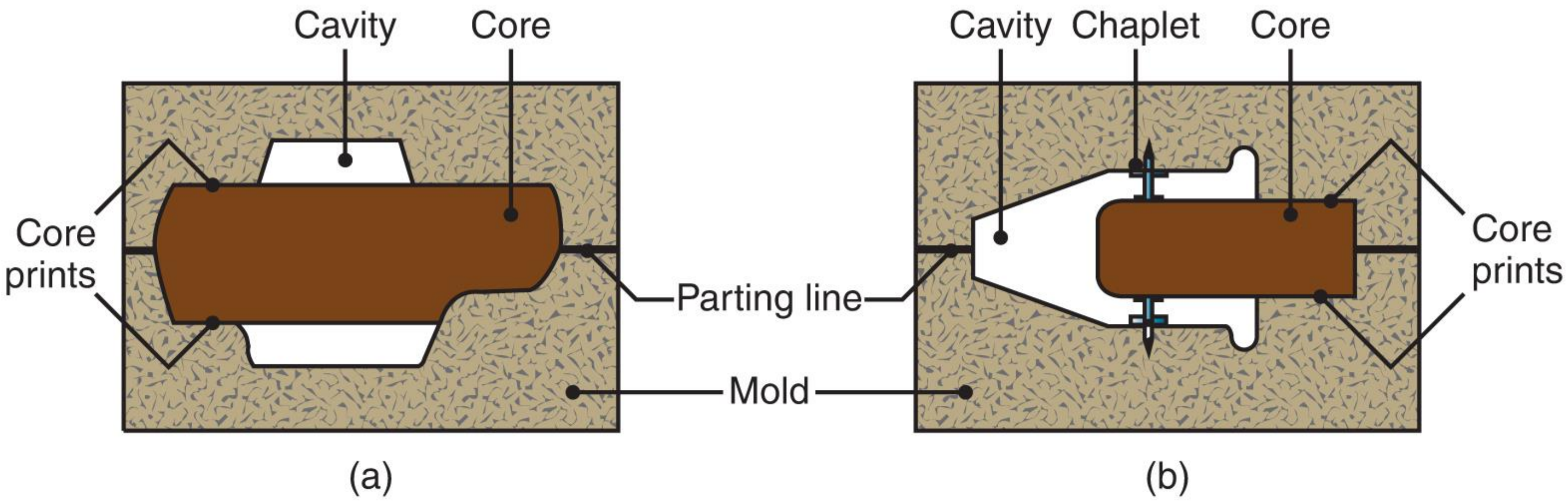
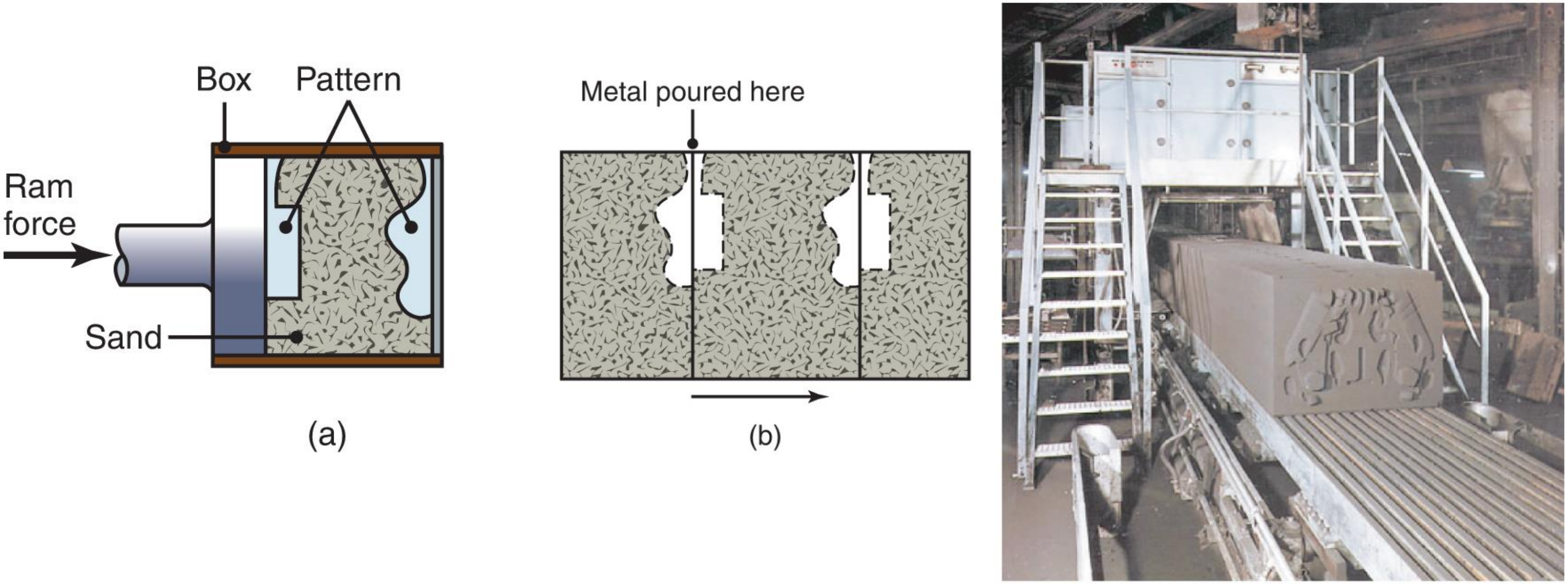


Figure 11.7

Vertical flaskless molding. (a) Sand is squeezed between two halves of the pattern. (b) Assembled molds pass along an assembly line for pouring. (c) A photograph of a vertical flaskless molding line.



(a) (b) (c)

Figure 11.8 (1 of 4)

The vacuum molding process. (a) A plastic sheet is thermoformed (see Section 19.6) over a pattern; (b) a vacuum flask is placed over the pattern, a pouring basin/sprue insert is located, and the flask is filled with sand. A second sheet is located on the top of the sand mold, and vacuum is applied to tightly compact the sand against the pattern. (c) A drag is also produced, along with cheeks, cores, etc., as in conventional sand casting; the cope and drag can be carefully transported without vacuum applied. (d) After the mold halves are joined, vacuum is applied to ensure mold strength, and molten metal is poured into the mold.

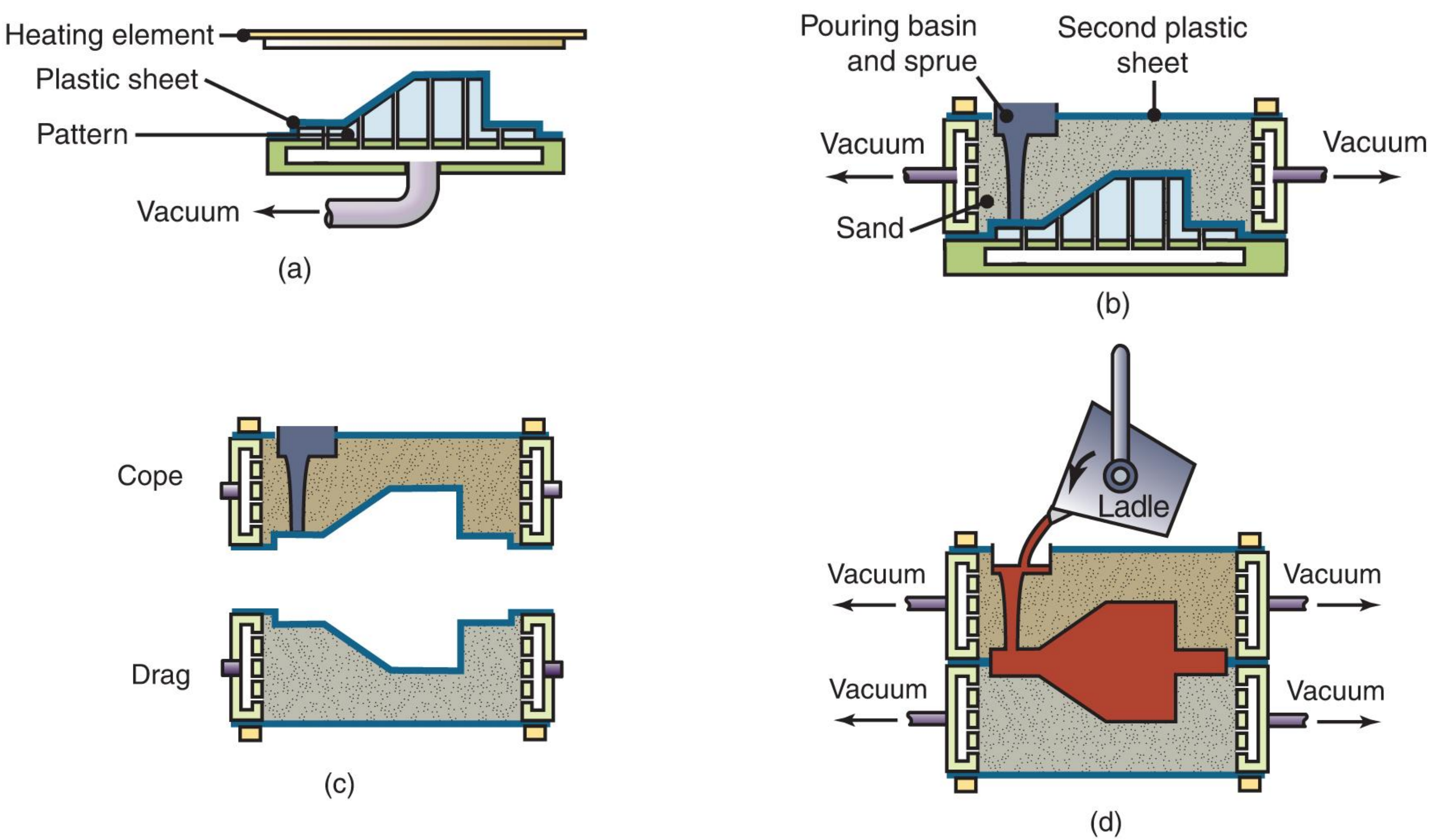
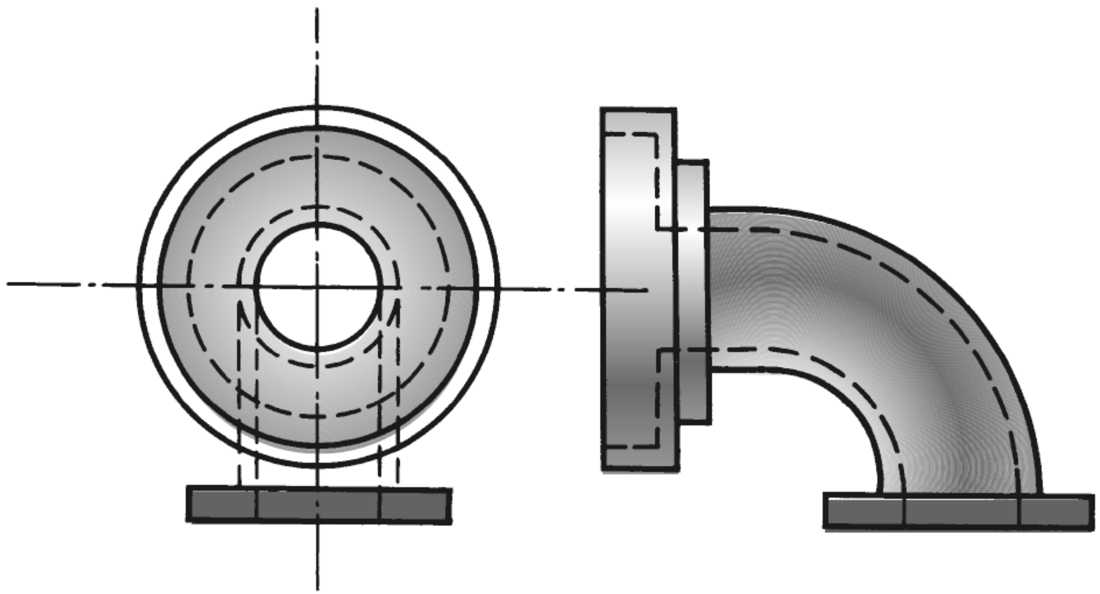


Figure 11.9 (1 of 11)

Schematic illustration of the sequence of operations for sand casting. (a) A mechanical drawing or CAD representation of the part is used to generate a design for the pattern. Considerations such as part shrinkage and draft must be included into the drawing.



Mechanical drawing of part

(a)

Figure 11.9 (2 of 11)

Schematic illustration of the sequence of operations for sand casting. (b–c) Patterns have been mounted on plates equipped with pins for alignment. Note also the presence of core prints designed to hold the core in place.

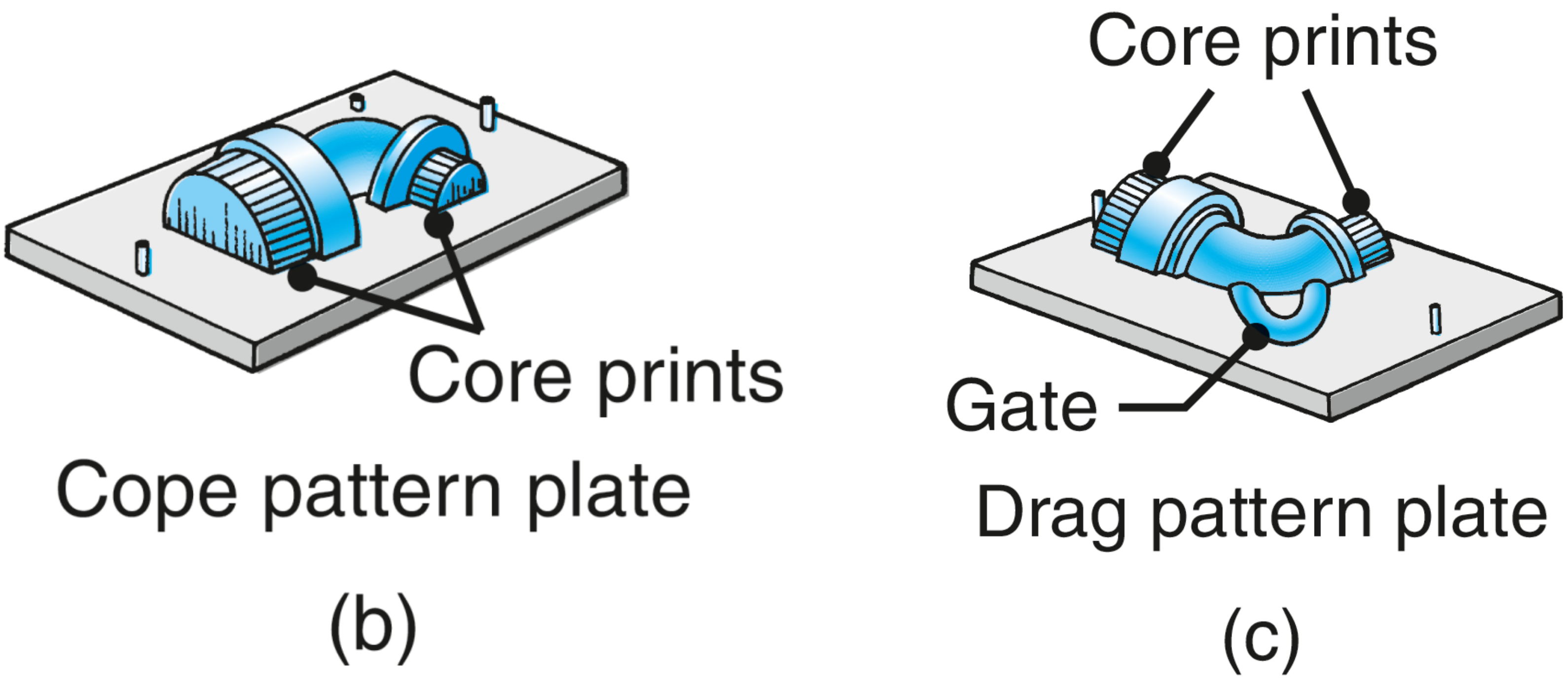


Figure 11.9 (3 of 11)

Schematic illustration of the sequence of operations for sand casting. (d–e) Core boxes produce core halves, which are pasted together. The cores will be used to produce the hollow area of the part shown in (a).

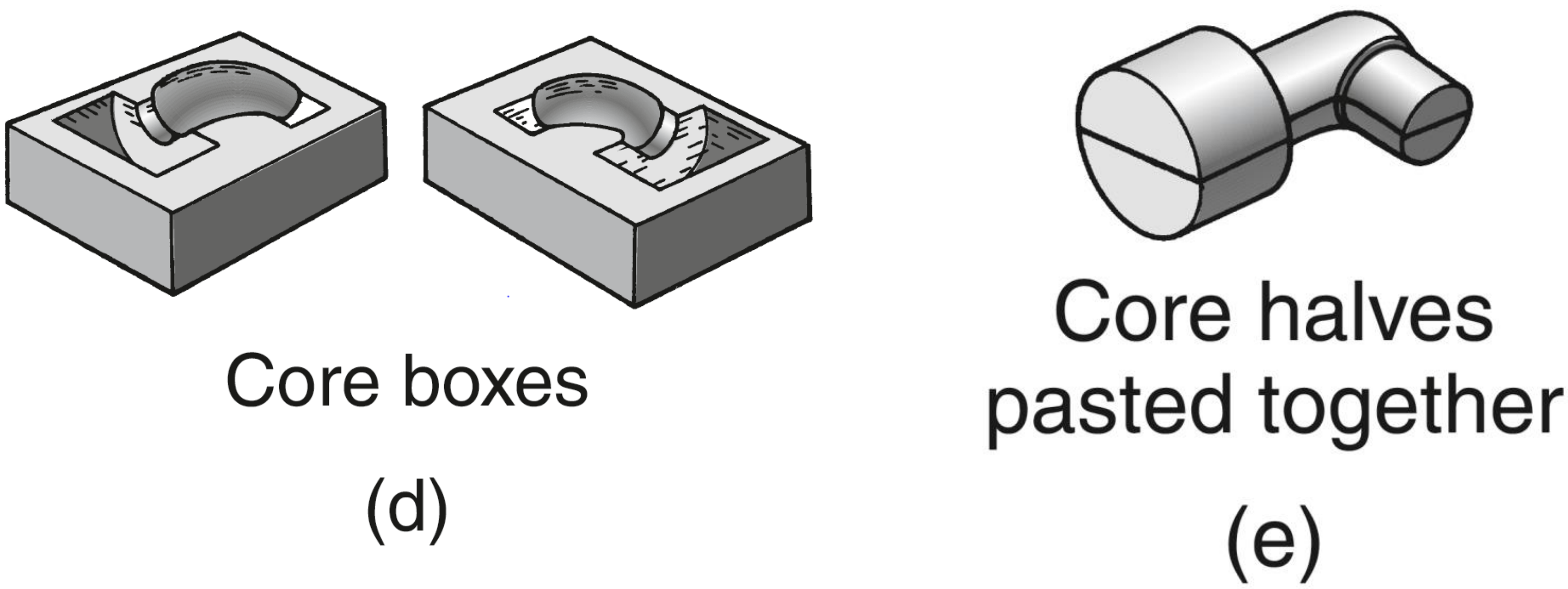
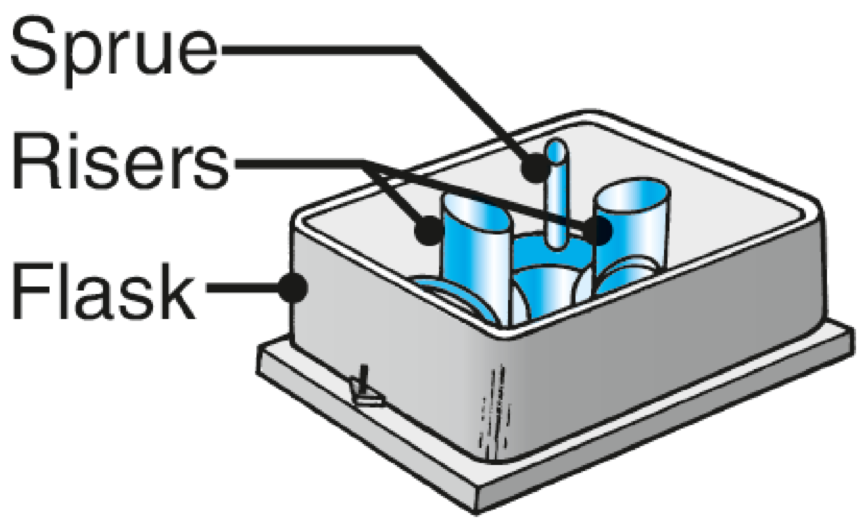


Figure 11.9 (4 of 11)

Schematic illustration of the sequence of operations for sand casting. (f) The cope half of the mold is assembled by securing the cope pattern plate to the flask with aligning pins and attaching inserts to form the sprue and risers.

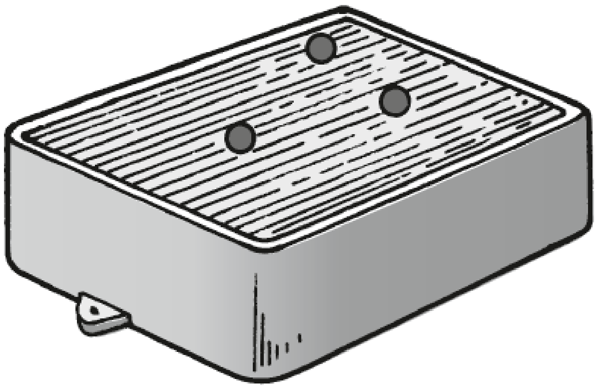


Cope ready for sand

(f)

Figure 11.9 (5 of 11)

Schematic illustration of the sequence of operations for sand casting. (g) The flask is rammed with sand, and the plate and inserts are removed.

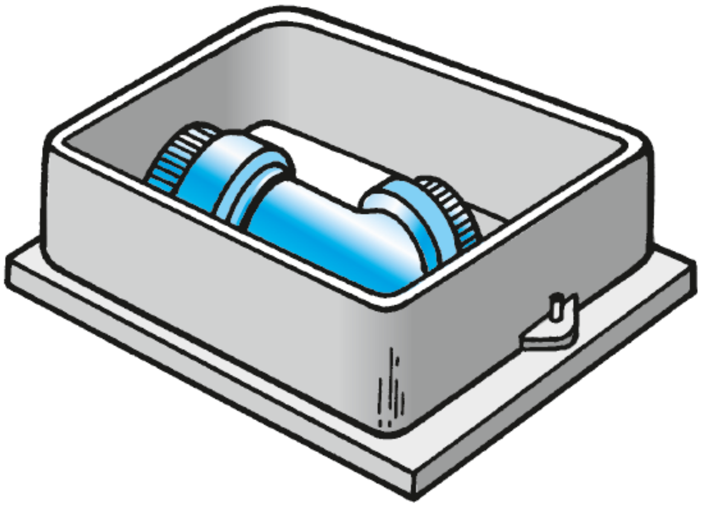


Cope after ramming with sand and removing pattern, sprue, and risers

(g)

Figure 11.9 (6 of 11)

Schematic illustration of the sequence of operations for sand casting. (h) The drag half is produced in a similar manner, with the pattern inserted. A bottom board is placed below the drag and is aligned with pins.

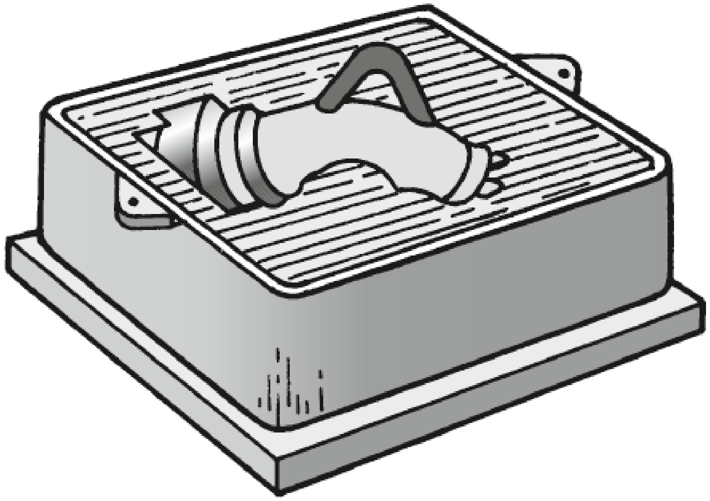


Drag ready
for sand

(h)

Figure 11.9 (7 of 11)

Schematic illustration of the sequence of operations for sand casting. (i) The pattern, flask, and bottom board are inverted, and the pattern is withdrawn, leaving the appropriate imprint.

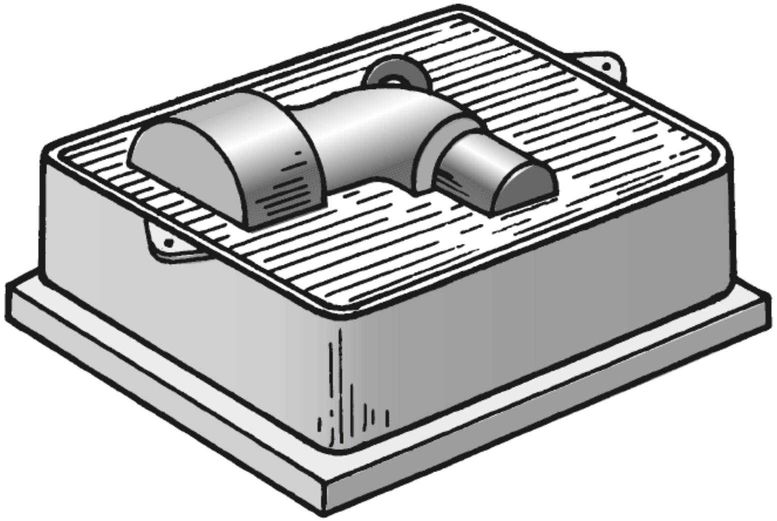


Drag after removing pattern

(i)

Figure 11.9 (8 of 11)

Schematic illustration of the sequence of operations for sand casting. (j) The core is set in place within the drag cavity.

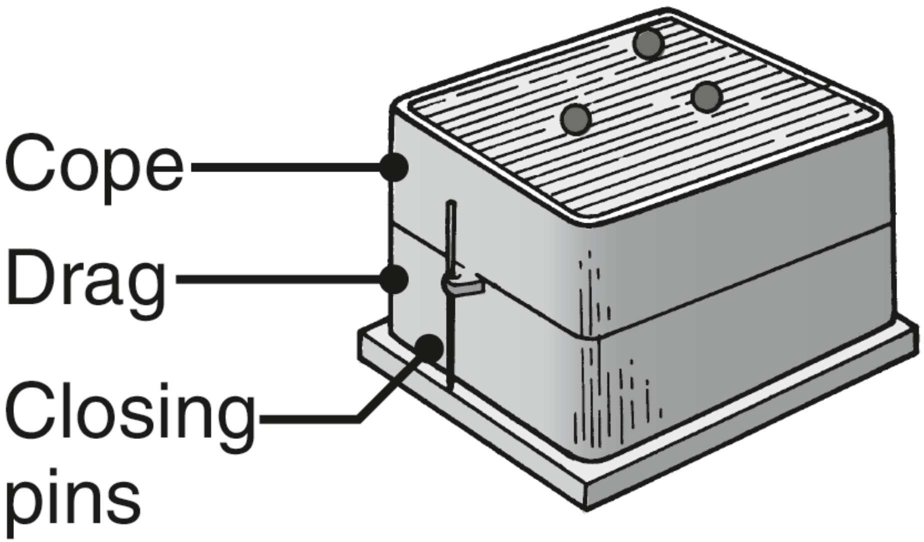


Drag with core
set in place

(j)

Figure 11.9 (9 of 11)

Schematic illustration of the sequence of operations for sand casting. (k) The mold is closed by placing the cope on top of the drag and securing the assembly with pins. The flasks are then subjected to pressure to counteract buoyant forces in the molten metal, which might lift the cope.

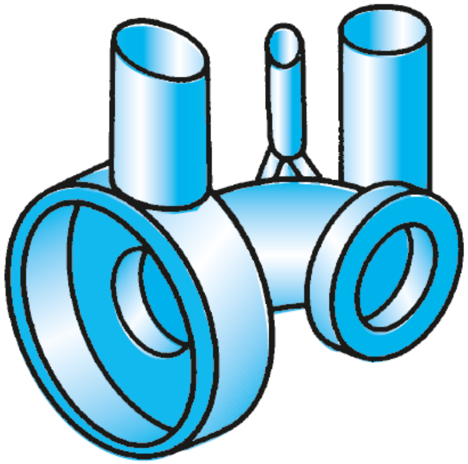


Cope and drag assembled and ready for pouring

(k)

Figure 11.9 (10 of 11)

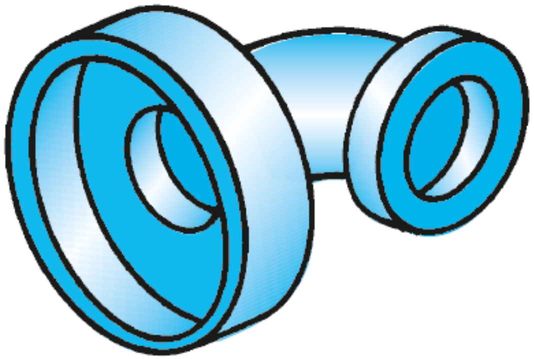
Schematic illustration of the sequence of operations for sand casting. (l) After the metal solidifies, the casting is removed from the mold.



(l)

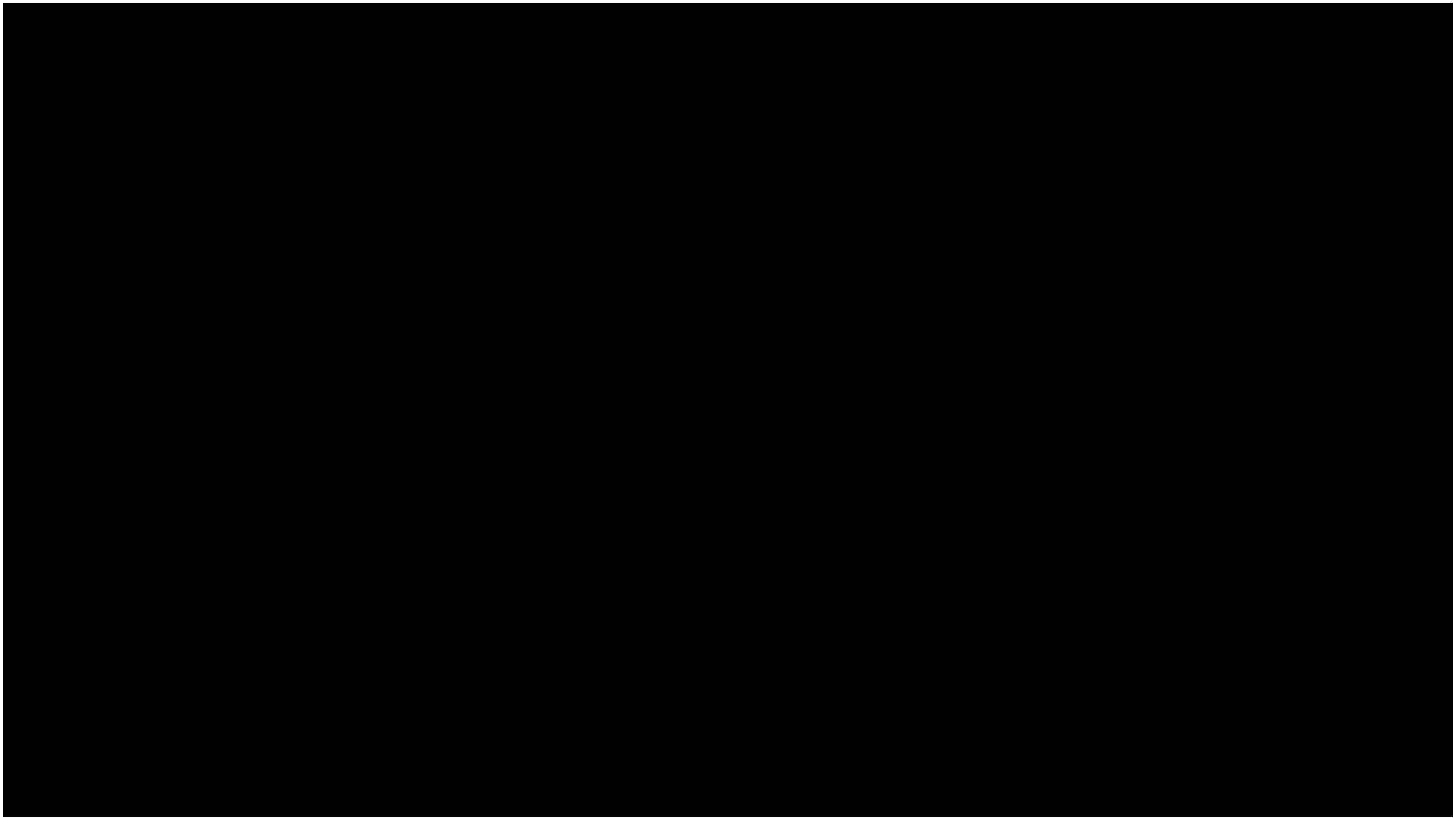
Figure 11.9 (11 of 11)

Schematic illustration of the sequence of operations for sand casting. (m) The sprue and risers are cut off and recycled, and the casting is cleaned, inspected, and heat treated (if necessary).



Source: Courtesy of Steel Founders' Society of America.

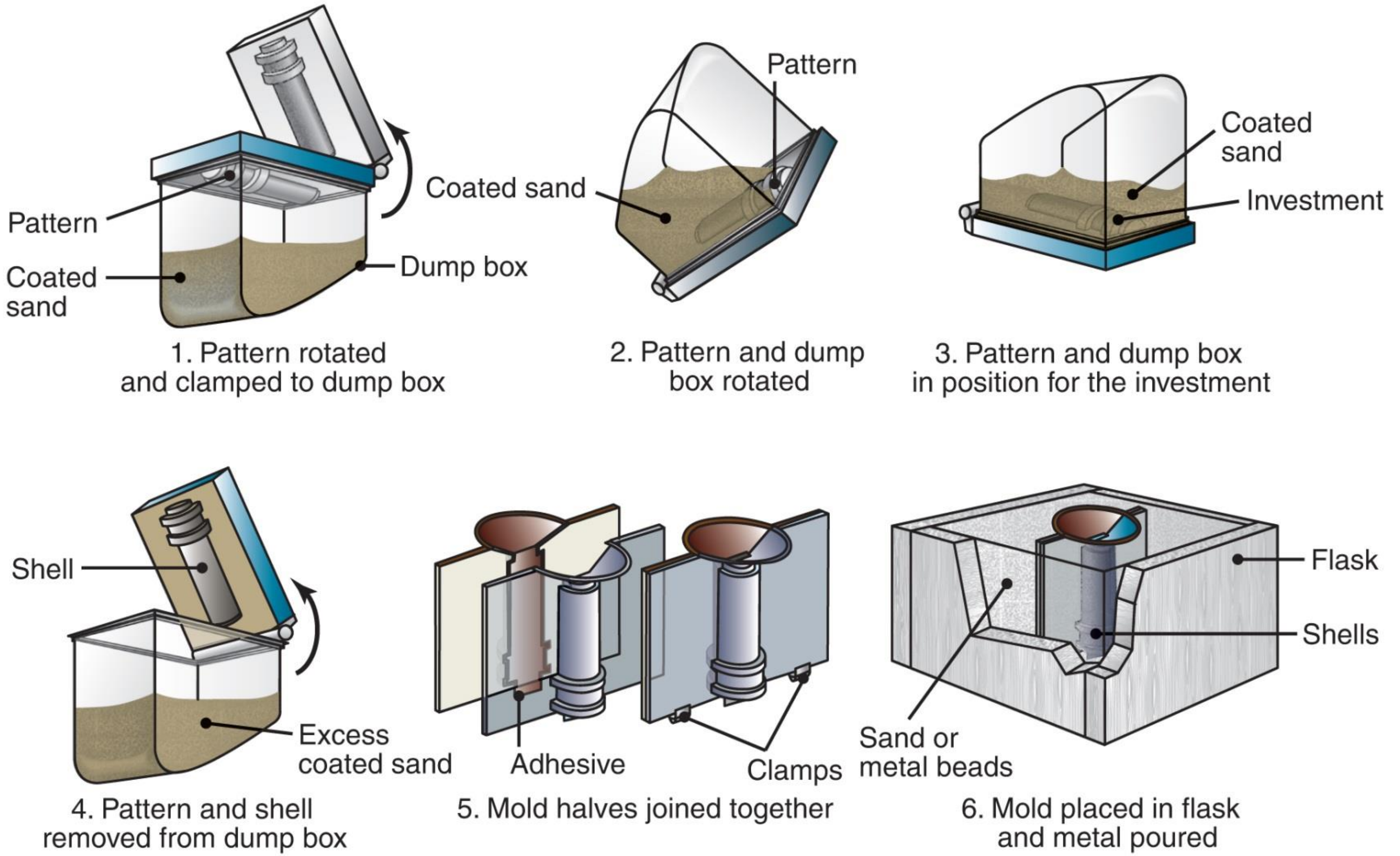
Sand Casting



https://youtu.be/szOwGvYO_Tc

Figure 11.10

The shell-molding process, also called the dump-box technique.



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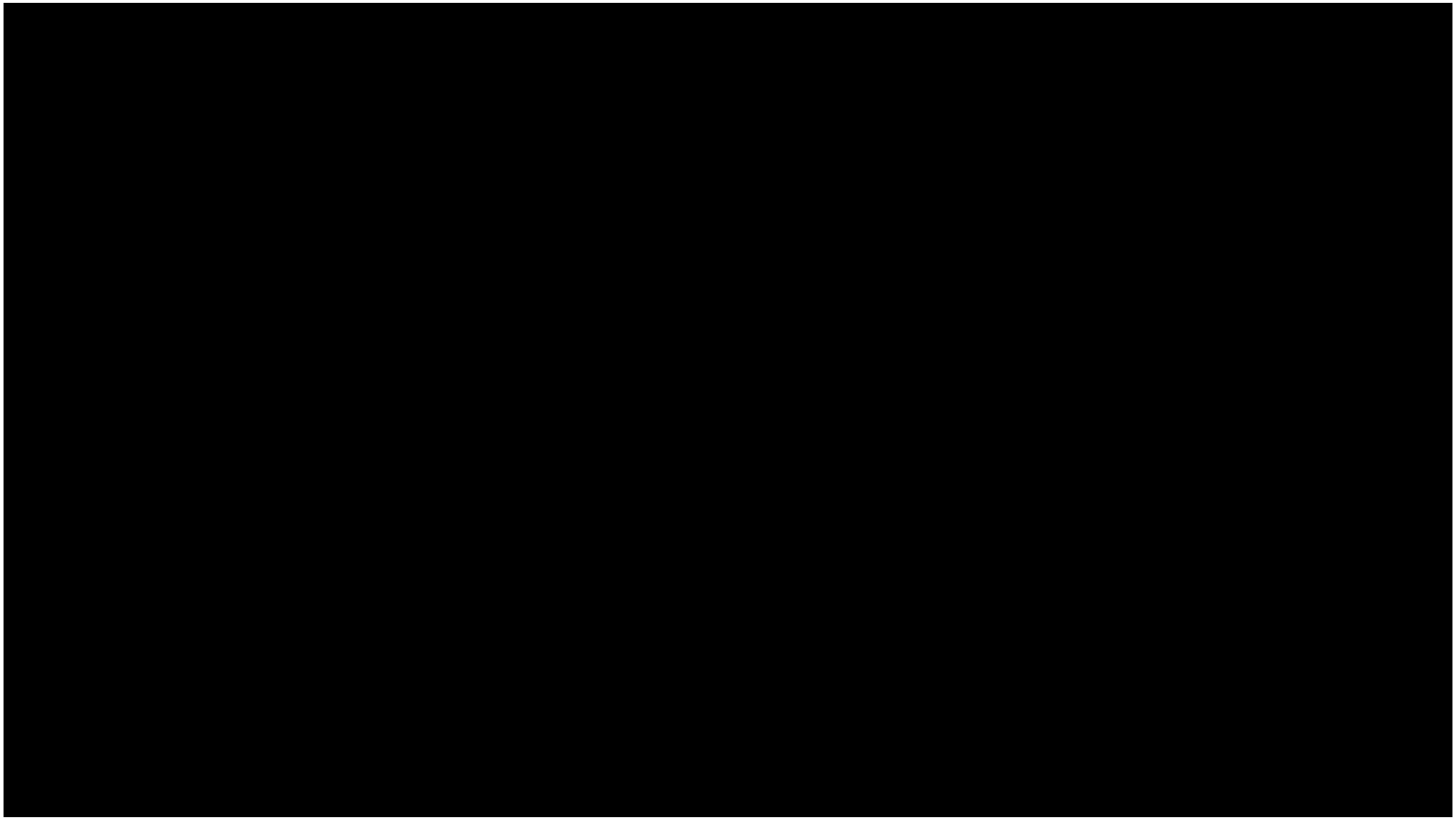
Shell Molding



https://youtu.be/44R2IbzTvt4

Figure 11.11 (1 of 3)

Sequence of operations in making a ceramic mold.

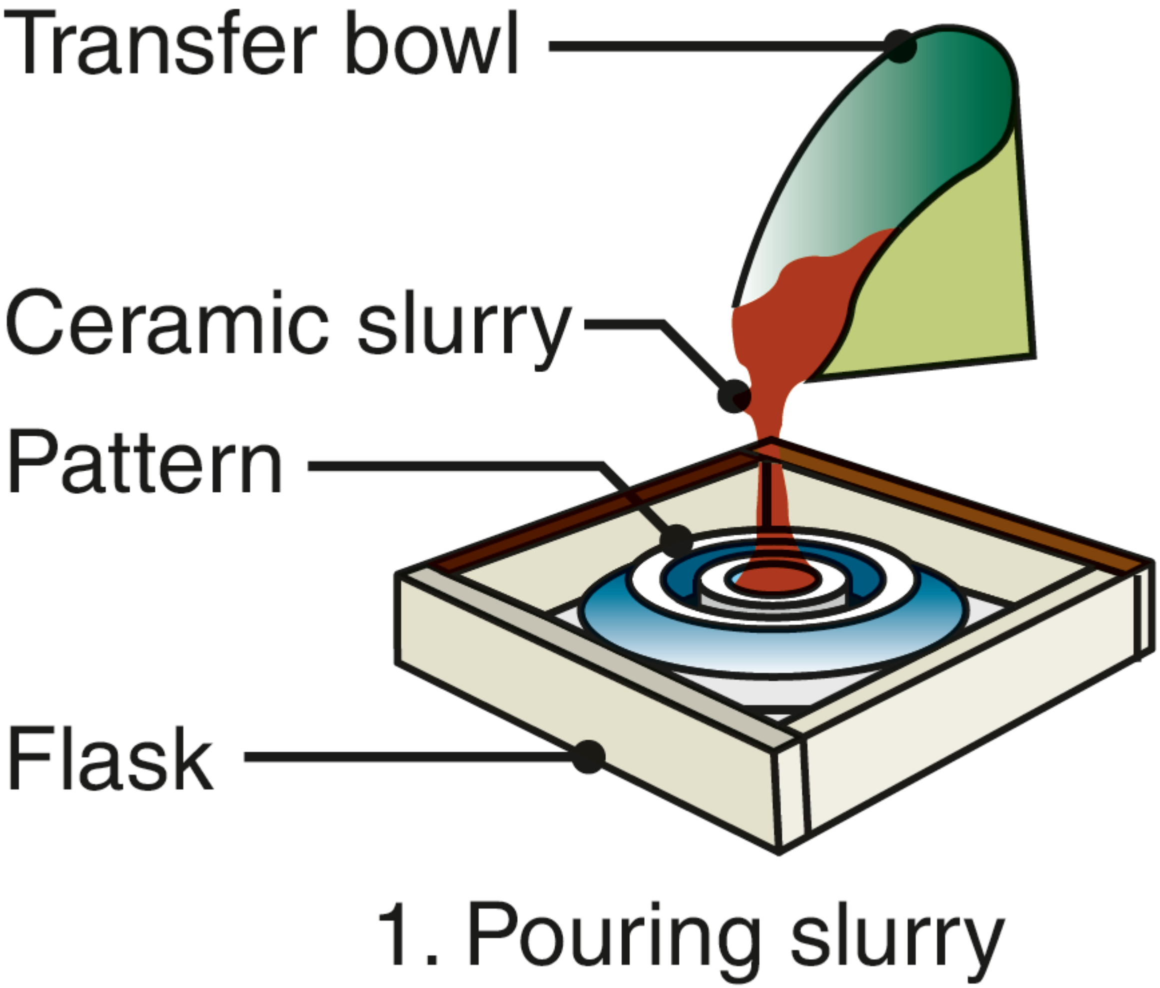
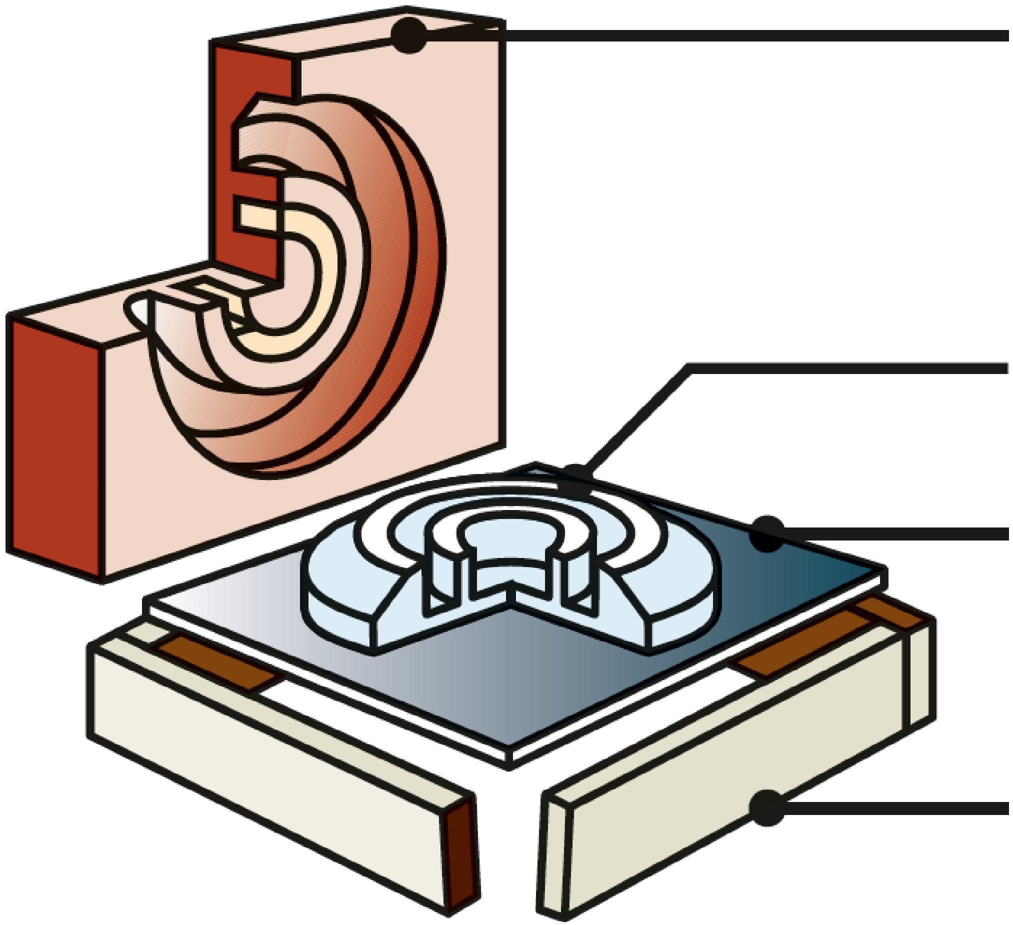
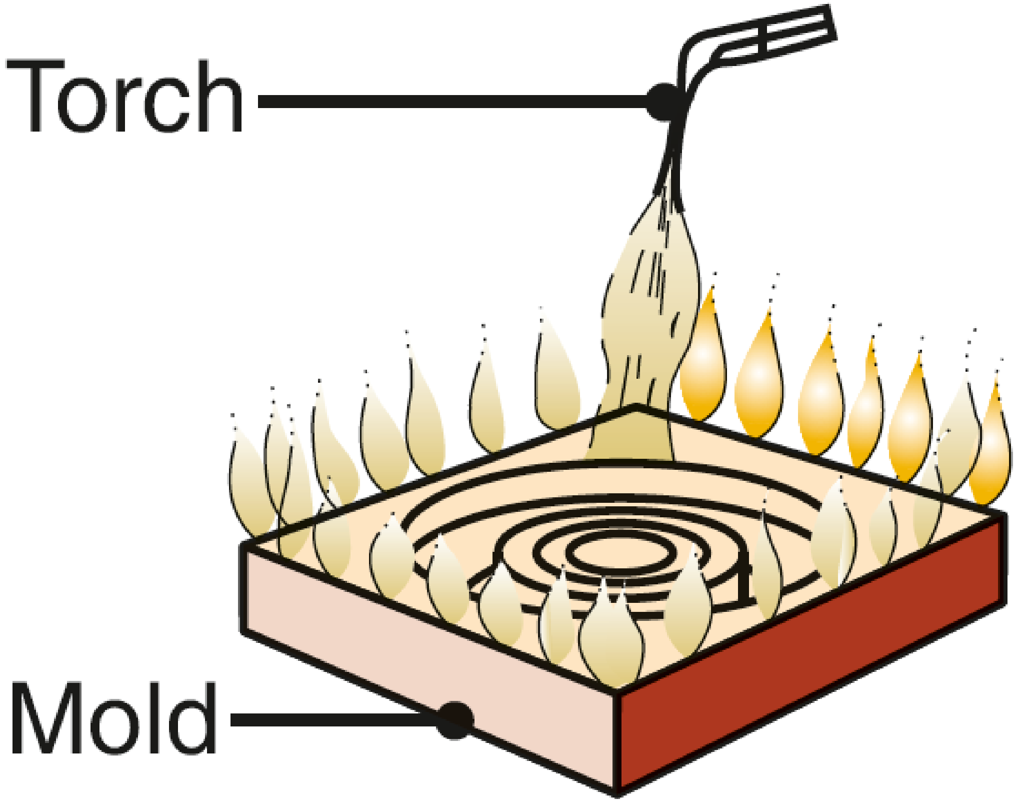


Figure 11.11 (2 of 3)



2. Stripping green mold

Figure 11.11 (3 of 3)

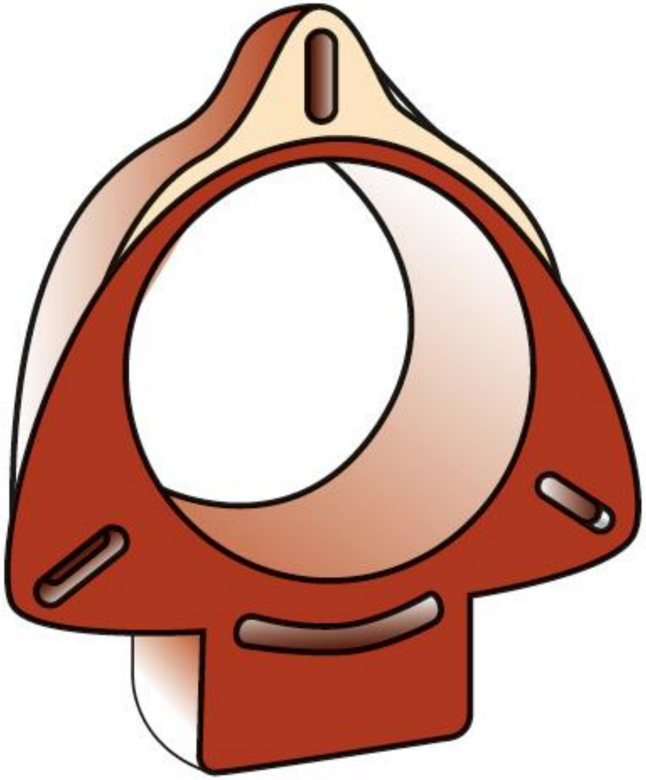


3. Burn-off

Source: *Metals Handbook,* Vol. 5, 8th ed, ASM International, 1970.

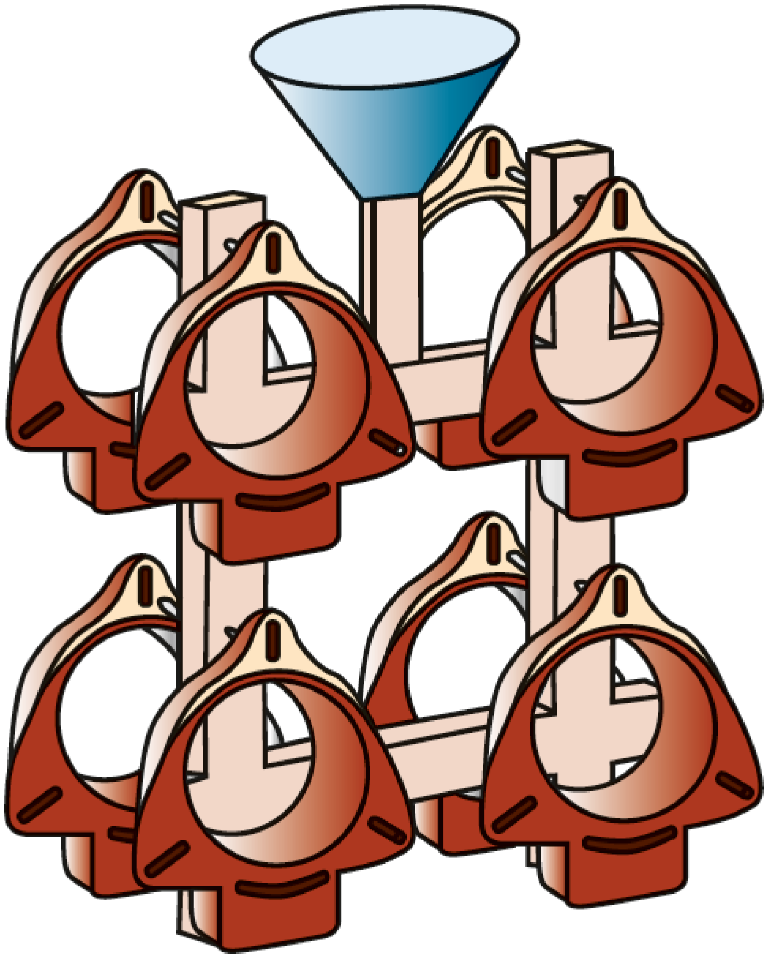
Figure 11.12 (1 of 6)

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



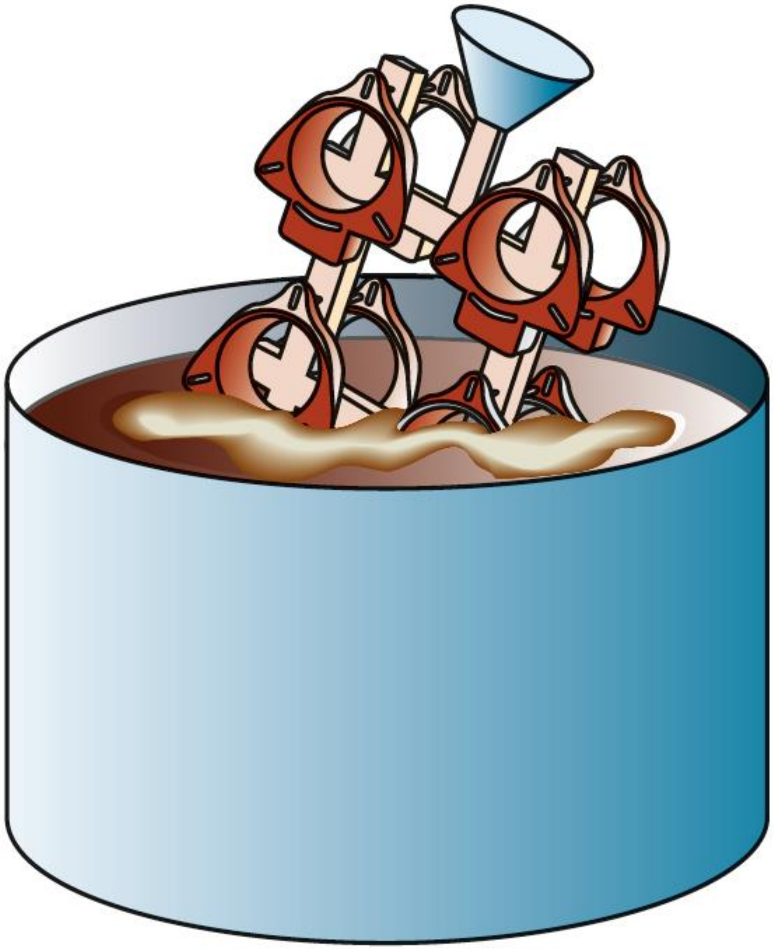
1. Pattern molding

Figure 11.12 (2 of 6)



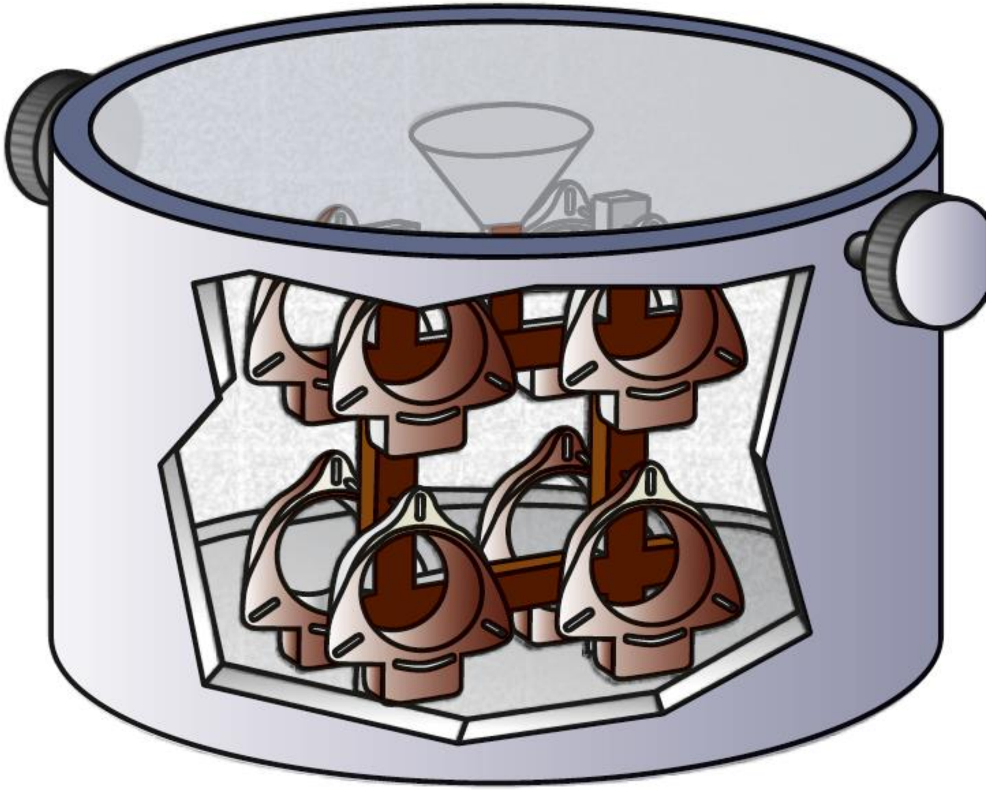
2. Cluster assembly

Figure 11.12 (3 of 6)



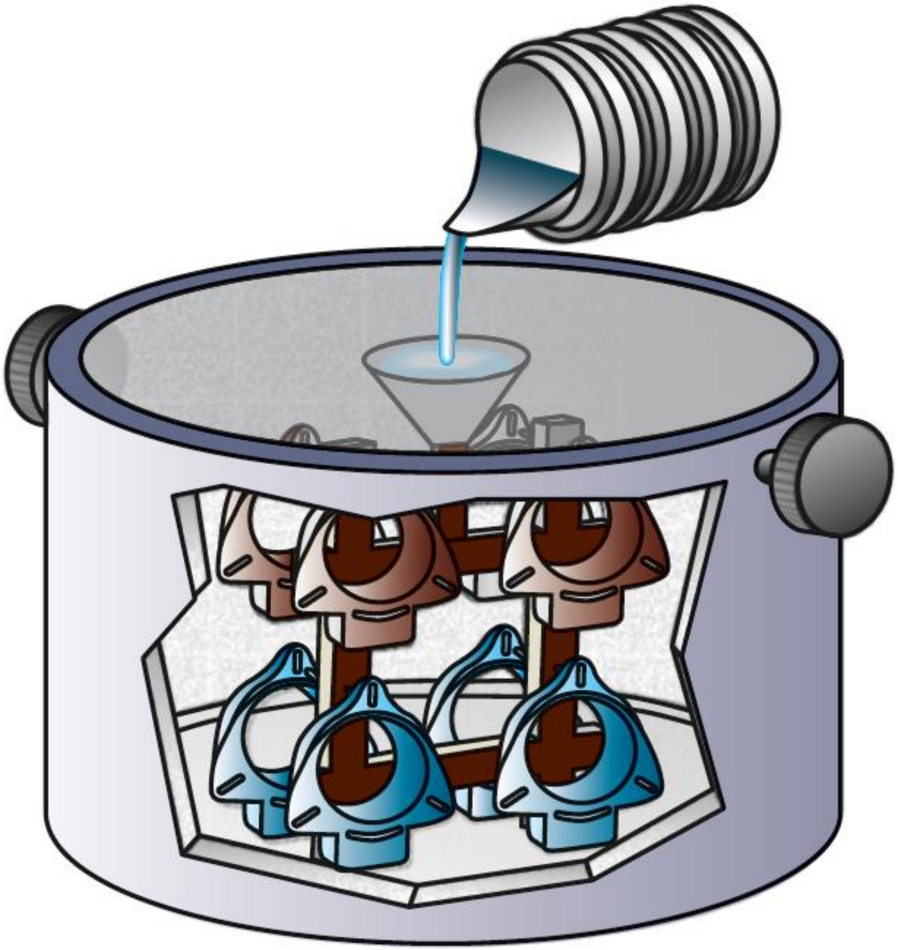
3. Coating

Figure 11.12 (4 of 6)



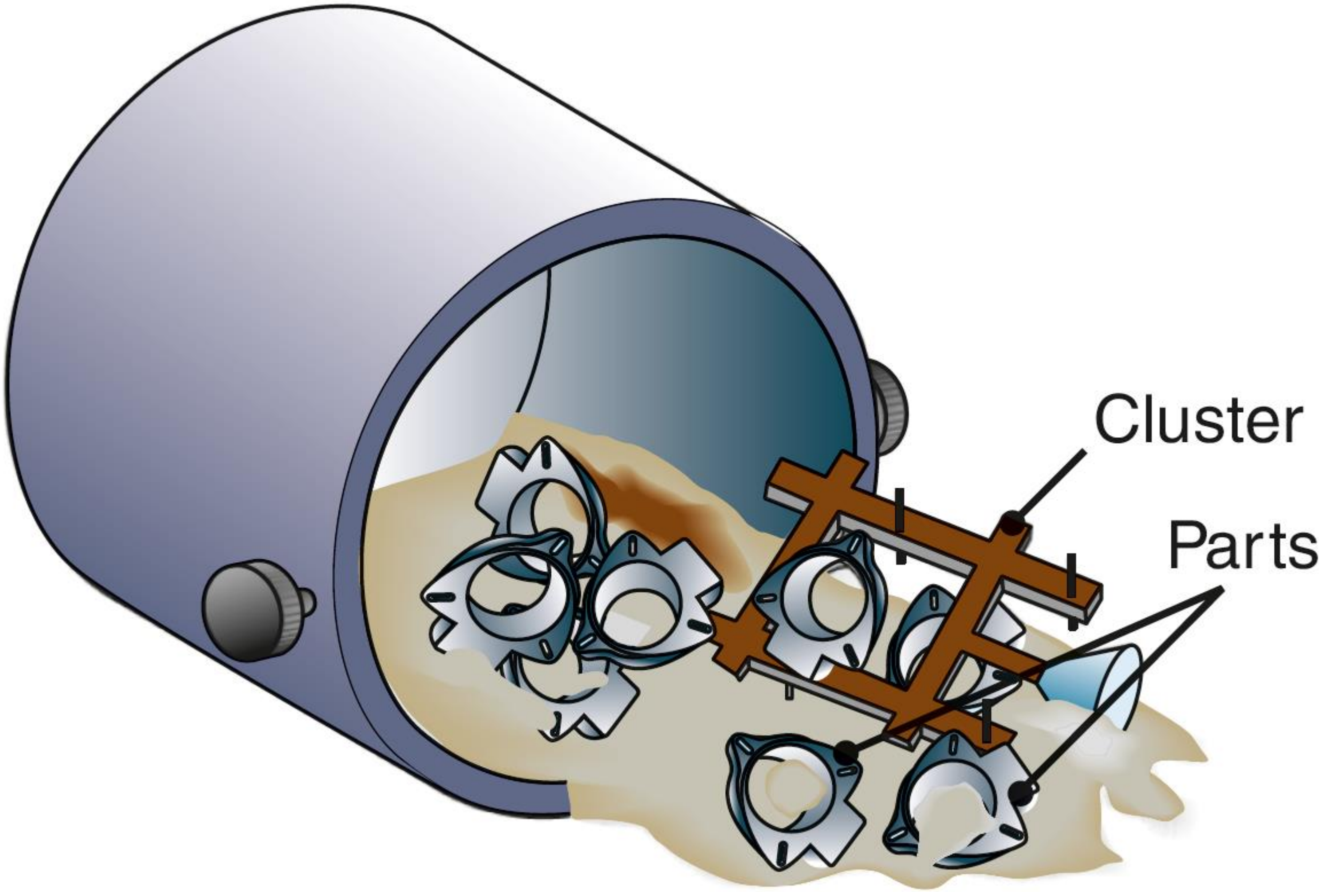
4. Compacted in sand

Figure 11.12 (5 of 6)



5. Casting

Figure 11.12 (6 of 6)



6. Shakeout

Figure 11.13 (1 of 3)

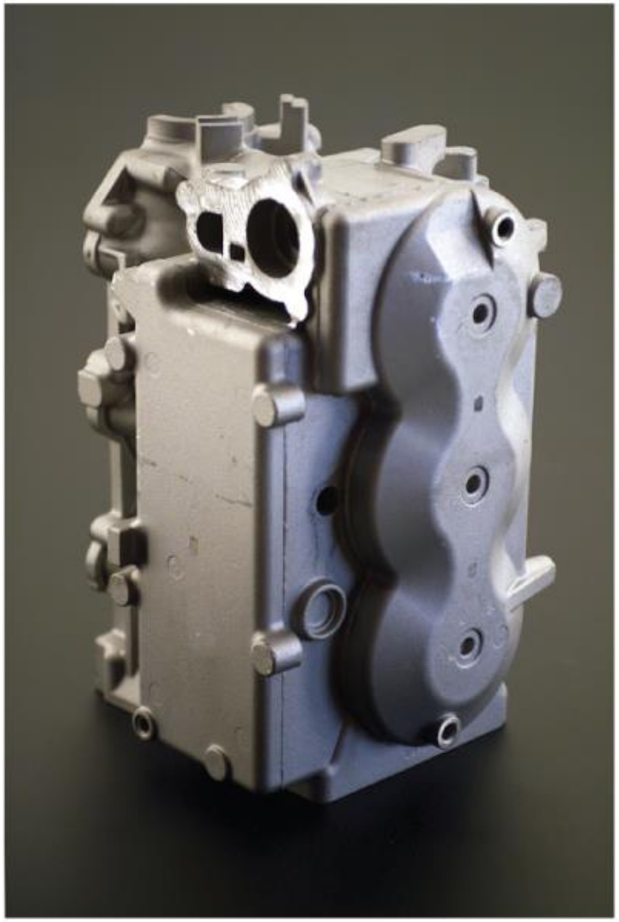
(a) Metal is poured into a mold for lost-foam casting of a 60-hp, three-cylinder marine engine.

(a)

Pearson

Figure 11.13 (2 of 3)

(b) finished engine block.



(b)

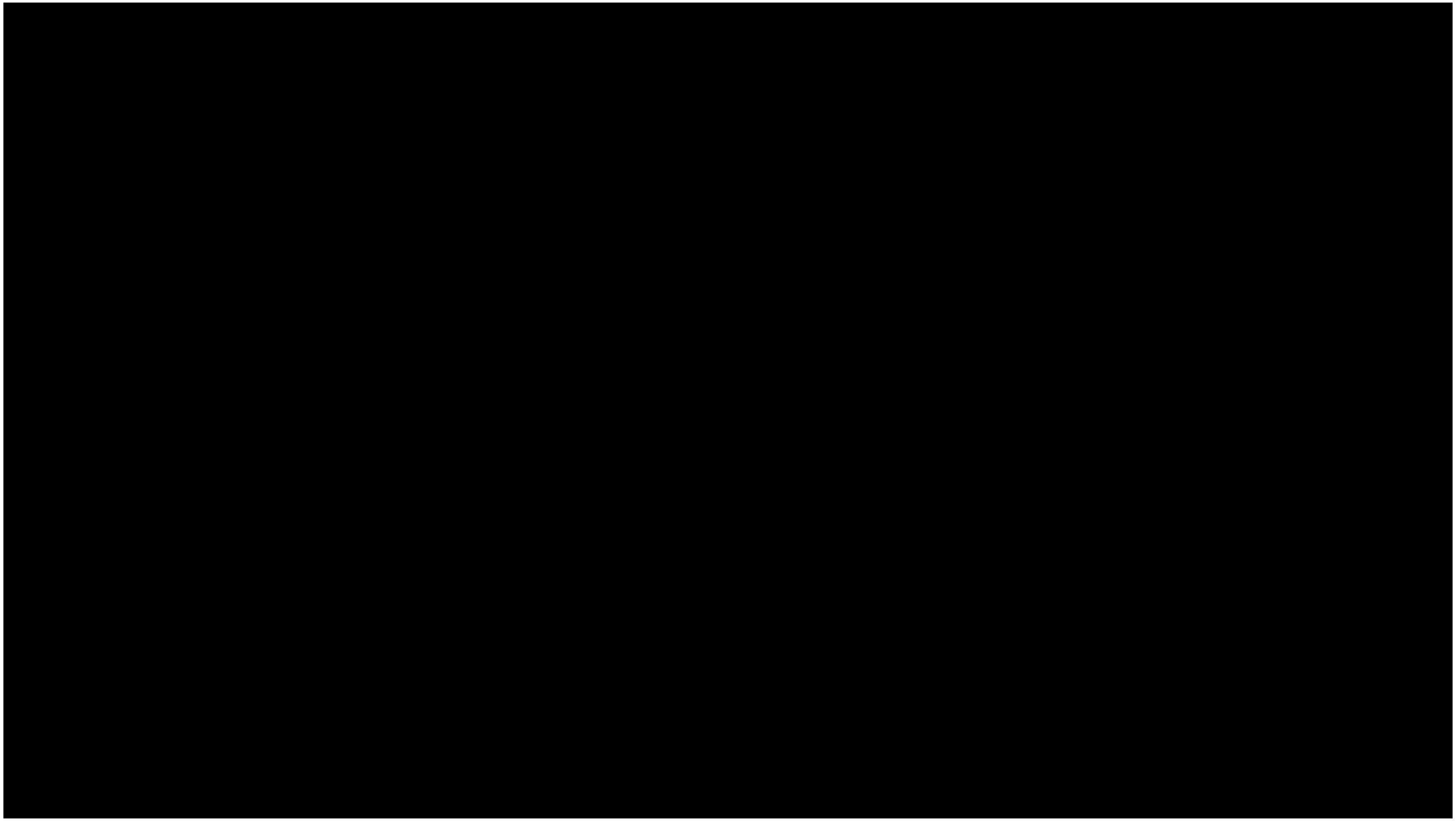
Figure 11.13 (3 of 3)

(c) completed outboard motor.

(c)

Source: Mercury Marine, a division of Brunswick Corporation.

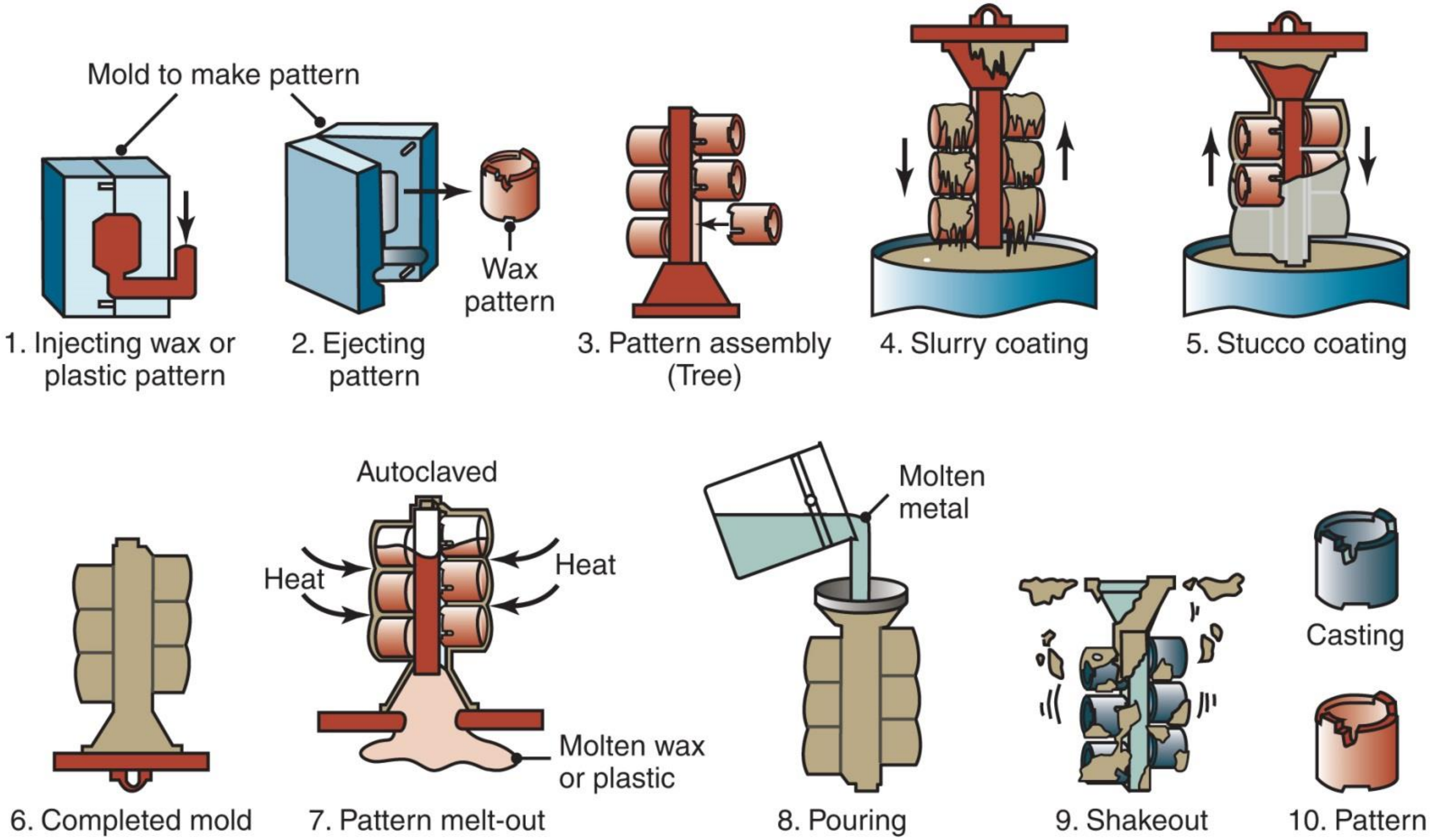
Lost Foam Casting



https://youtu.be/HFITqk2KTjw

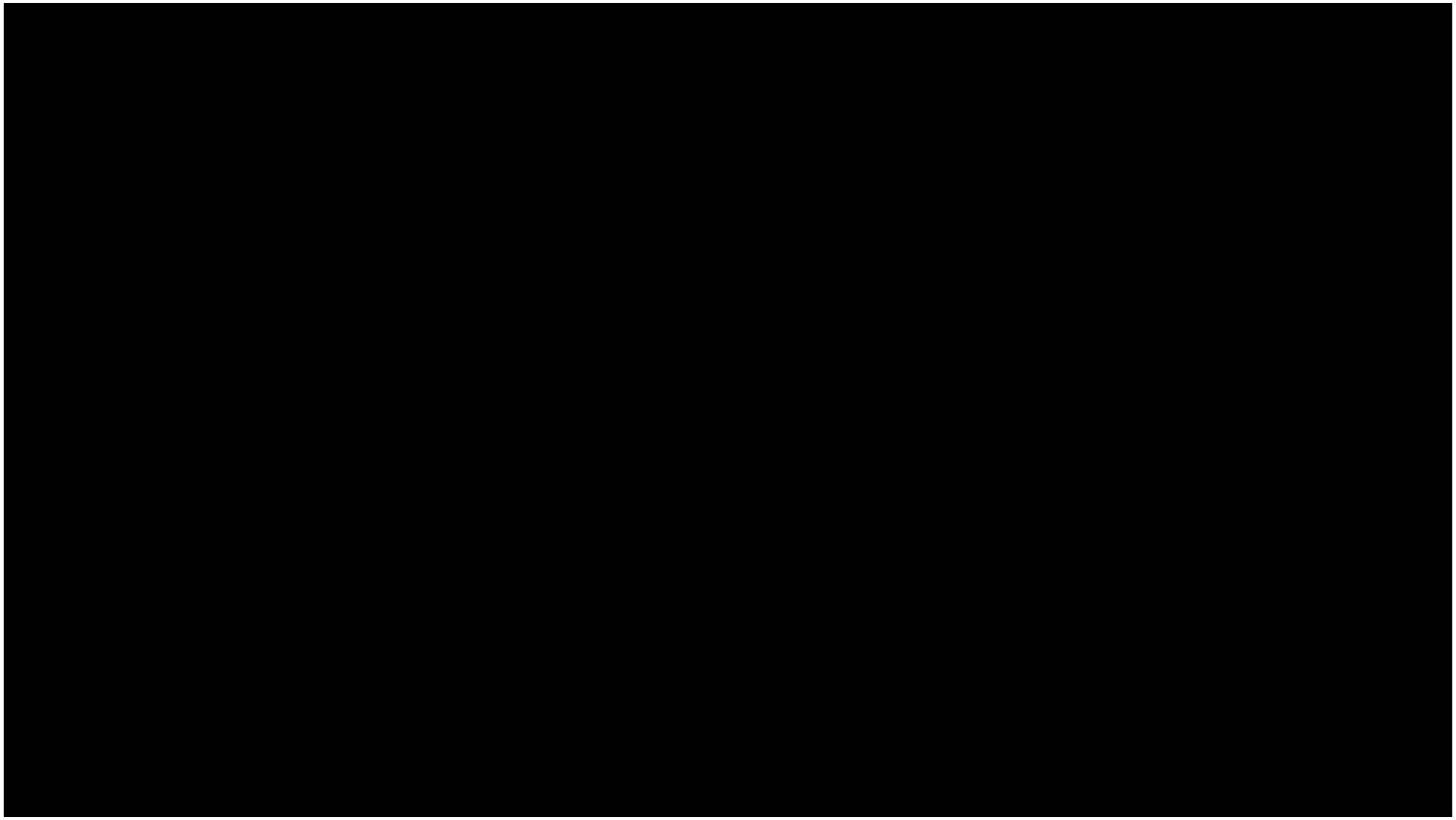
Figure 11.14

Schematic illustration of the investment-casting (lost-wax) process. Castings produced by this method can be made with very fine detail and from a variety of metals.



Source: Courtesy of Steel Founders' Society of America.

Lost Wax Casting



https://youtu.be/Xeg575g_Cgs

Table 11.3

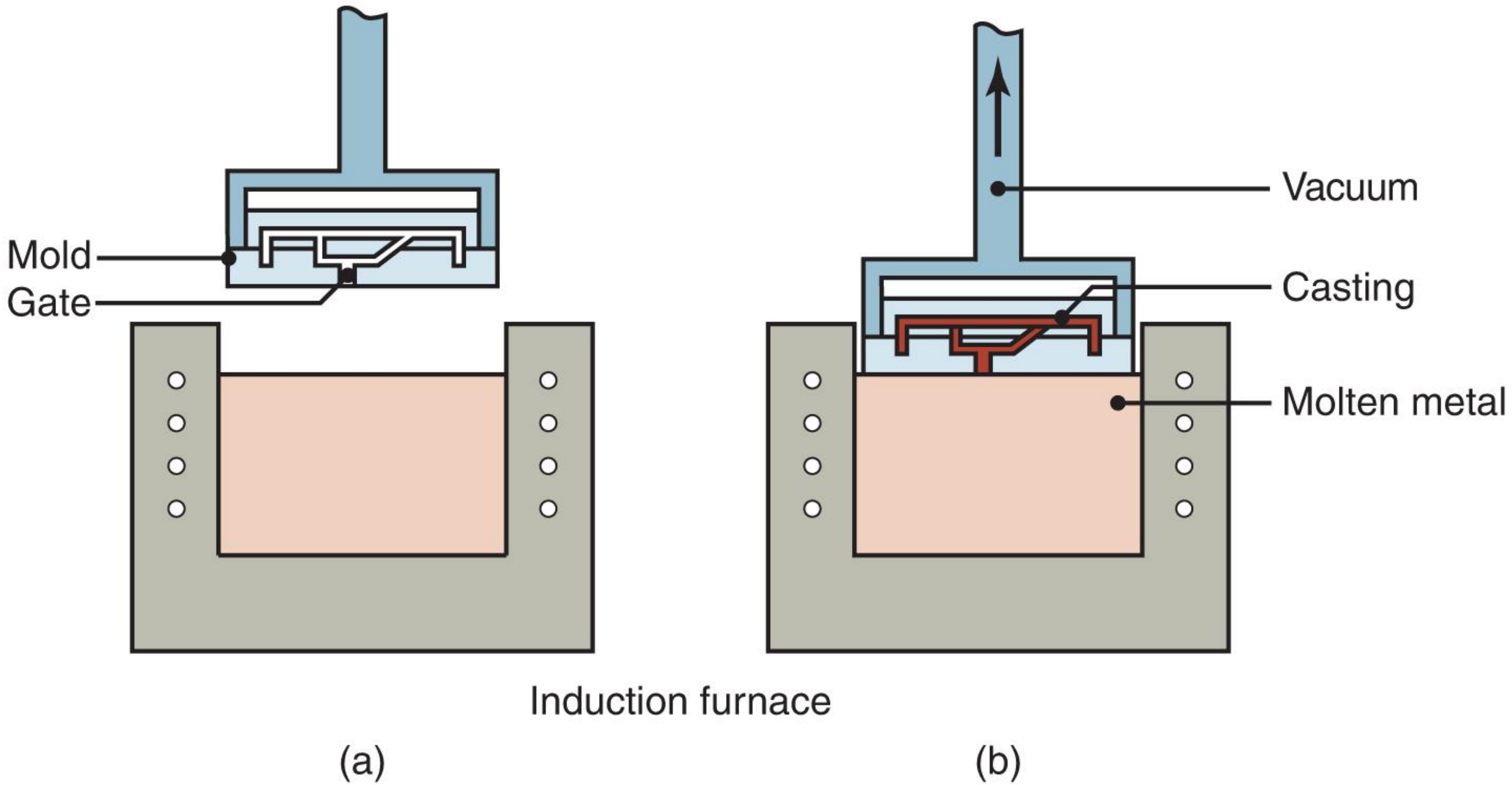
Properties and Typical Applications of Some Common Die-casting Alloys.

Alloy	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Applications
Aluminum				
380 (3.5 Cu–8.5 Si)	320	160	2.5	Appliances, automotive components, electrical motor frames and housings
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 AZ91 B (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
No. 5 (4 Al–1 Cu)	320	—	7	Appliances, automotive parts, building hardware, business equipment

Source: American Die Casting Institute.

Figure 11.17

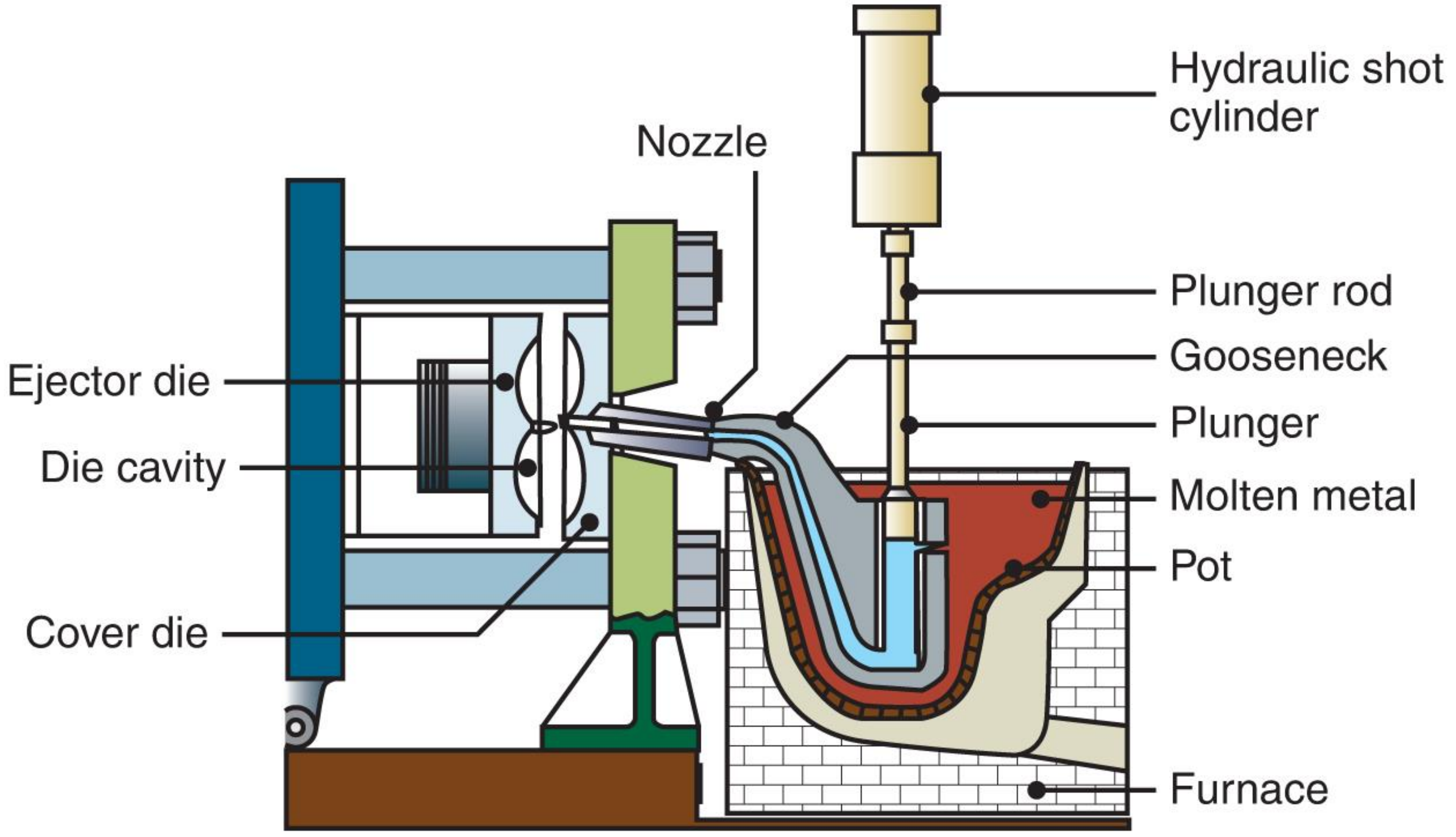
Schematic illustration of the vacuum-casting process. Note that the mold has a bottom gate. (a) Before and (b) after immersion of the mold into the molten metal.



Source: After R. Blackburn.

Figure 11.18

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



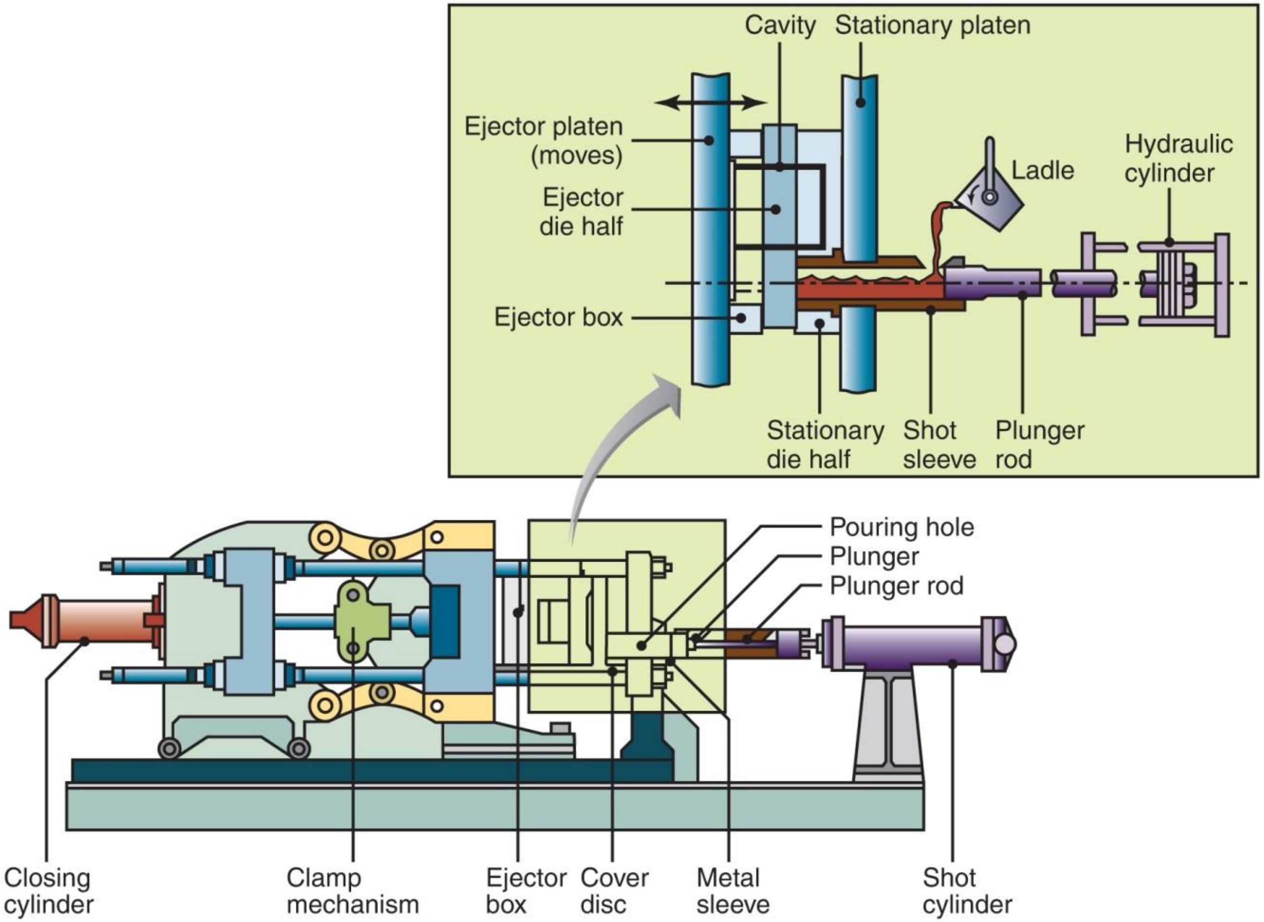
Pearson

Hot Chamber Die Casting

https://youtu.be/bzSSfBgkWfc

Figure 11.19

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



Pearson

Cold Chamber Die Casting

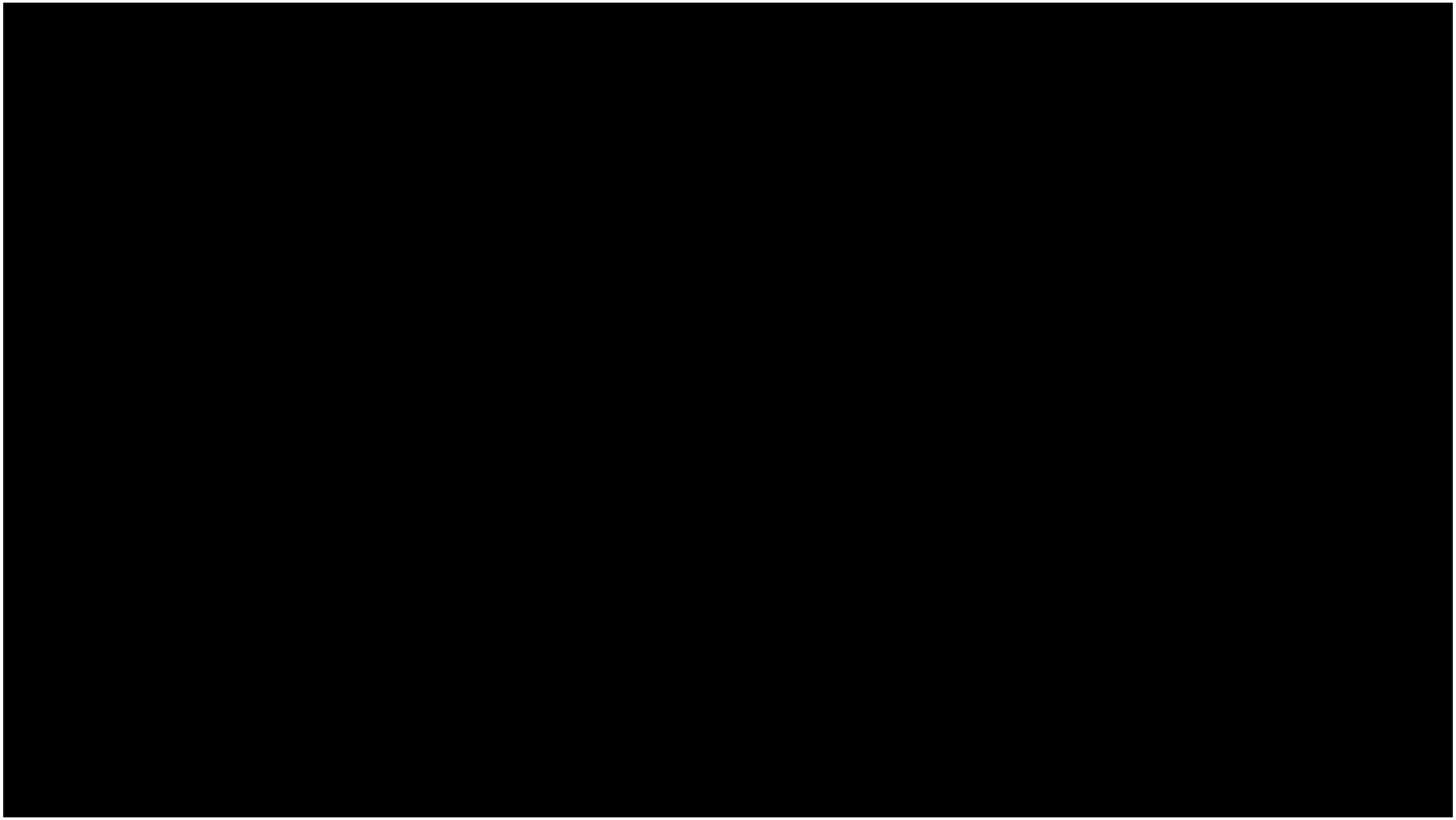


Figure 11.22 (1 of 2)

(a) Schematic illustration of the centrifugal-casting process. Pipes, cylinder liners, and similarly shaped parts can be cast with this process.

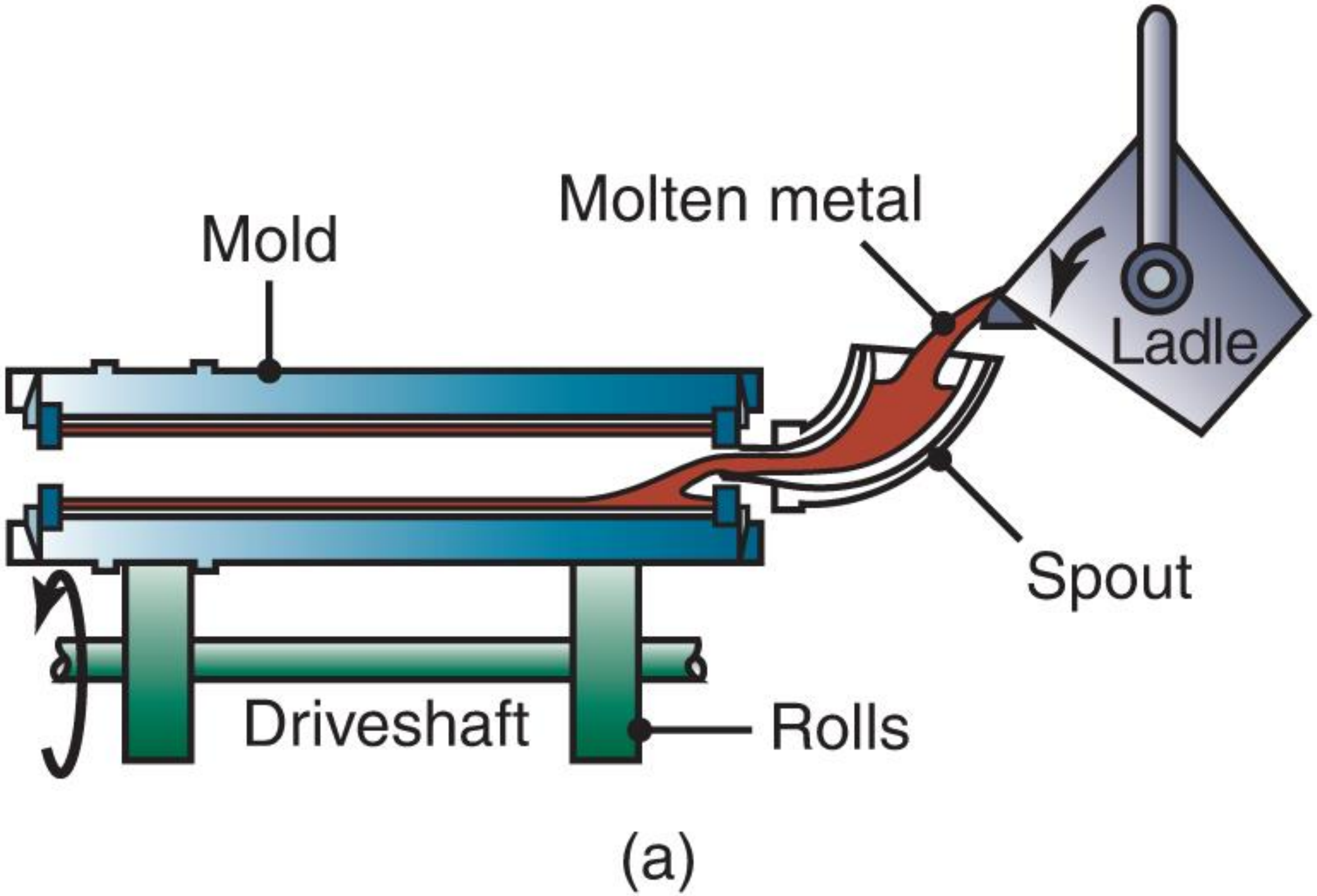
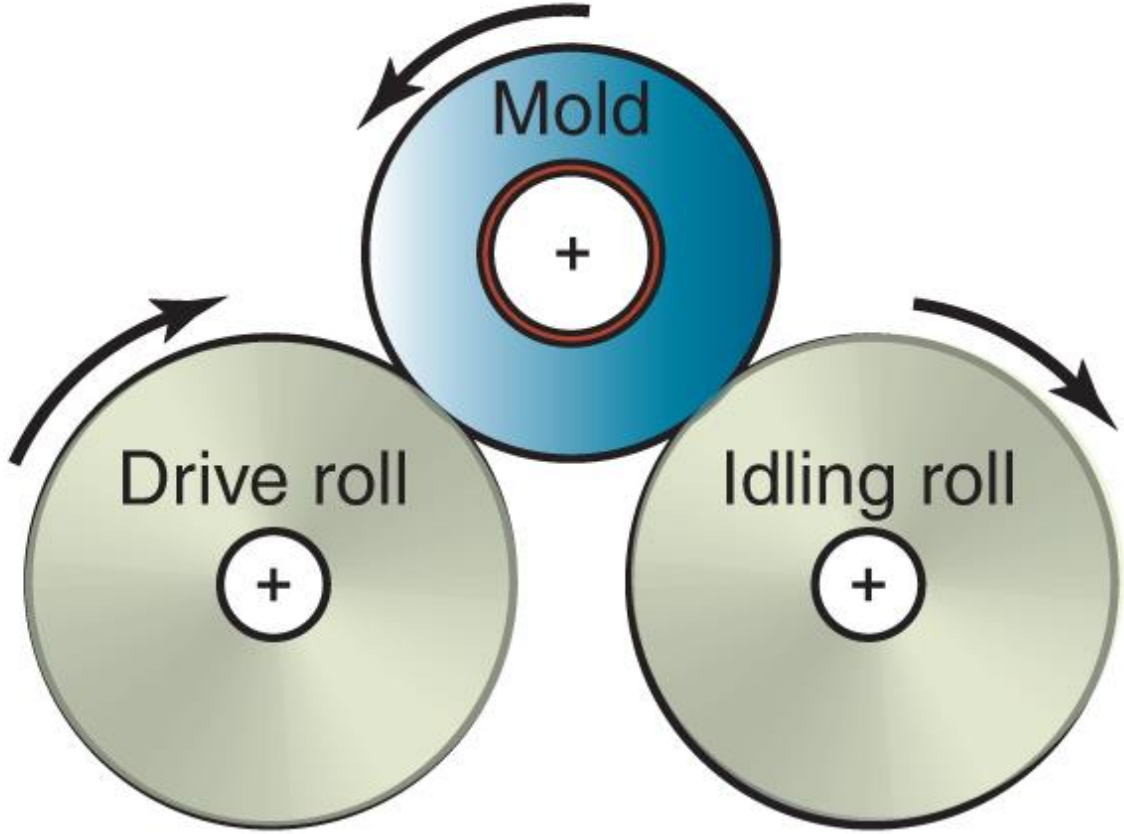


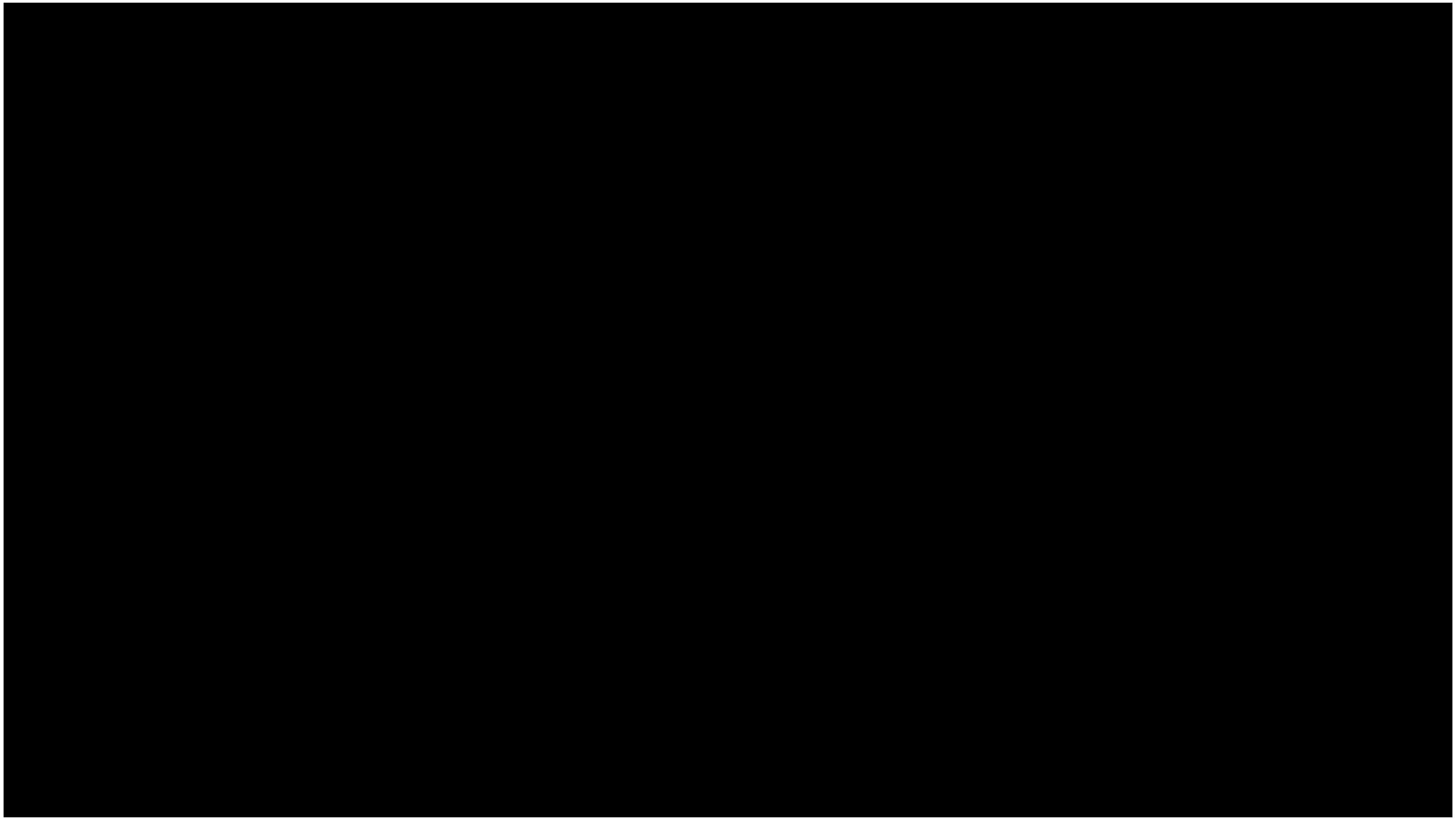
Figure 11.22 (2 of 2)

(b) Side view of the machine.



(b)

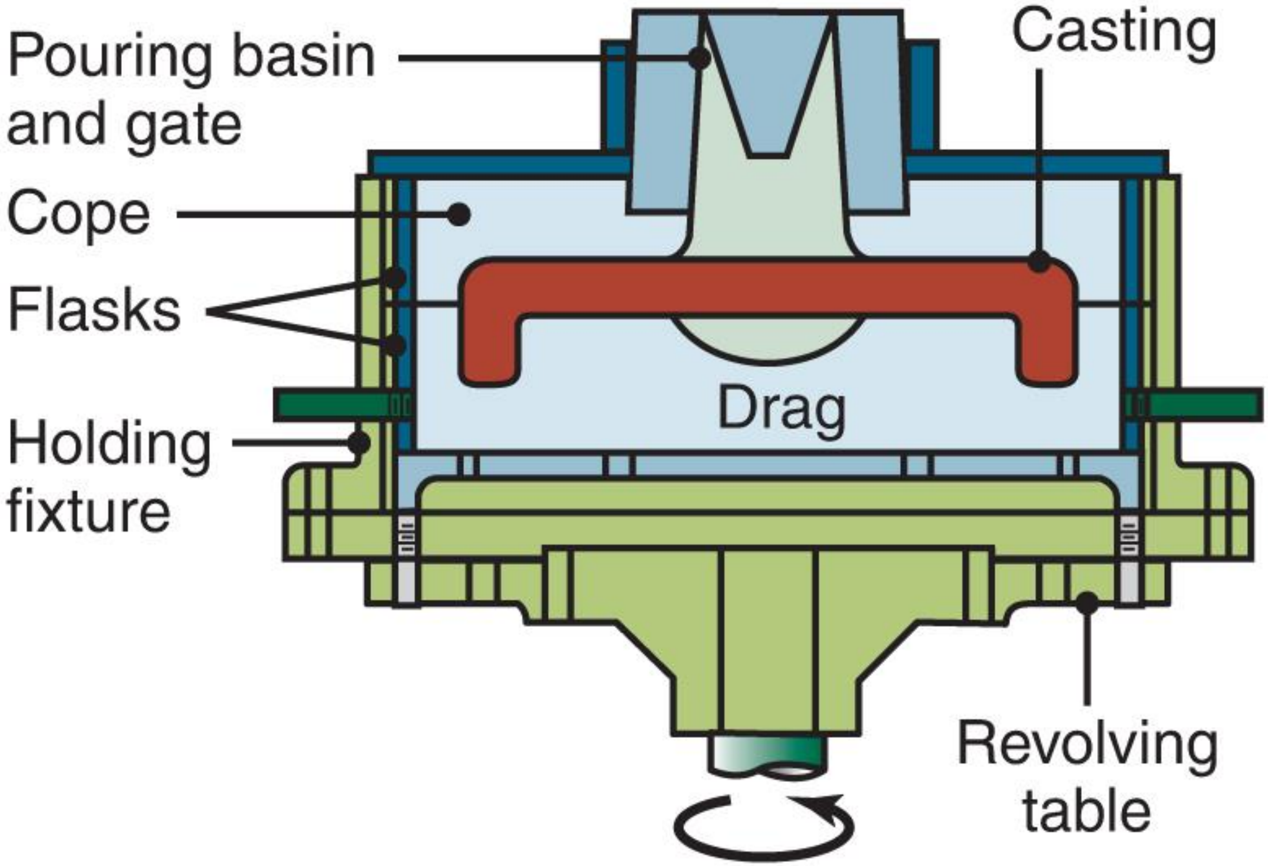
Centrifugal Casting



https://youtu.be/ojagGoNTyFs

Figure 11.23 (1 of 2)

(a) Schematic illustration of the semicentrifugal casting process. Wheels with spokes can be cast by this process.



(a)

Figure 11.23 (2 of 2)

(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 force.

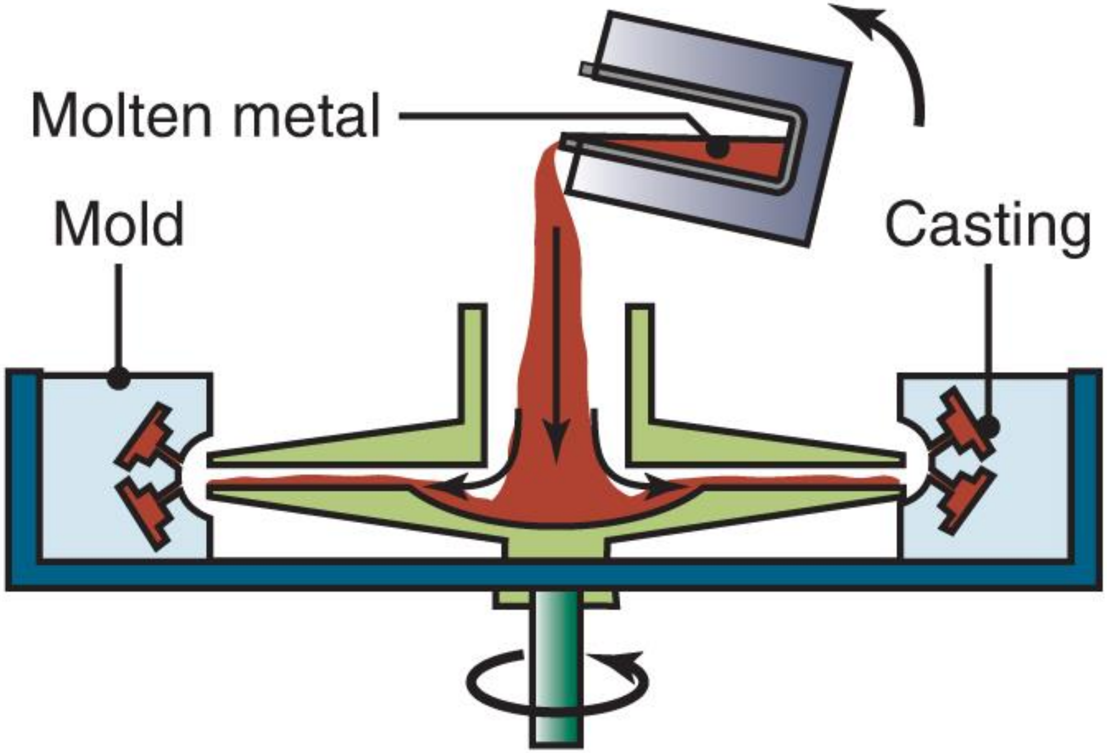


Figure 11.24 (1 of 4)

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

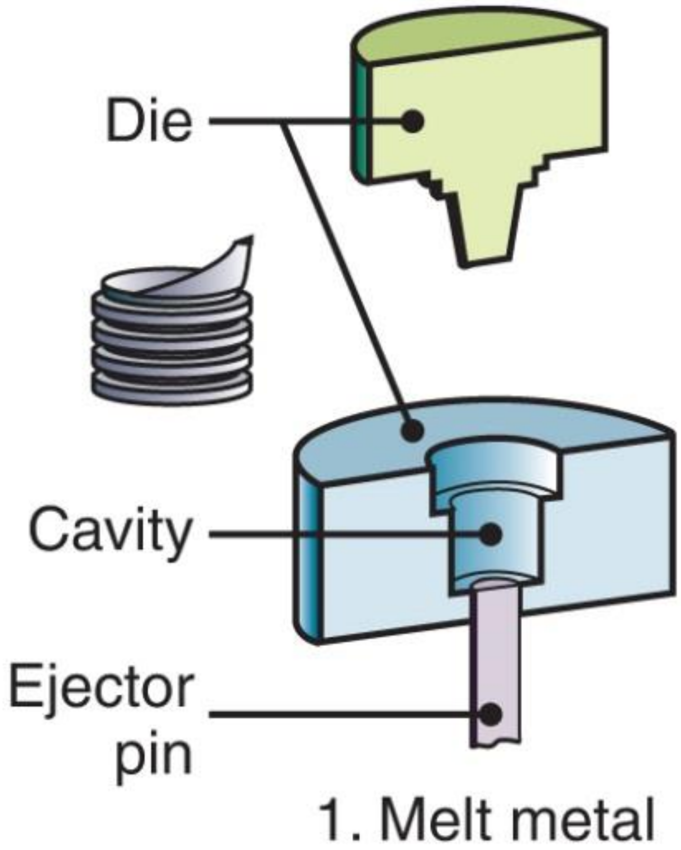
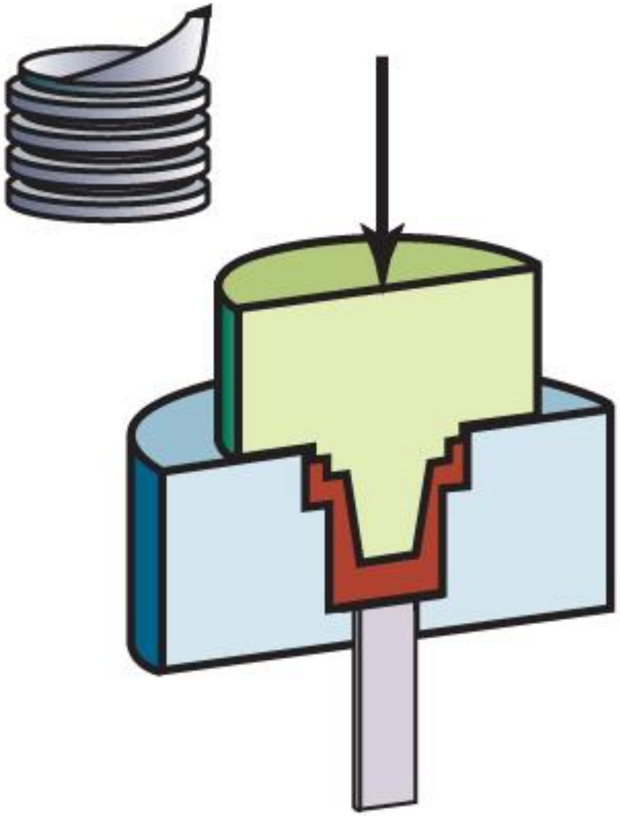


Figure 11.24 (2 of 4)

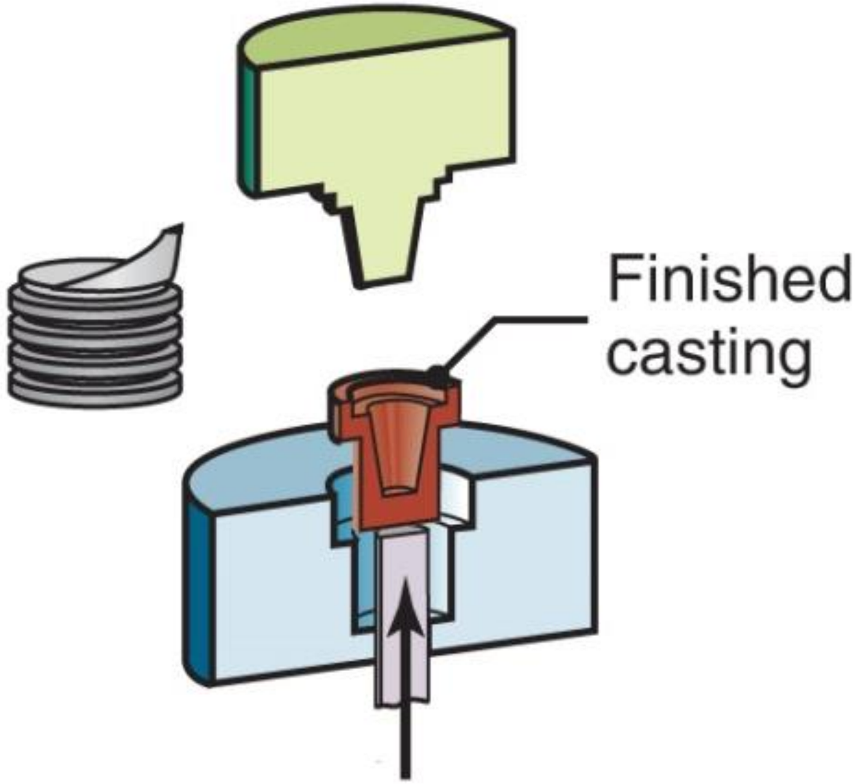
2. Pour molten metal into die

Figure 11.24 (3 of 4)



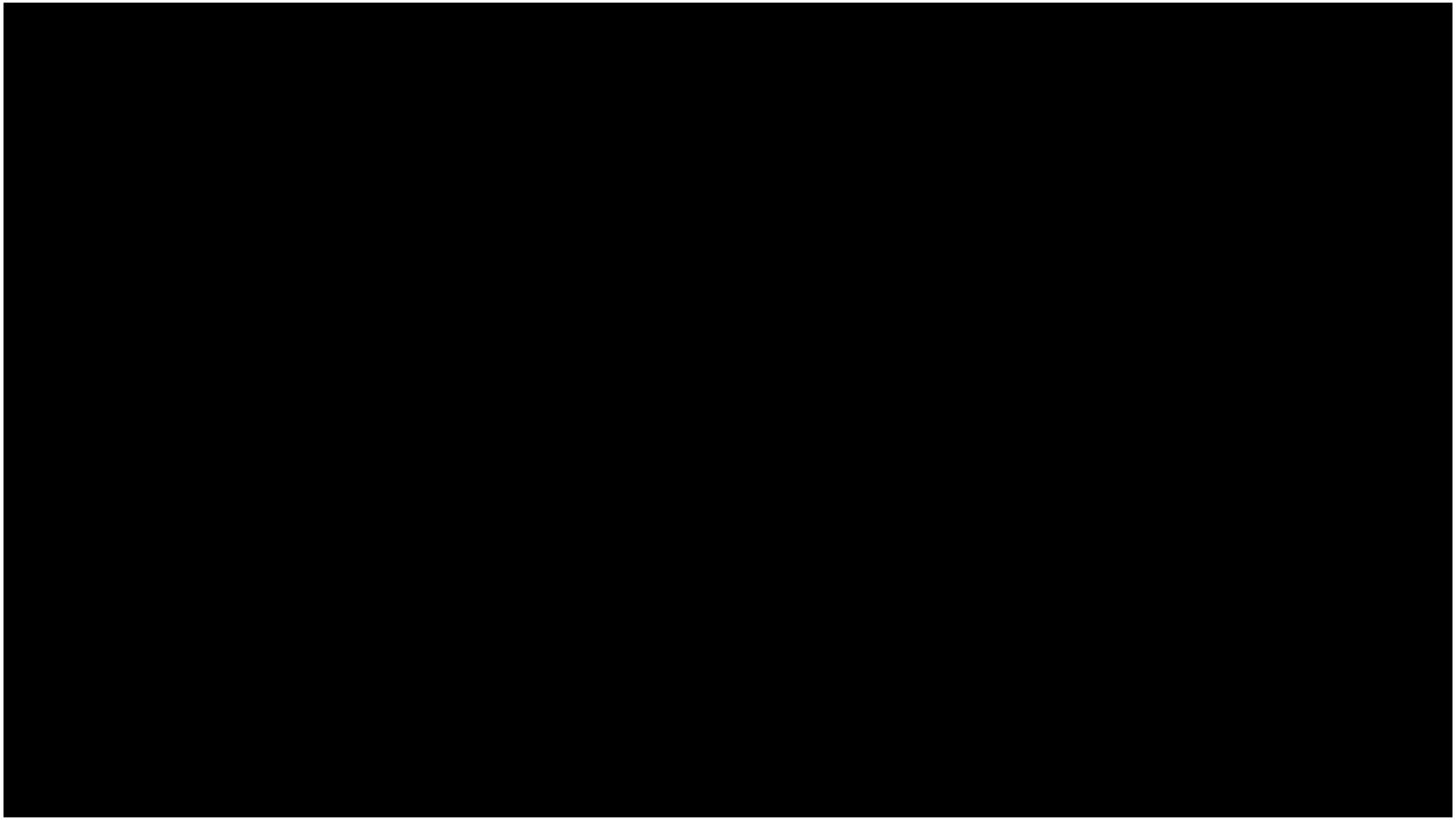
3. Close die and apply pressure

Figure 11.24 (4 of 4)



4. Eject squeeze casting,
charge melt stock,
repeat cycle

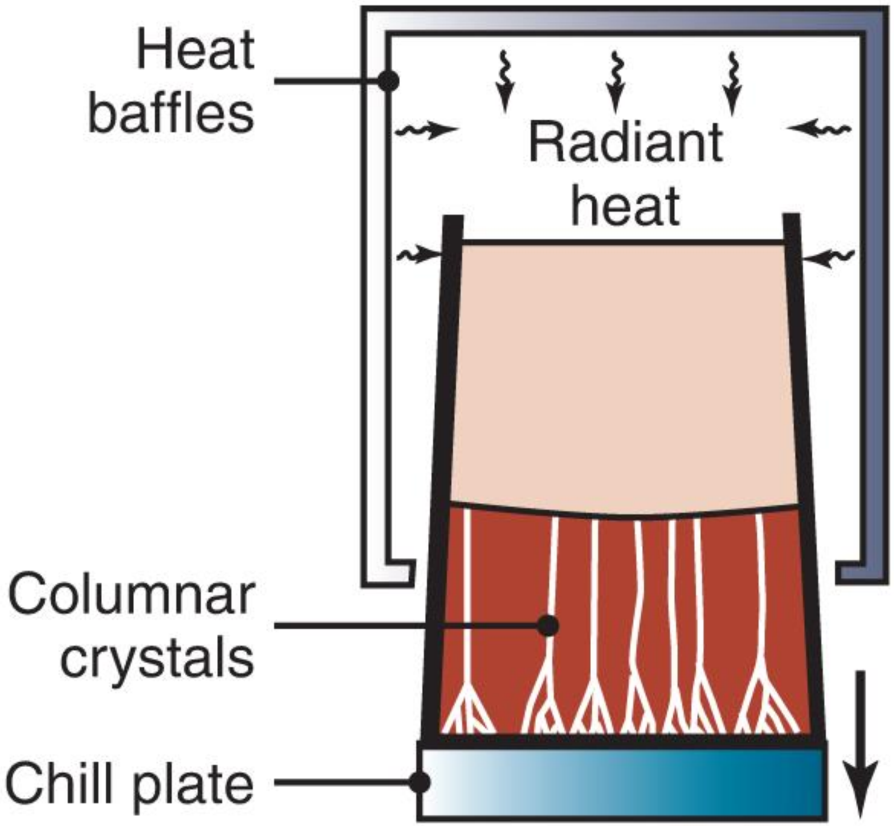
Squeeze Casting



https://youtu.be/GEexf3Fmz9k

Figure 11.25 (1 of 3)

Methods of casting turbine blades: (a) directional solidification.

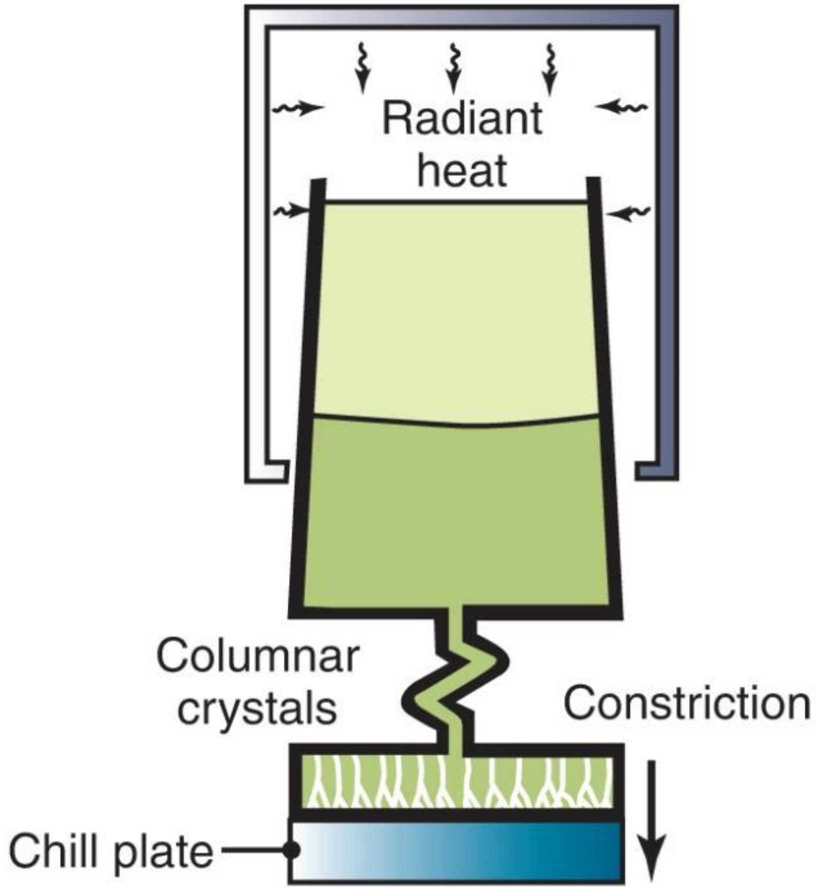


(a)

Source: (a) After B.H. Kear

Figure 11.25 (2 of 3)

Methods of casting turbine blades: (b) method to produce a single-crystal blade.



(b)

Source: (b) After B.H. Kear

Figure 11.25 (3 of 3)

Methods of casting turbine blades: (c) a single-crystal blade with the constriction portion still attached (see also Fig. 1.1).

(c)

Source: (c) Courtesy of ASM International.

Figure 11.26 (1 of 3)

Two methods of crystal growing: (a) crystal pulling (Czochralski process).

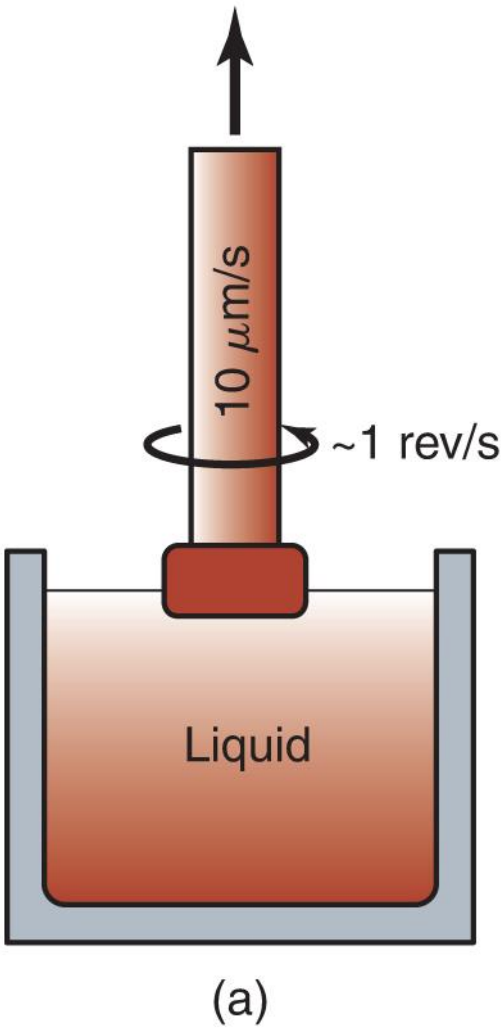
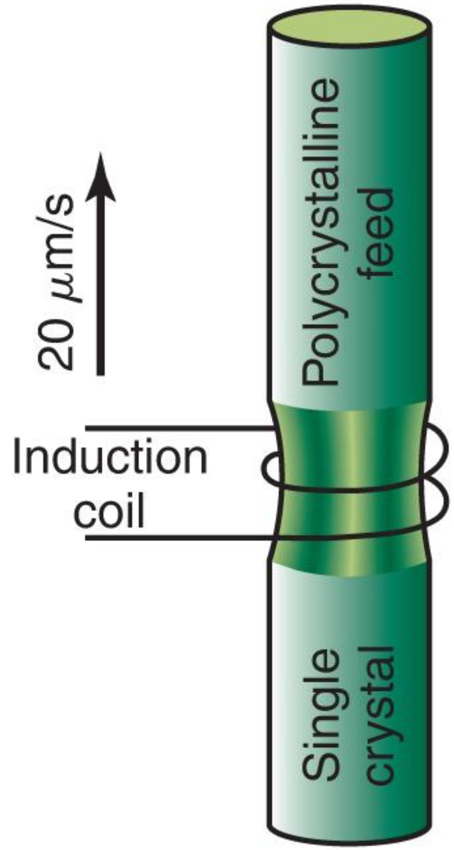


Figure 11.26 (2 of 3)

Two methods of crystal growing: (b) the floating-zone method.



(b)

Figure 11.26 (3 of 3)

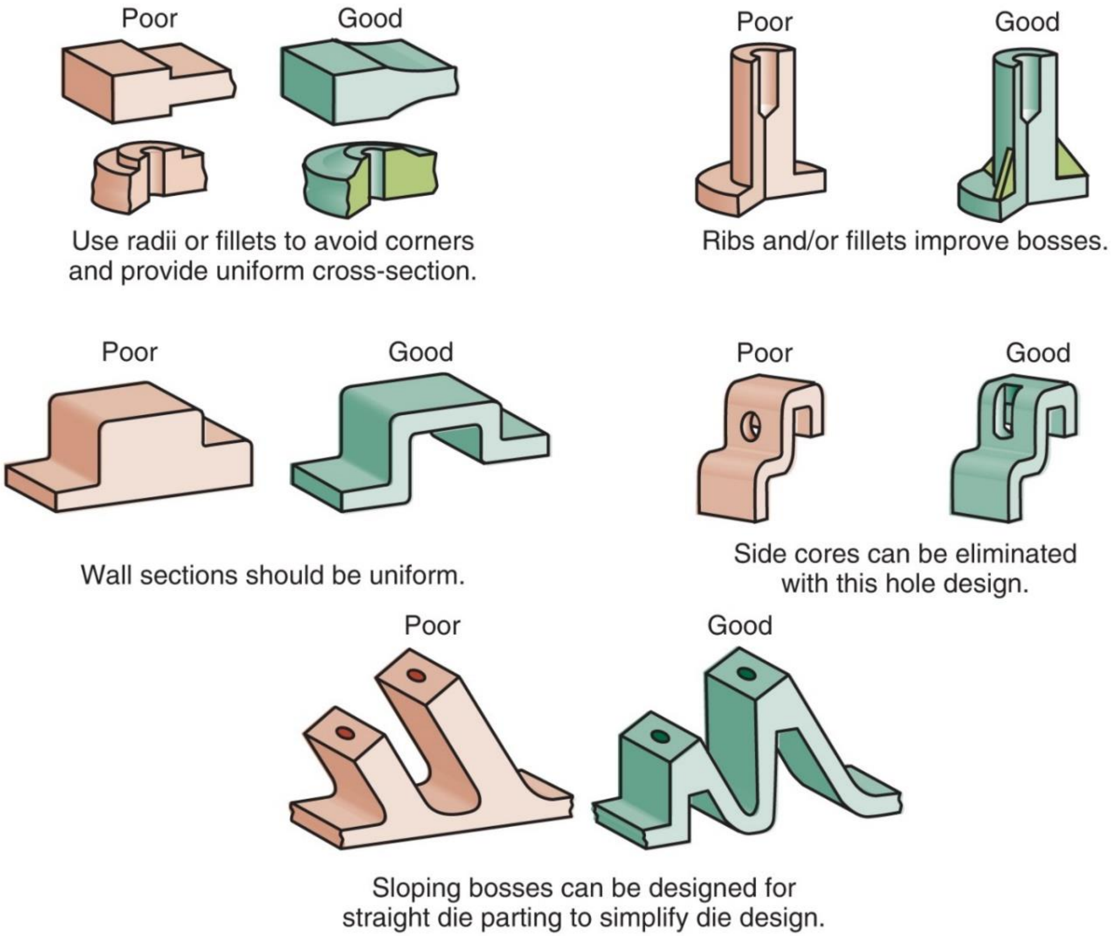
Two methods of crystal growing: (c) A single-crystal ingot produced by the Czochralski process.

(c)

Source: Courtesy of Intel Corp.

Figure 12.1

Suggested design modifications to avoid defects in castings.



Source: Courtesy of the American Die Casting Institute.

Figure 12.2 (1 of 5)

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.

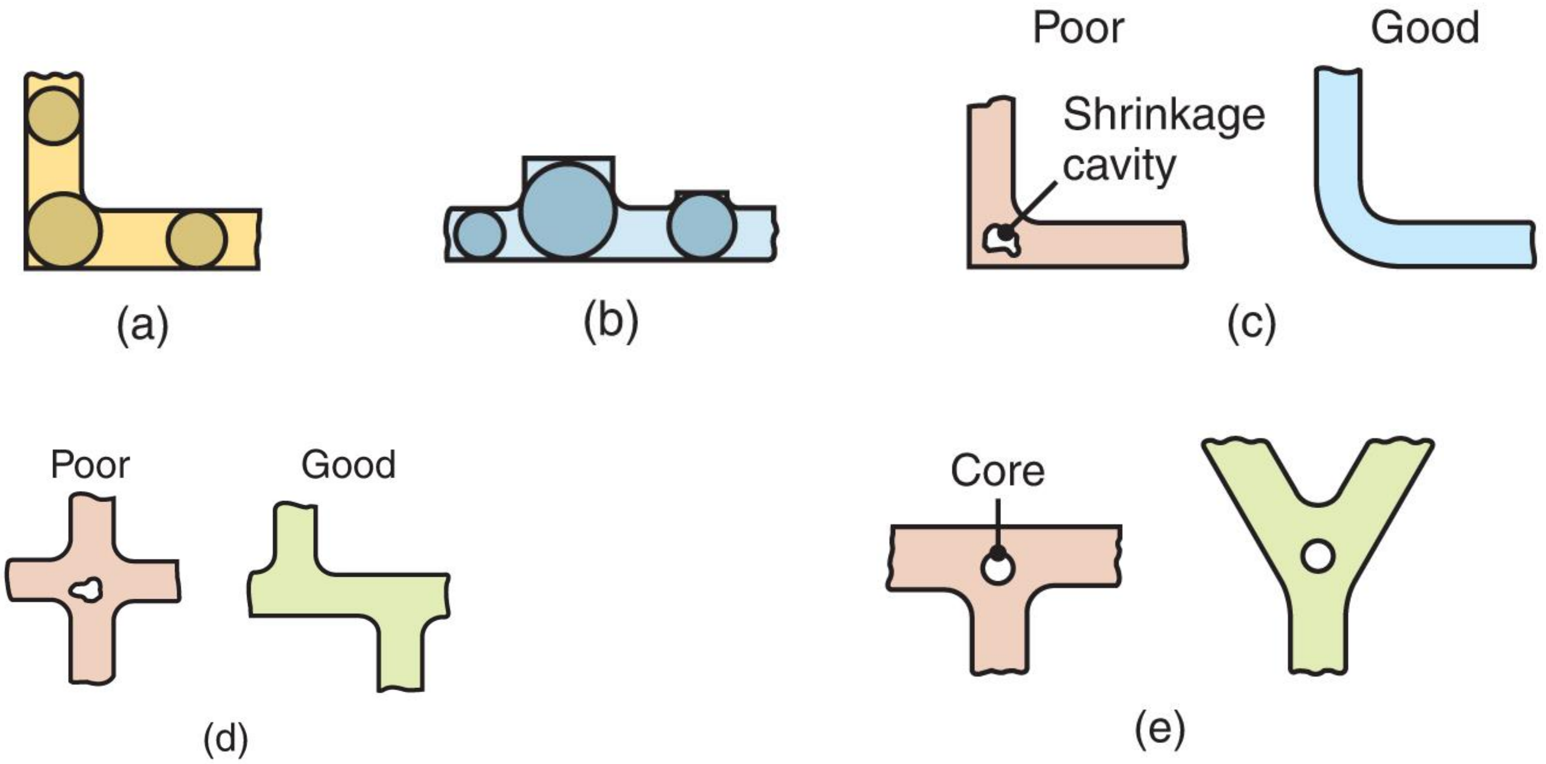


Figure 12.3 (1 of 4)

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.

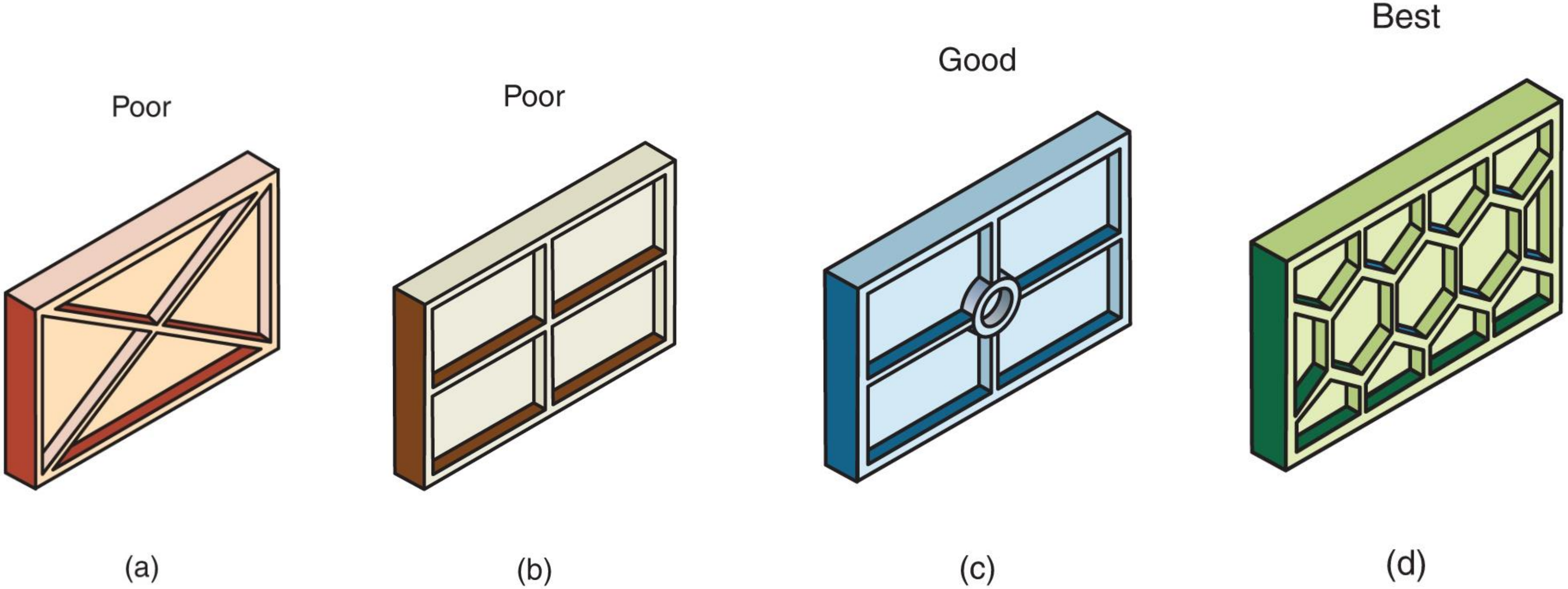


Table 12.1

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

Figure 12.4 (1 of 5)

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

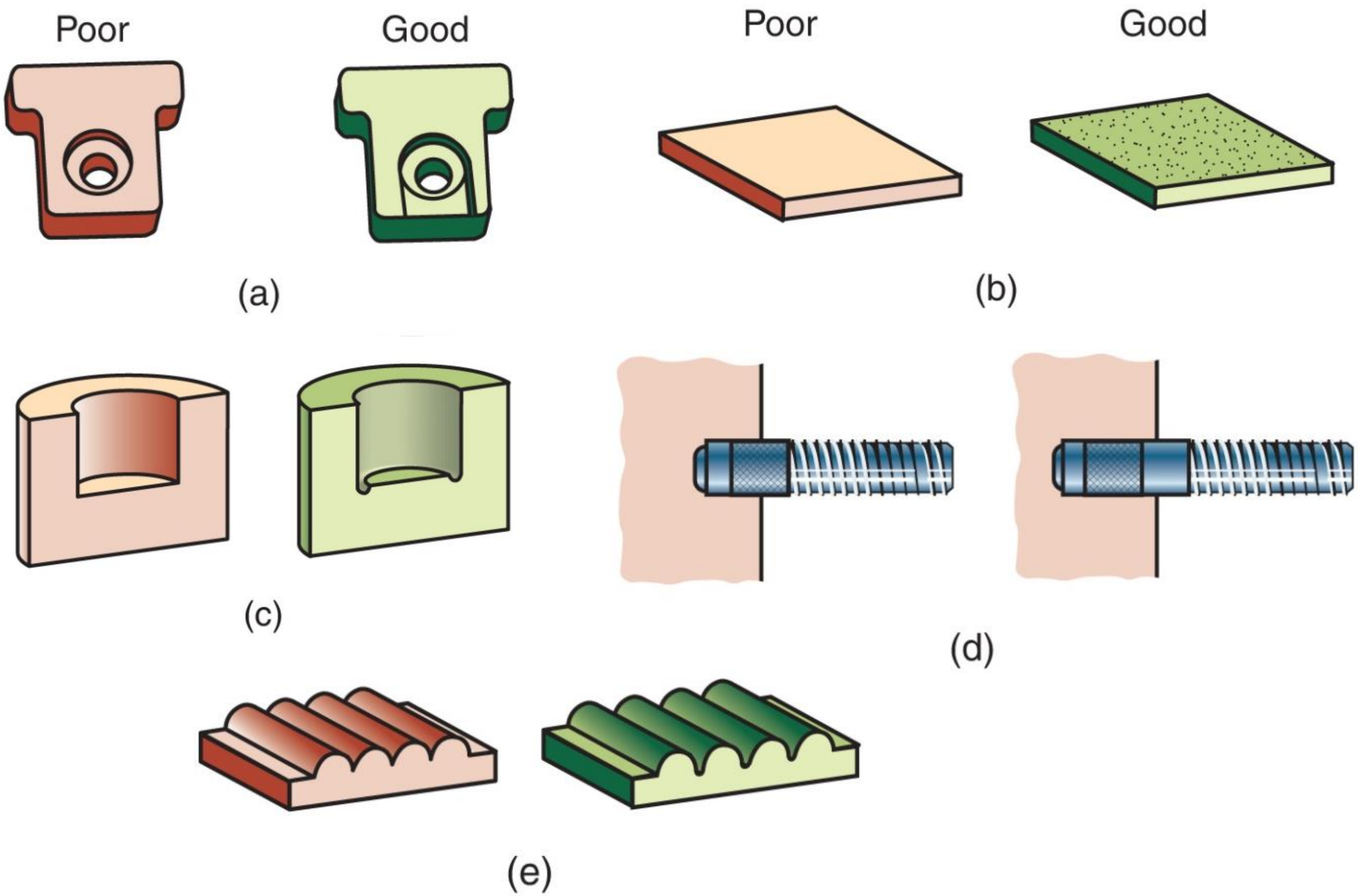


Figure 12.5 (1 of 8)

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.

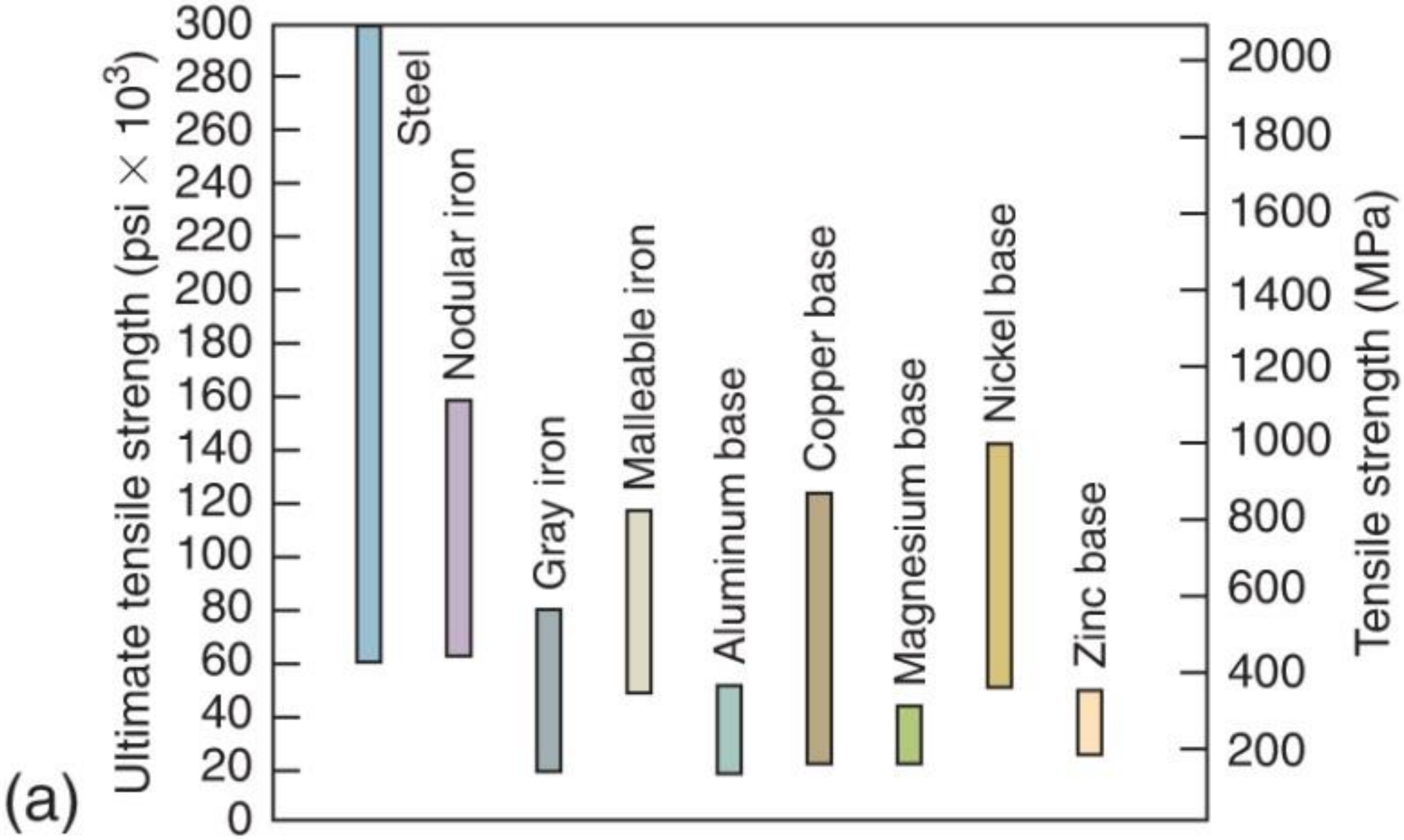
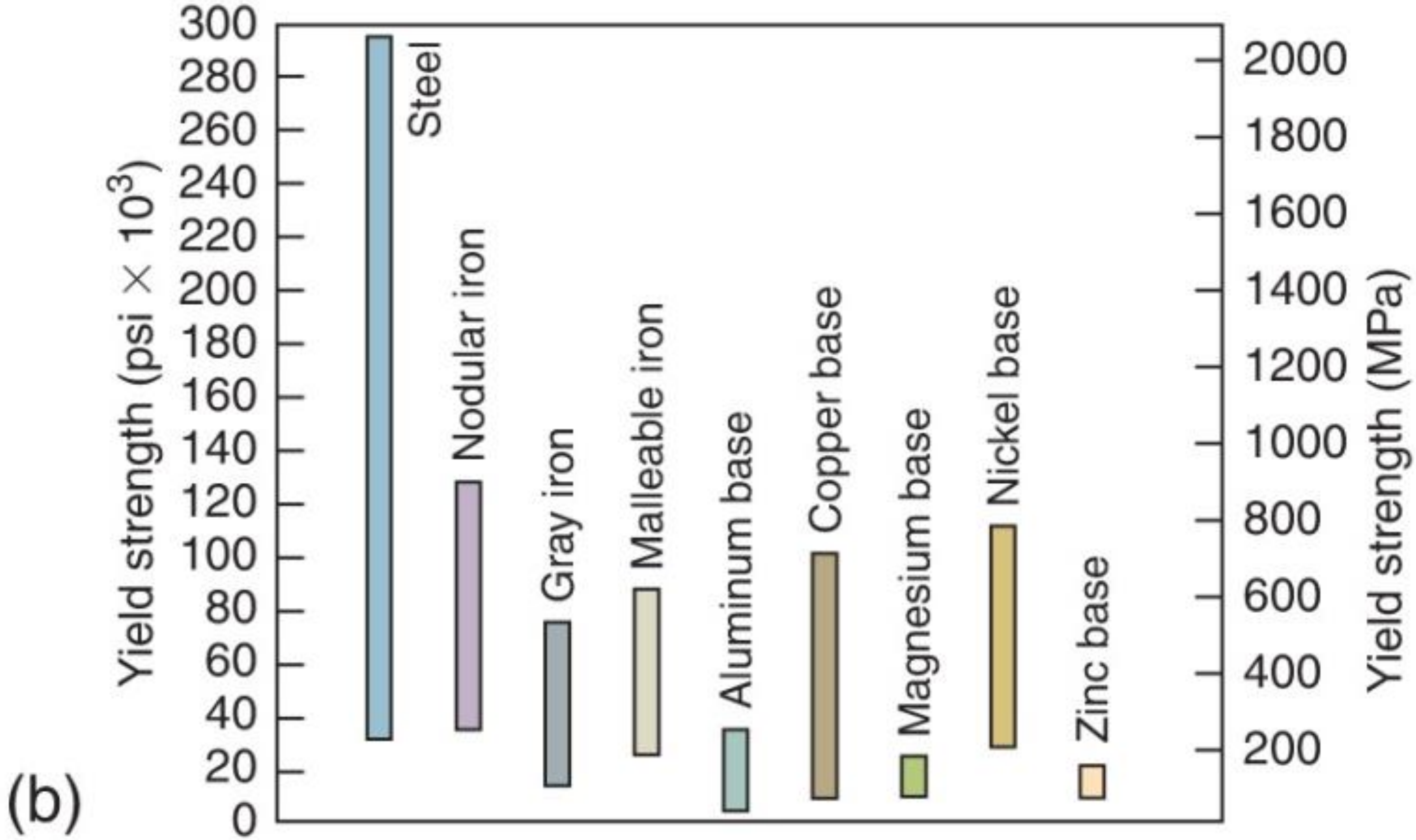


Figure 12.5 (2 of 8)



Pearson

Figure 12.5 (3 of 8)

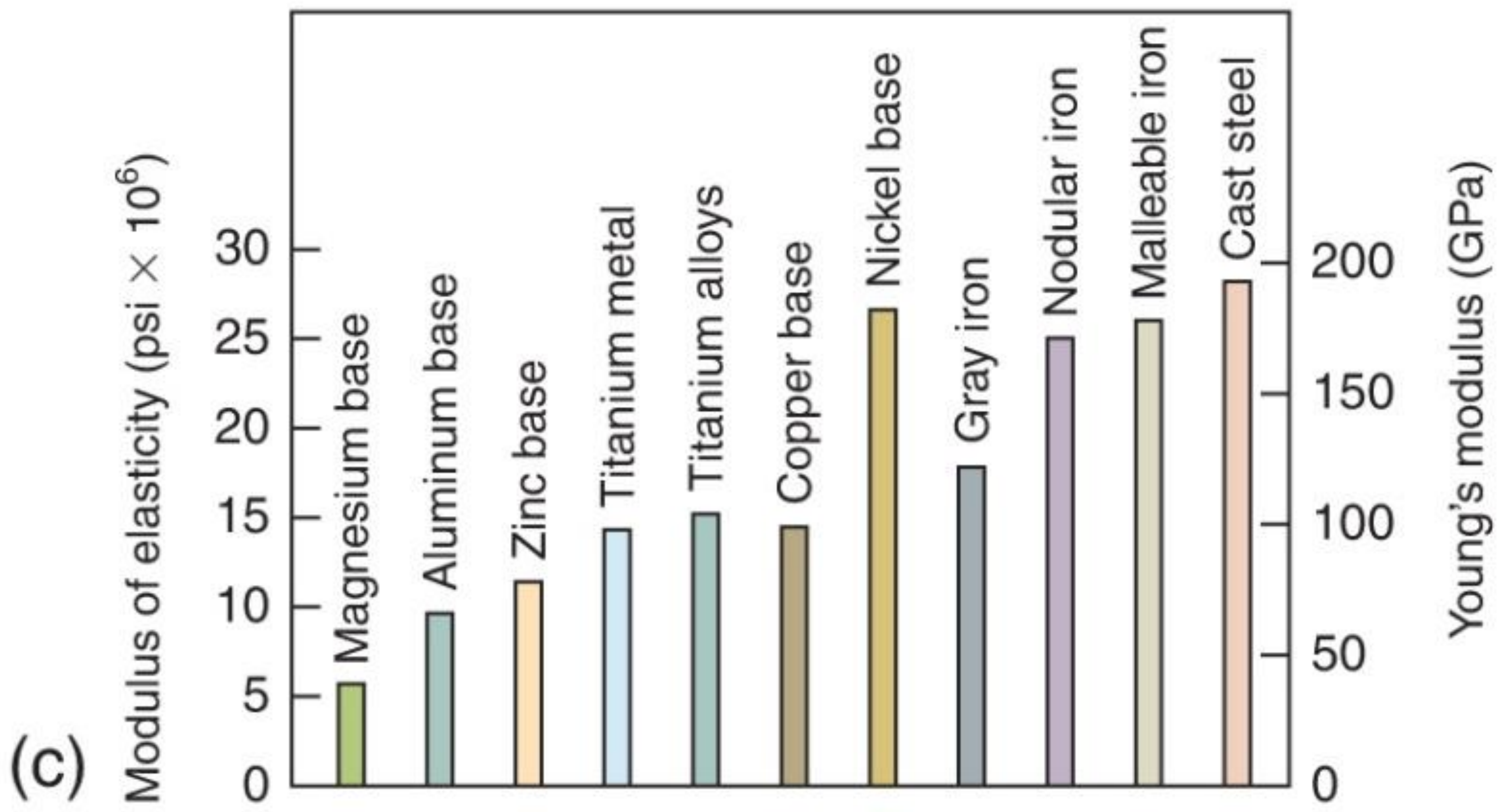


Figure 12.5 (4 of 8)

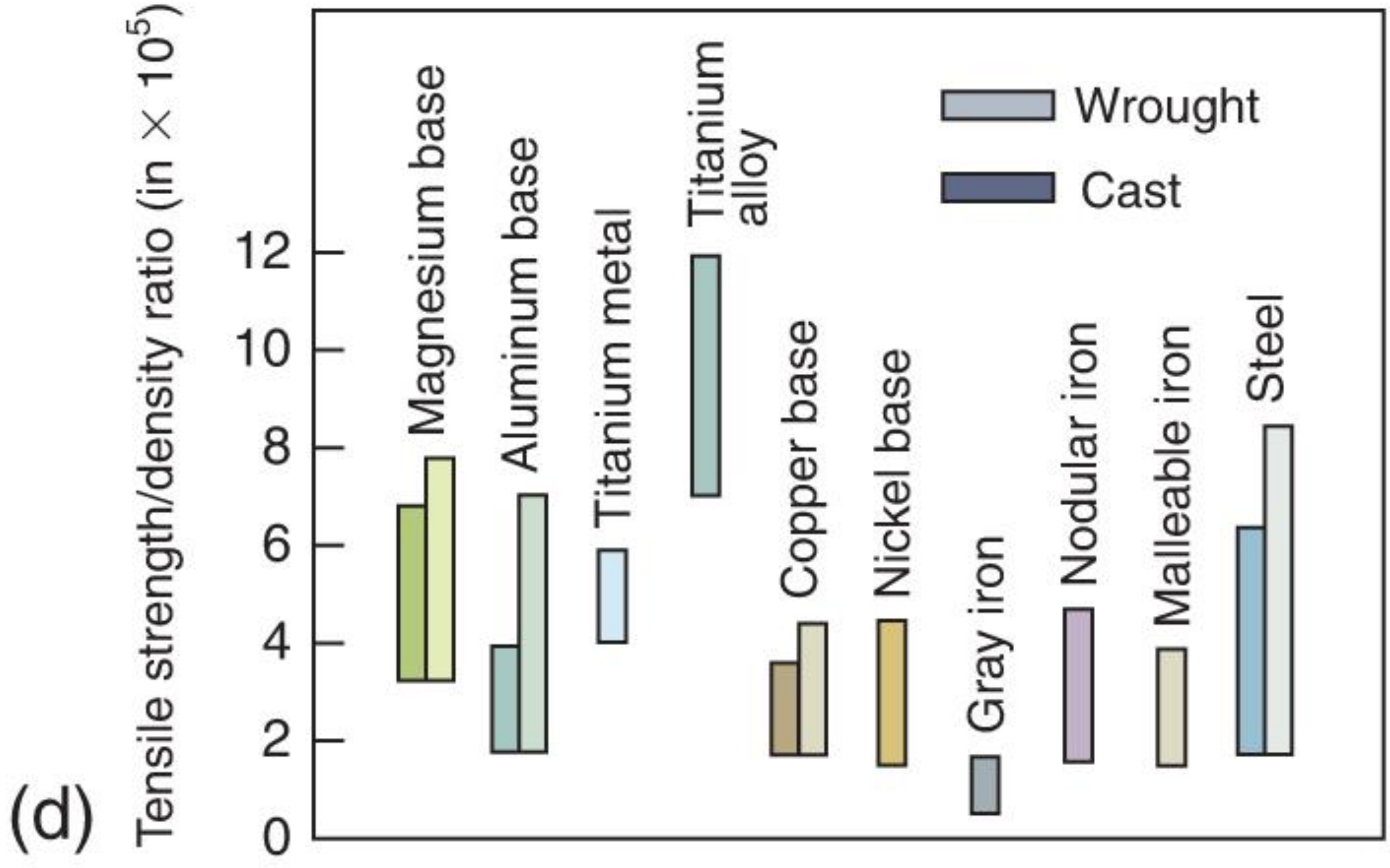


Figure 12.5 (5 of 8)

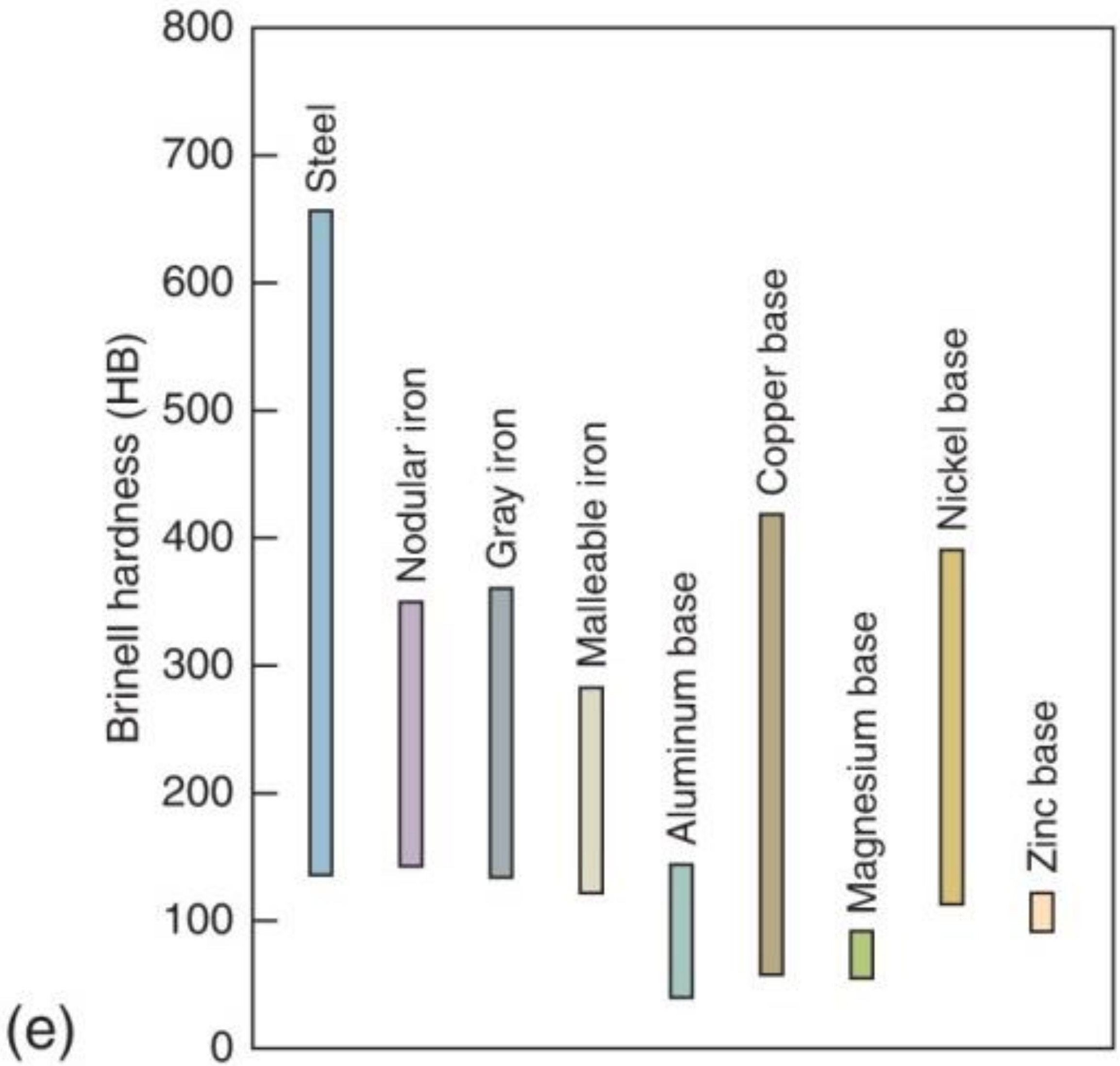


Figure 12.5 (6 of 8)

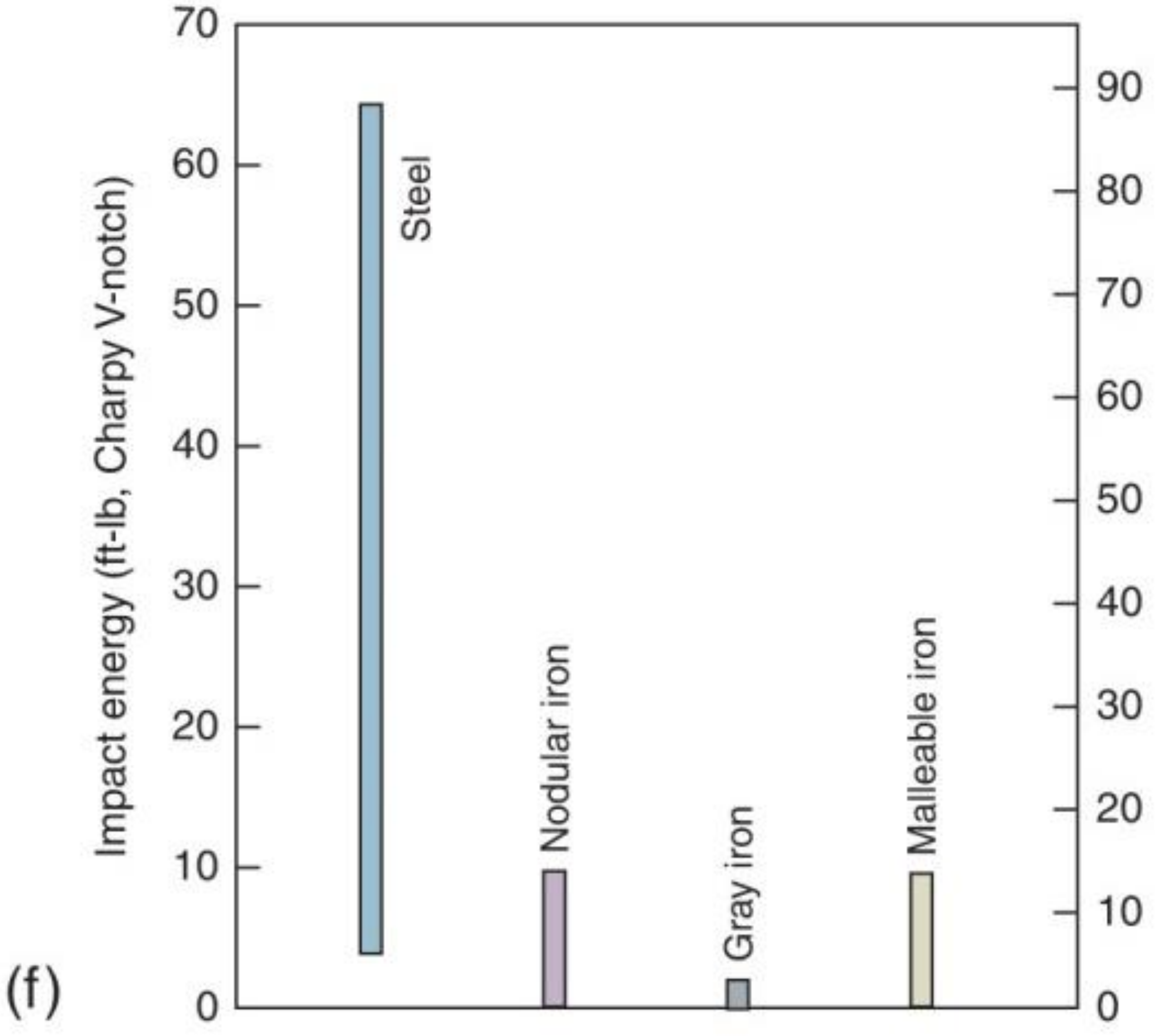


Figure 12.5 (7 of 8)

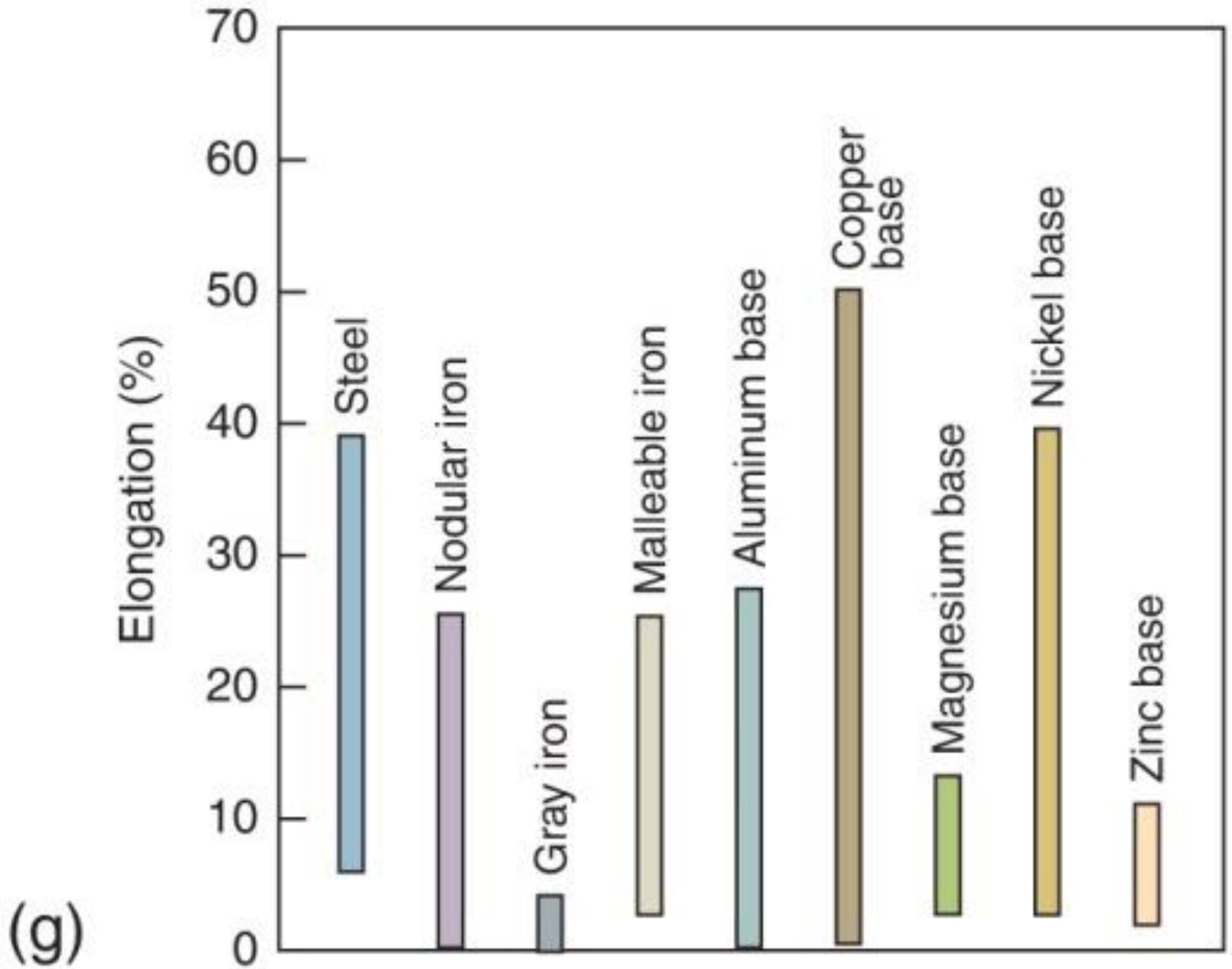
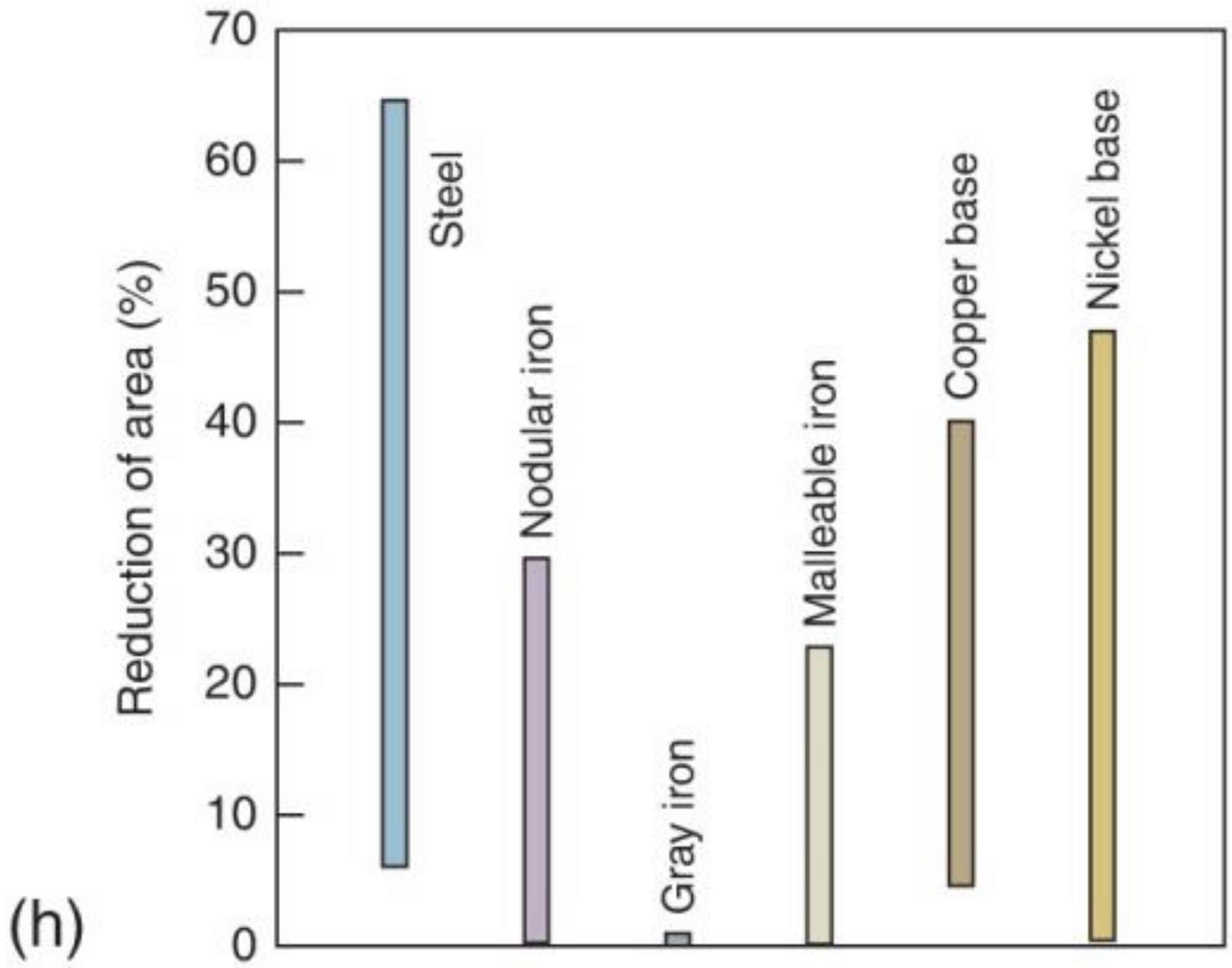


Figure 12.5 (8 of 8)



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 12.6

General Cost Characteristics of Casting Processes.

	Cost*			Production rate
Casting process	Die	Equipment	Labor	(pieces/hr)
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.