Metal Casting

Manufacturing

Processes

Outline

- Sand Casting
- Shell Mold Casting
- Composite Molds
- Expendable Pattern Casting
- Plaster Mold Casting
- Ceramic Mold Casting
- Investment Casting
- Pressure Casting
- Vacuum Casting
- Die Casting
- **Centrifugal Casting**
- **Squeeze Casting and Semisolid Metal Forming**
- **Casting Single Crystals**
- **Rapid Solidification**
- **Melting**
- **Design Considerations**

Two Categories of Casting Processes

Expendable mold processes - mold is sacrificed to remove part

- Advantage: more complex shapes possible
- Disadvantage: production rates often limited by time to make mold rather than casting itself

Permanent mold processes - mold is made of metal and can be used to make many castings

- Advantage: higher production rates
- Disadvantage: geometries limited by need to open mold

General Characteristics of Casting

	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+
Typ. surface finish (μm R_a)	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
Typ. dimensional tolerance	1.6-4 (0.25 for small)	±0.003		±0.005–0.010	±0.005	±0.015	±0.001–0.005	±0.015
Cost[1,2]								
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[2,3]	Days	Weeks	weeks	Days	Weeks	Weeks	Weeks-months	Months
Typical production rate[2,3]	1-20	5-50	1-20	1-10	1-1000	5-50	2-200	1-1000
Minimum quantity[2,3]	1	100	500	10	10	1000	10,000	10-10,000

Notes:

1. Relative rating, 1 best, 5 worst. For example, 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 only general; significant variations can occur depending on the manufacturing methods used.
2. Data taken from Schey, J.A., *Introduction to Manufacturing Processes*, 3rd ed, 2000.
3. Approximate values without the use of rapid prototyping technologies.

TABLE 5.2 General characteristics of casting processes.

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Typical Casting Metals

Aluminum
Aluminum-silicon alloy
Aluminum-copper
Brass
Gray cast iron
Copper
Lead
Steel

Overview of Sand Casting

- Most widely used casting process, accounting for a significant majority of total tonnage cast
- Nearly all alloys can be sand casted, including metals with high melting temperatures, such as steel, nickel, and titanium
- Castings range in size from small to very large
- Production quantities from one to millions

Steps in Sand Casting in detail

1. Place pattern on molding board.
2. Place drag parting surface down on molding board.
3. Riddle sand over pattern until covered.
4. Press sand around pattern with fingers.
5. Completely fill drag with sand.
6. Use a ram to pack sand.
7. Remove excess sand with strike rod.
8. Make vent holes for gases to escape.
9. Place bottom board on drag.
10. Turn over drag and remove molding board.
11. Smooth molding sand.
12. Add fine coat of parting sand.
13. Place the cope on the drag.
14. Add sprue pin ~ 1” to side of pattern.
15. Fill, ram, & vent cope as done.
16. Withdraw sprue pin.
17. Create a funnel opening.
18. Separate cope from drag.
19. Moisten drag mold edges with swab.
20. Use draw spike to loosen pattern.
21. Remove the pattern.
22. Cut gate from sprue to pattern cavity.
23. Cut riser in cope to channel hot metal.
24. Spray, swab, or dust the mold surfaces with coating material.
25. Re-assemble cope and drag to prepare for pouring.
26. Weight cope to prevent seepage at parting line.
27. Pour the metal.
28. Allow to cool.
29. Separate and clean casting.
30. Reclaim the sand & clean the flask.

Making the Sand Mold

- The *cavity* in the sand mold is formed by packing sand around a pattern, then separating the mold into two halves and removing the pattern
- The mold must also contain gating and riser system
- If casting is to have internal surfaces, a *core* must be included in mold
- A new sand mold must be made for each part produced

The Pattern

A full-sized model of the part, slightly enlarged to account for shrinkage and machining allowances in the casting

Pattern materials:

- Wood - common material because it is easy to work, but <u>it warps</u>
- Metal - <u>more expensive</u> to make, but lasts much longer
- Plastic - compromise between wood and metal

Types of Patterns

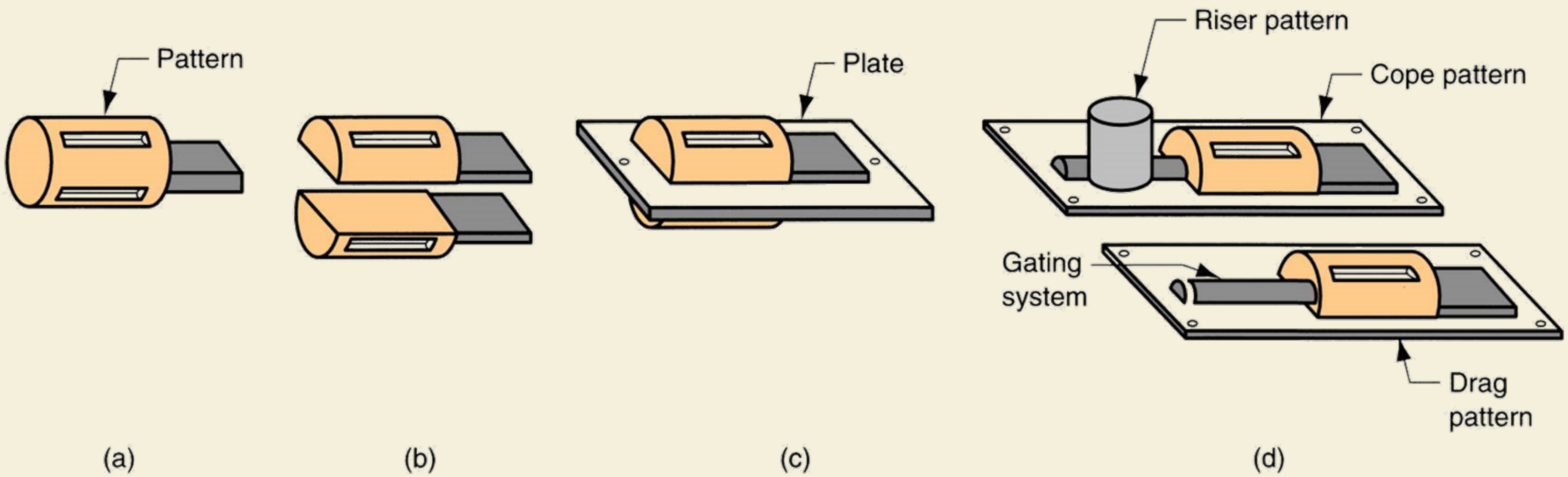
Figure 11.3 Types of patterns used in sand casting:

(a) solid pattern

(b) split pattern

(c) match-plate pattern

(d) cope and drag pattern



Core

- Full-scale model of interior surfaces of part
- It is inserted into the mold cavity prior to pouring
- The molten metal flows and solidifies between the mold cavity and the core to form the casting's external and internal surfaces.
- May require supports to hold it in position in the mold cavity during pouring, called *chaplets*

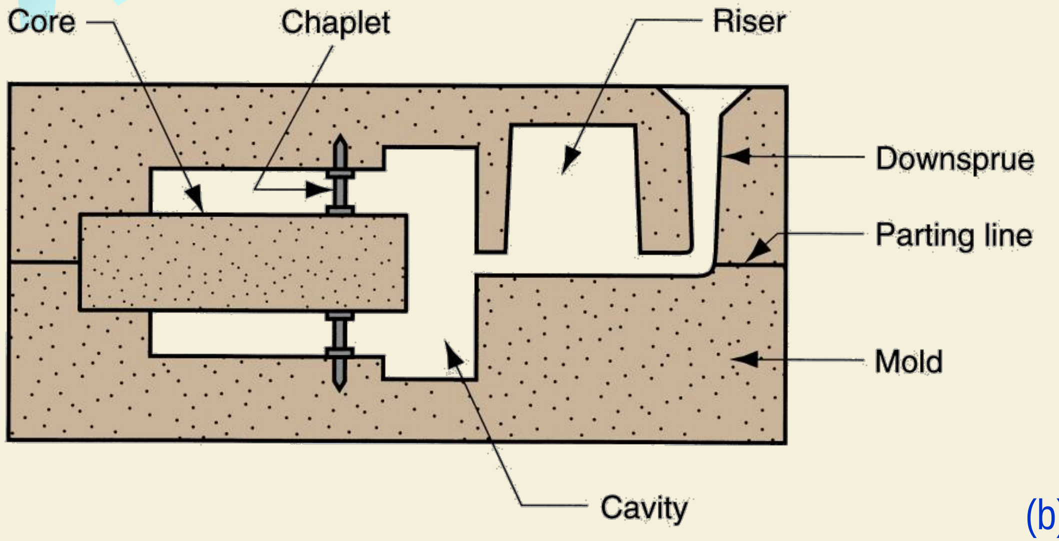
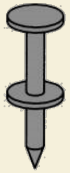
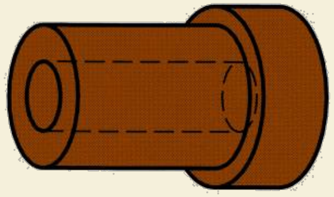


Figure 11.4 (a) Core held in place in the mold cavity by chaplets,



(b) possible chaplet design,



(c) casting with internal cavity.

Desirable Mold Properties

- Strength - to maintain shape and resist erosion
- Permeability - to allow hot air and gases to pass through voids in sand
- Thermal stability - to resist cracking on contact with molten metal
- Collapsibility - ability to give way and allow casting to shrink without cracking the casting
- Reusability - can sand from broken mold be reused to make other molds?

Erosion: to eat into or away by slow destruction of substance
Permeability: capable of being penetrable

Foundry Sands

- Silica (SiO_2) or silica *mixed* with other minerals

- Good refractory properties - capacity to endure high temperatures

- Small grain size yields better surface finish on the cast part

- Large grain size is more permeable, allowing gases to escape during pouring

- Irregular grain shapes strengthen molds due to interlocking, compared to round grains

Disadvantage: interlocking tends to reduce permeability

Binders Used with Foundry Sands

Sand is held together by a mixture of water and bonding clay

- Typical mix: 90% sand, 3% water, and 7% clay

Other bonding agents also used in sand molds:

- Organic resins (eg , phenolic resins)
- Inorganic binders (eg , sodium silicate and phosphate)

Additives are sometimes combined with the mixture to increase strength and/or permeability

Phenol = a corrosive poisonous crystalline acidic compound C_6H_5OH present in the tars of coal and wood that in dilute solution is used as a disinfectant

Types of Sand Mold

Green-sand molds - mixture of sand, clay, and water;

- “Green" means mold contains moisture at time of pouring

Dry-sand mold - organic binders rather than clay

- And mold is baked to improve strength

Skin-dried mold - drying mold cavity surface of a green-sand mold to a depth of 10 to 25 mm, using torches or heating lamps

Buoyancy in Sand Casting Operation

- During pouring, buoyancy of the molten metal tends to displace the core, which can cause casting to be defective
- Force tending to lift core = weight of displaced liquid less the weight of core itself

$$F_b = W_m - W_c$$

where F_b = buoyancy force;

W_m = weight of molten metal displaced; and

W_c = weight of core

Mold Features

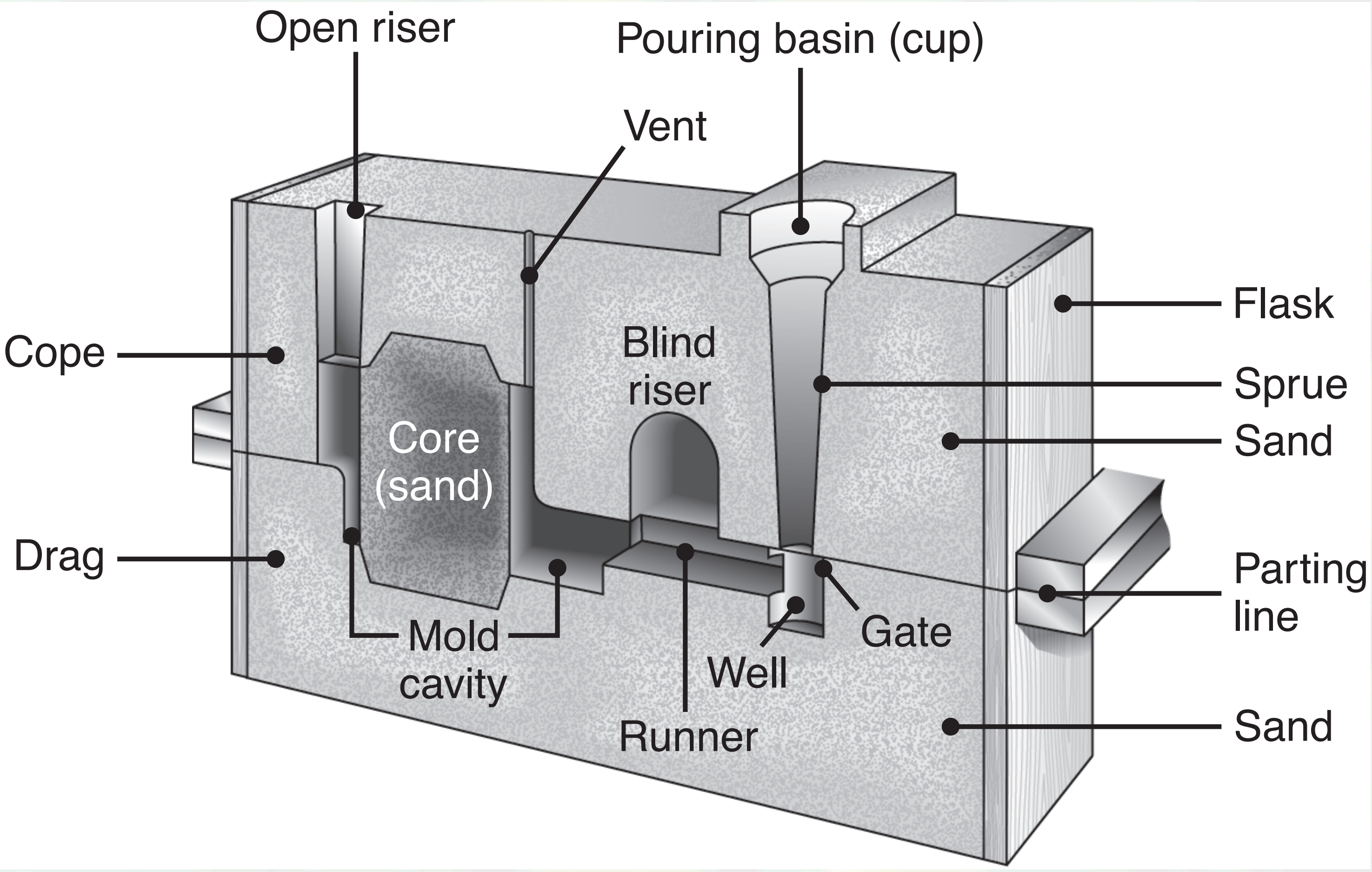


FIGURE 5.10 Schematic illustration of a typical sand mold showing various features.

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Temperature Distribution

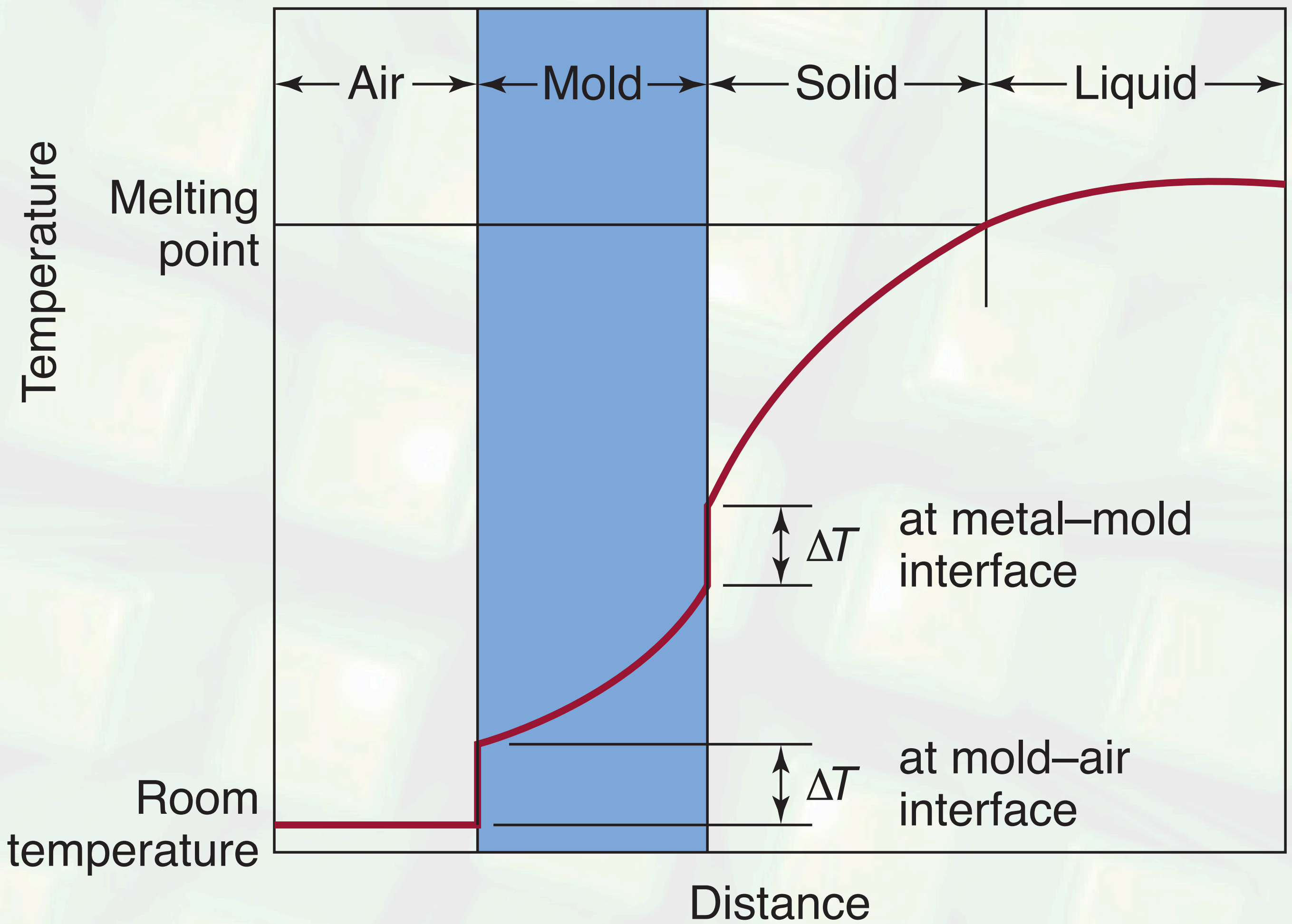

FIGURE 5.11 Temperature distribution at the mold wall and liquid-metal interface during solidification of metals in casting.

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Skin on Casting

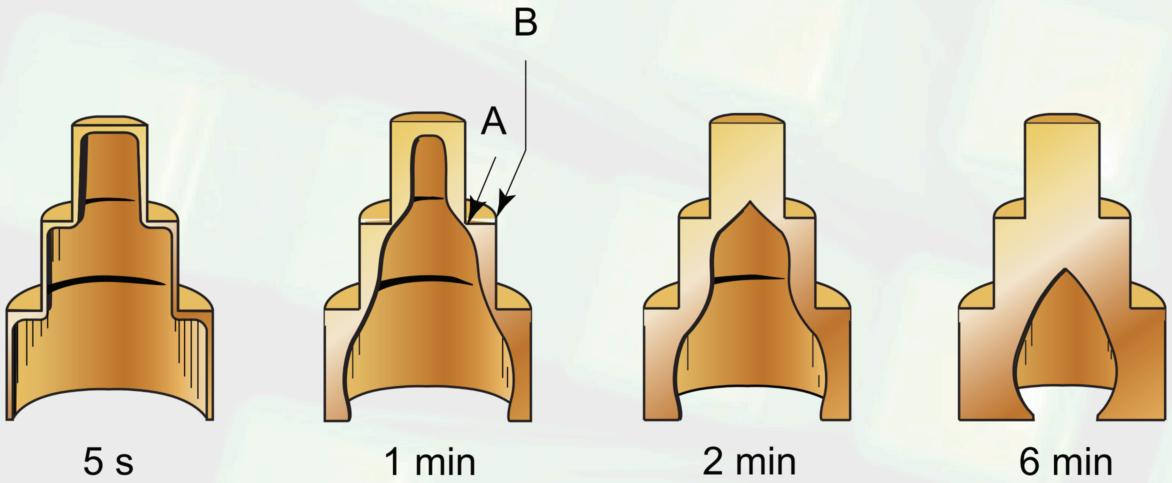

FIGURE 5.12 Solidified skin on a steel casting; the remaining molten metal is poured out at the times indicated in the figure. Hollow ornamental and decorative objects are made by a process called slush casting, which is based on this principle. *Source:* After H.F. Taylor, J. Wulff, and M.C. Flemings.

Chvorinov's Rule:

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

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Shrinkage

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

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

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Typical Applications & Characteristics

Type of Alloy	Application	Castability*	Weldability*	Machinability*
Aluminum	Pistons, clutch housings, intake manifolds, engine blocks, heads, cross members, valve bodies, oil pans, suspension components	G-E	F*	G-E
Copper	Pumps, valves, gear blanks, marine propellers	F-G	F	G-E
Gray Iron	Engine blocks, gears, brake disks and drums, machine bases	E	D	G
Magnesium	Crankcase, transmission housings, portable computer housings, toys	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
Nodular iron	Crankshafts, heavy-duty gears	G	D	G
Steel (carbon and low alloy)	Die blocks, heavy-duty gear blanks, aircraft undercarriage members, railroad wheels	F	E	F-G
Steel (high alloy)	Gas turbine housings, pump and valve components, rock crusher jaws	F	E	F
White iron (Fe_3C)	Mill liners, shot blasting 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.

TABLE 5.3 Typical applications for castings and casting characteristics.

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Properties & Applications of Cast Iron

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	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 resistance
Malleable	Ferritic	365	240	18	Hardware, pipe fittings, general engineering service
	Pearlitic	450	310	10	Couplings
	Tempered	700	550	2	Gears, connecting rods
White	Pearlitic	275	275	0	Wear resistance, mill rolls

TABLE 5.4 Properties and typical applications of cast irons.

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Nonferrous Alloys

Alloy	Condition	Casting Method*	UTS (MPa)	Yield Strength (MPa)	Elongation in 50 mm (%)	Hardness (HB)
Aluminum						
357	T6	S	345	296	2.0	90
380	F	D	331	165	3.0	80
390	F	D	279	241	1.0	120
Magnesium						
AZ63A	T4	S, P	275	95	12	—
AZ91A	F	D	230	150	3	—
QE22A	T6	S	275	205	4	—
Copper						
Brass C83600	—	S	255	177	30	60
Bronze C86500	—	S	490	193	30	98
Bronze C93700	—	P	240	124	20	60
Zinc						
No. 3	—	D	283	—	10	82
No. 5	—	D	331	—	7	91
ZA27	—	P	425	365	1	115

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

TABLE 5.5 Typical properties of nonferrous casting alloys.

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Sand Casting

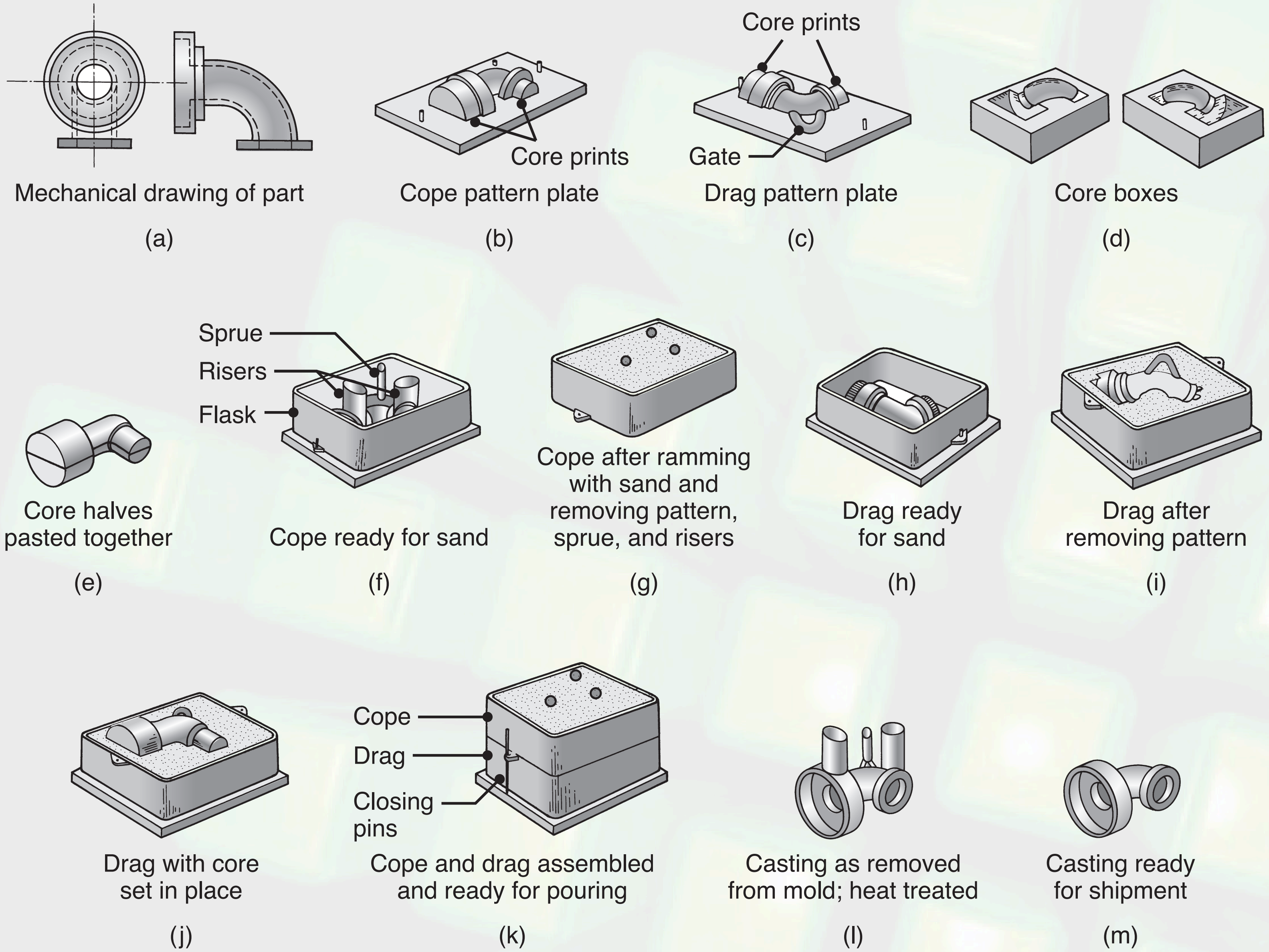

FIGURE 5.16 Schematic illustration of the sequence of operations in sand casting. (a) A mechanical drawing of the part, used to create patterns. (b-c) Patterns mounted on plates equipped with pins for alignment. Note the presence of core prints designed to hold the core in place. (d-e) Core boxes produce core halves, which are pasted together. The cores will be used to produce the hollow area of the part shown in (a). (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. (g) The flask is rammed with sand and the plate and inserts are removed. (h) The drag half is produced in a similar manner. (j) The core is set in place within the drag cavity. (k) The mold is closed by placing the cope on top of the drag and securing the assembly with pins. (l) After the metal solidifies, the casting is removed from the mold. (m) The sprue and risers are cut off and recycled, and the casting is cleaned, inspected, and heat treated (when necessary). *Source:* Courtesy of Steel Founders' Society of America.

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Shell-Molding Process

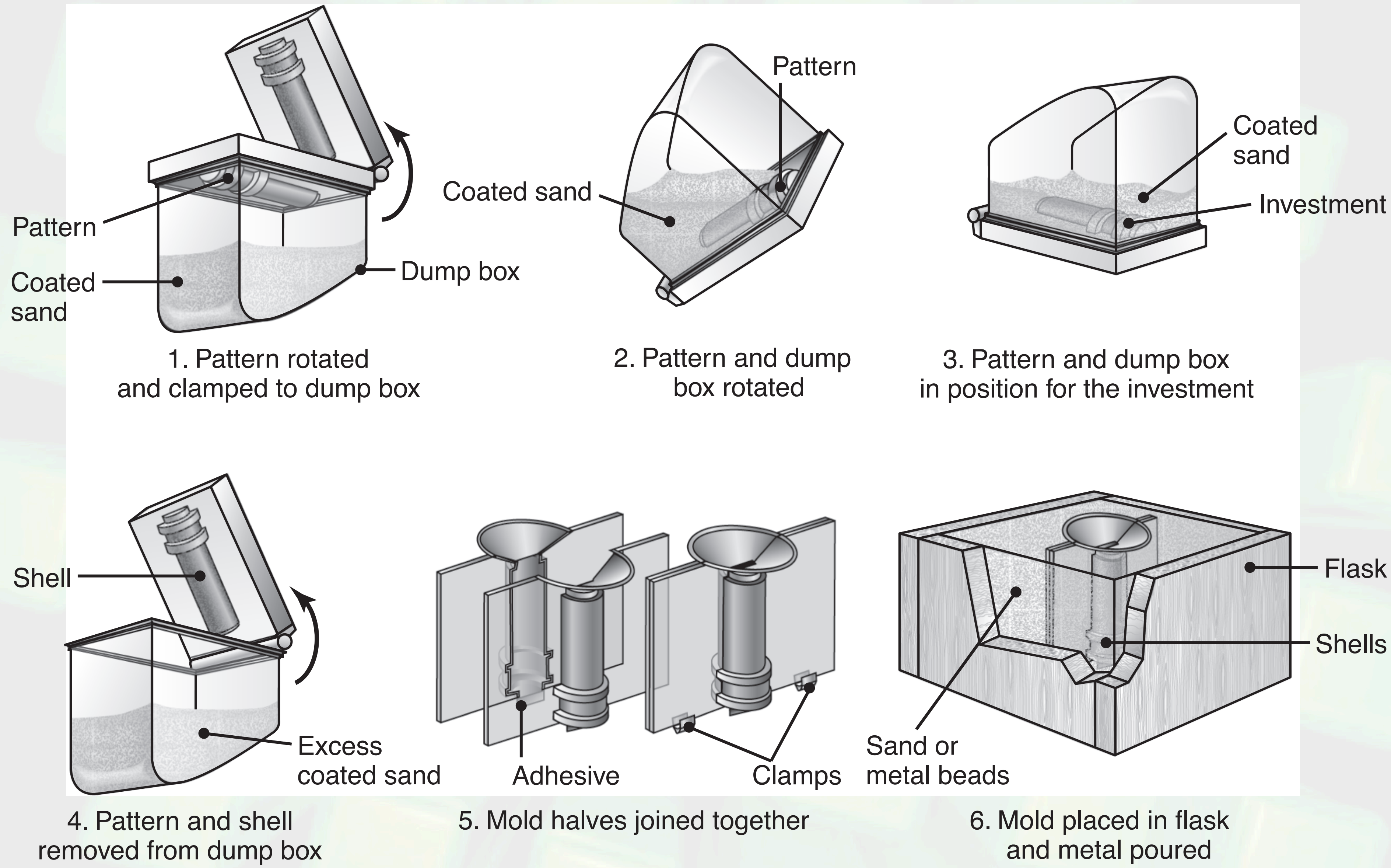

FIGURE 5.17 Schematic illustration of the shell-molding process, also called the *dump-box* technique.

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Caramic Mold Manufacture

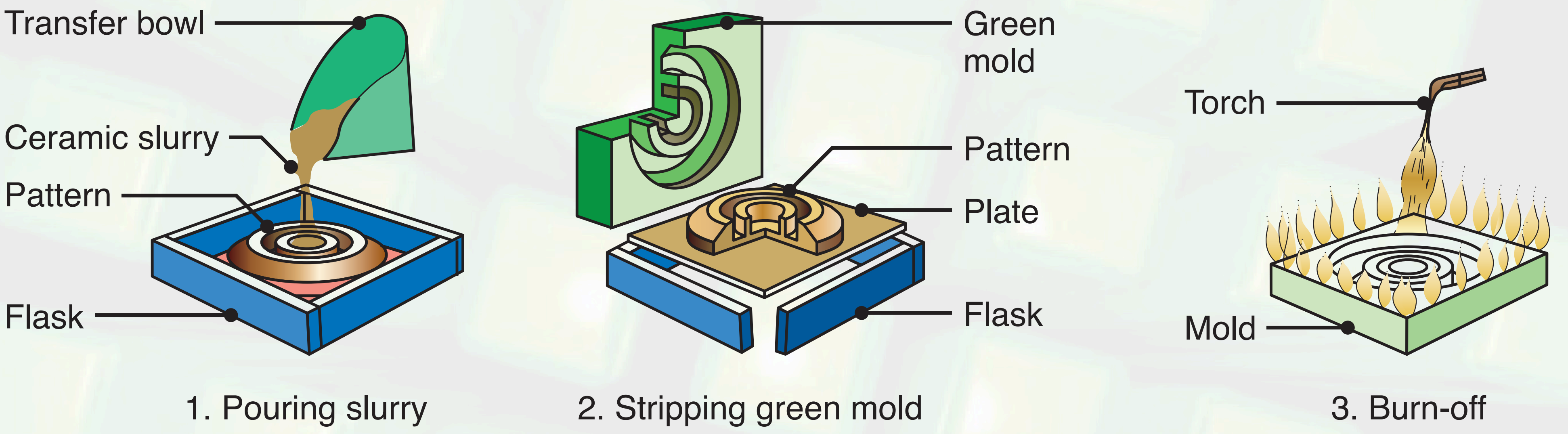

FIGURE 5.18 Sequence of operations in making a ceramic mold.

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Vacuum-Casting Process

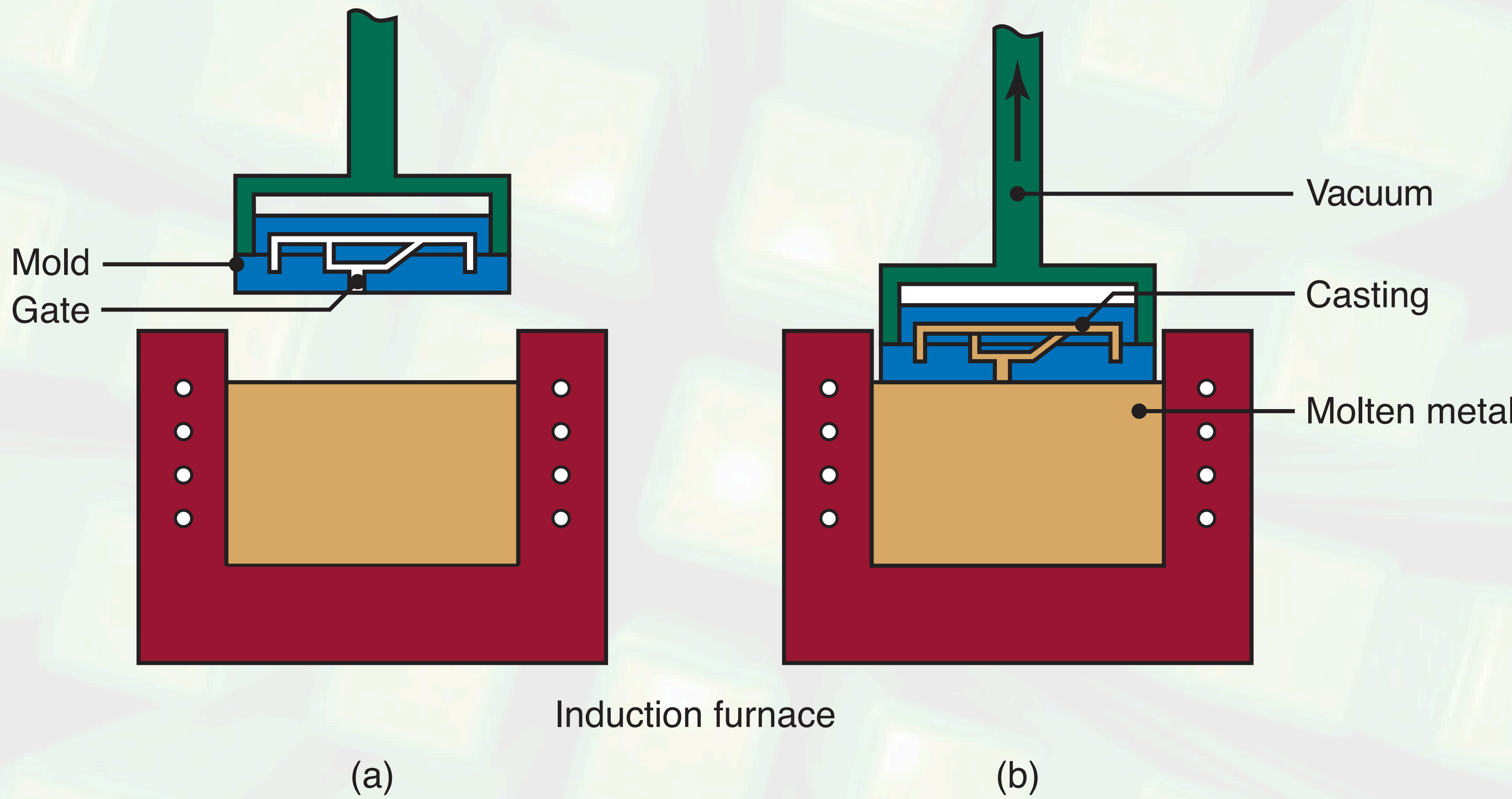

FIGURE 5.19 Schematic illustration of the vacuum-casting process. Note that the mold has a bottom gate. (a) before and (b) after immersion of the mold into the molten metal. *Source:* After R. Blackburn.

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Evaporative Pattern Casting

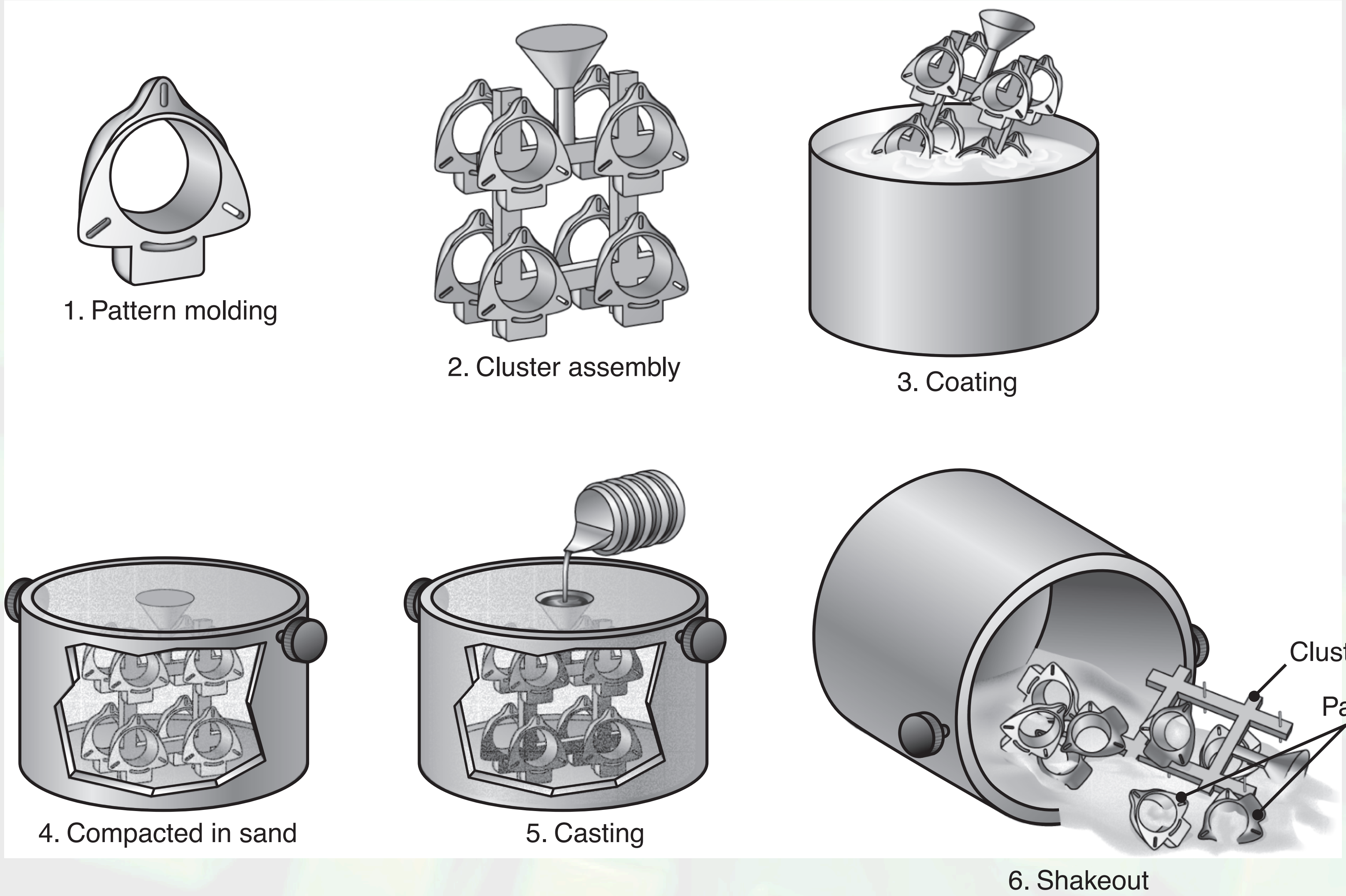

FIGURE 5.20 Schematic illustration of the expendable-pattern casting process, also known as lost-foam or evaporative-pattern casting.

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Investment Casting

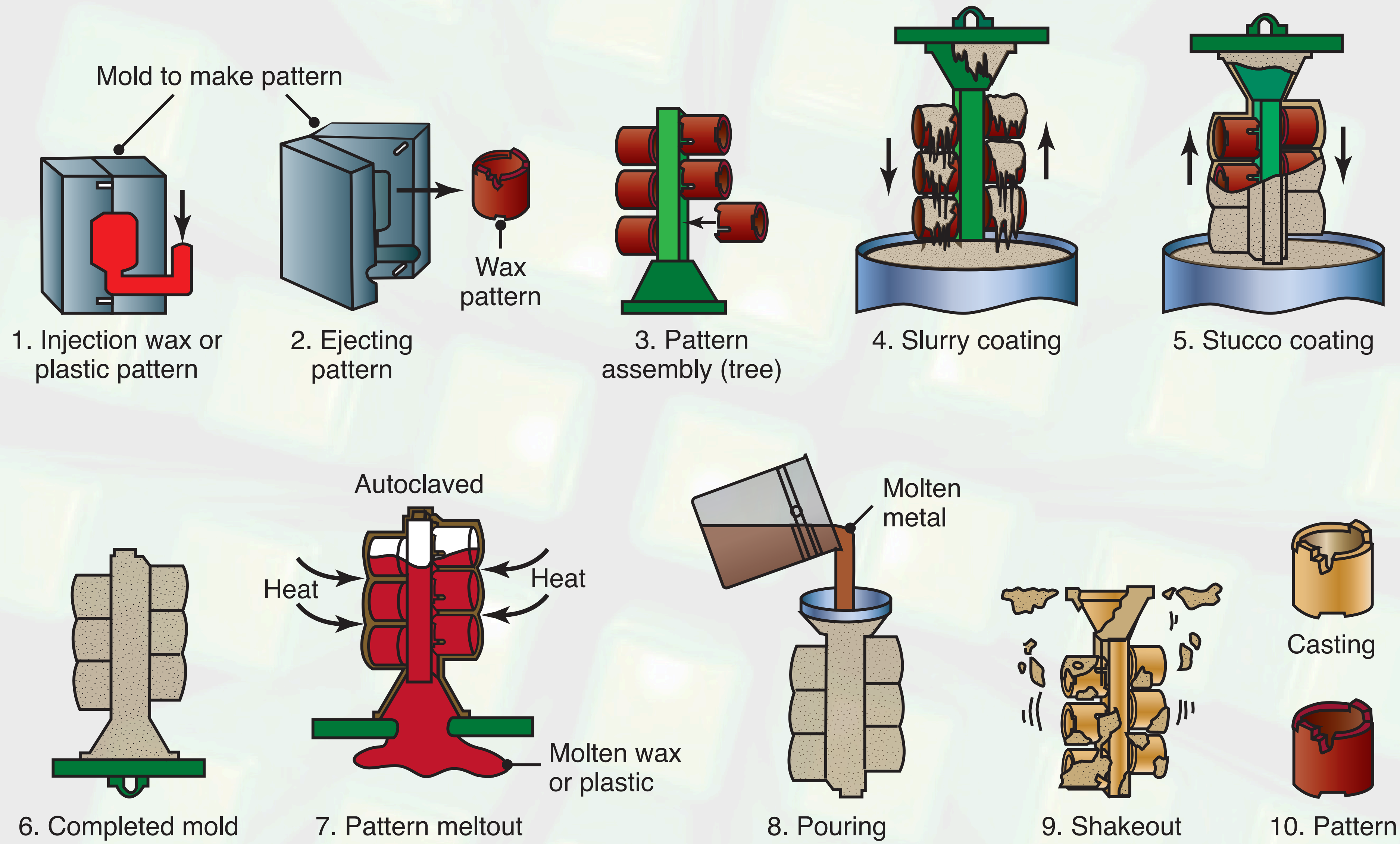

FIGURE 5.21 Schematic illustration of investment casting (lost wax process). Castings by this method can be made with very fine detail and from a variety of metals. *Source:* Steel Founders' Society of America.

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Rotor Microstructure

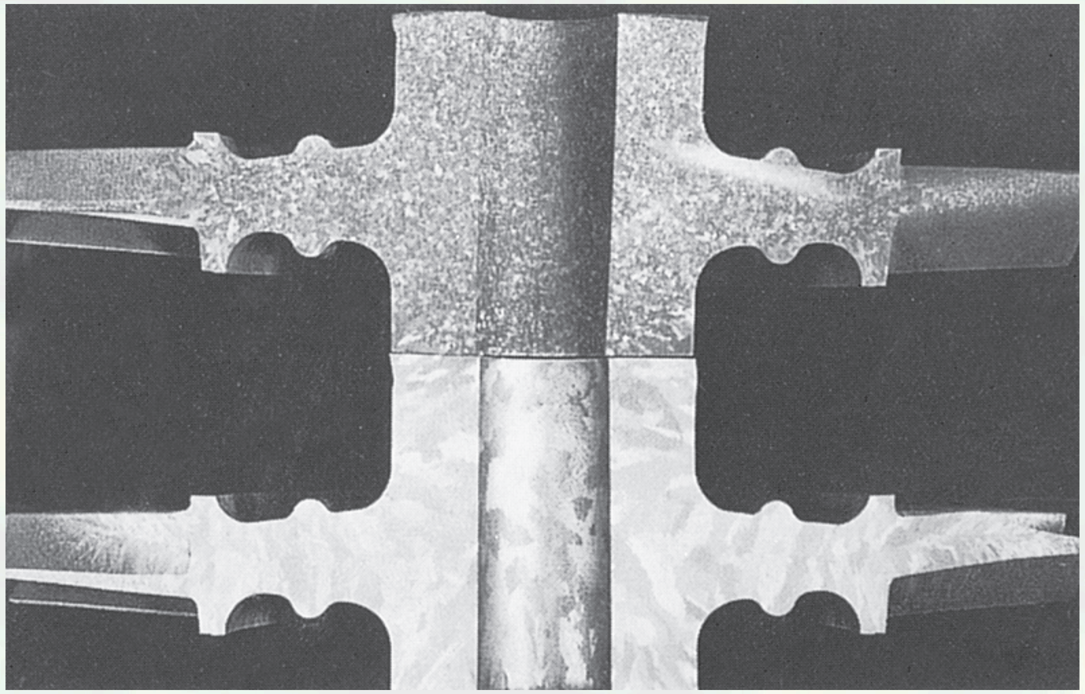

FIGURE 5.22 Microstructure of a rotor that has been investment cast (top) and conventionally cast (bottom). *Source: Advanced Materials and Processes*, October 1990, p. 25. ASM International.

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Pressure & Hot-Chamber Die Casting

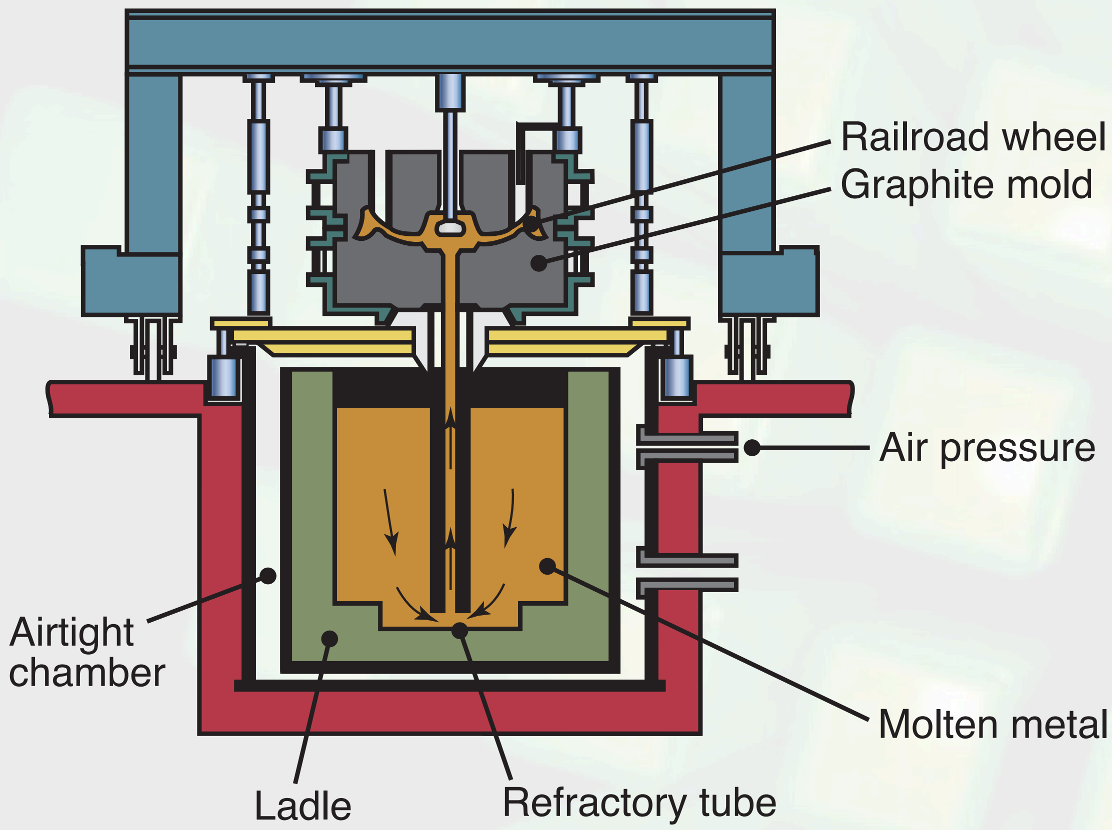

FIGURE 5.23 The pressure casting process, utilizing graphite molds for the production of steel railroad wheels. *Source:* Griffin Wheel Division of Amsted Industries Incorporated.

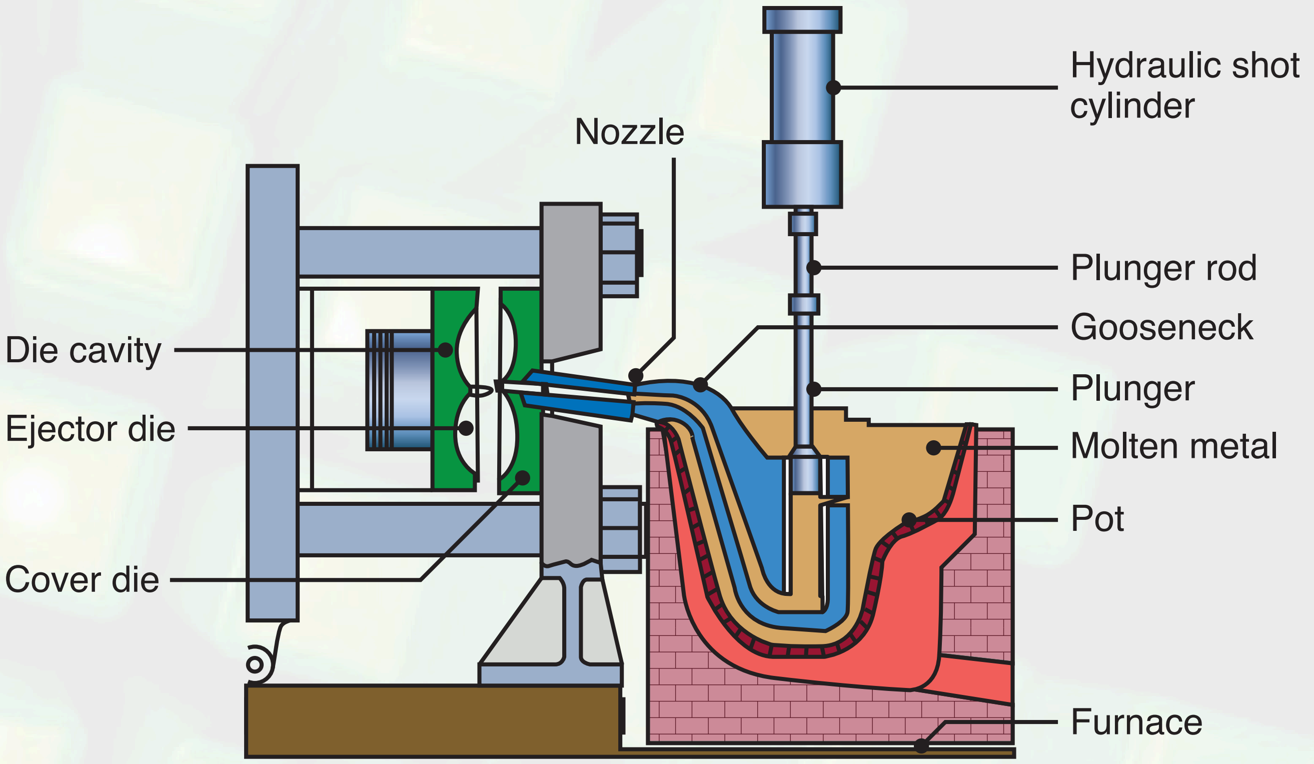

FIGURE 5.24 Schematic illustration of the hot-chamber die-casting process.

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Cold-Chamber Die Casting

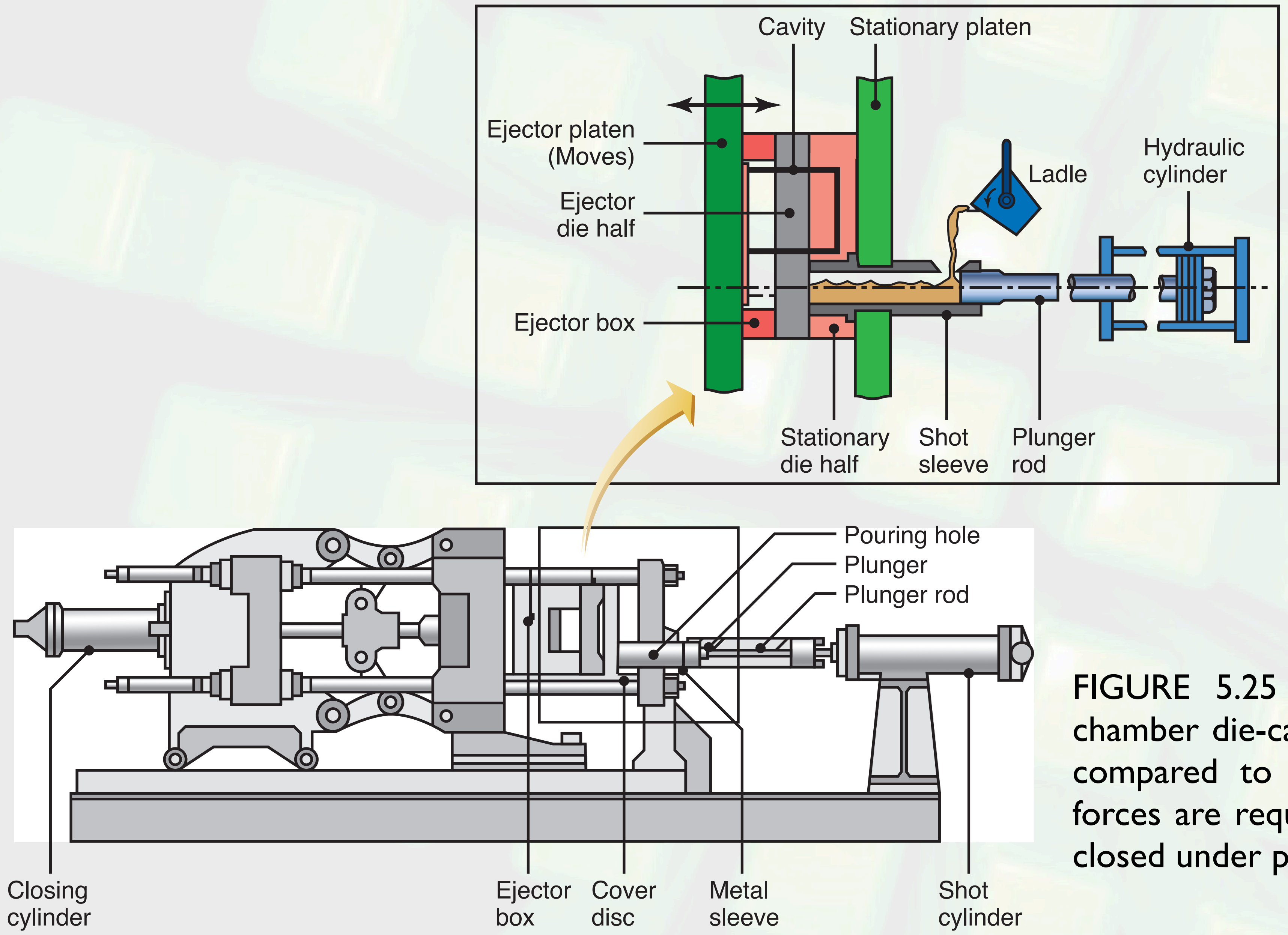

FIGURE 5.25 Schematic illustration of the cold-chamber die-casting process. These machines are large compared to the size of the casting, because high forces are required to keep the two halves of the die closed under pressure.

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Properties of 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, engine blocks.
Aluminum 13 (12 Si)	300	150	2.5	Complex shapes with thin walls, parts requiring strength at elevated temperatures
Brass 858 (60 Cu)	380	200	15	Plumbing fixtures, lock hardware, bushings, ornamental castings
Magnesium AZ91B (9 Al - 0.7 Zn)	230	160	3	Power tools, automotive parts, sporting goods
Zinc No. 3 (4 Al)	280	—	10	Automotive parts, office equipment, household utensils, building hardware, toys
Zinc No. 5 (4 Al - 1 Cu)	320	—	7	Appliances, automotive parts, building hardware, business equipment

Source: The North American Die Casting Association

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

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Centrifugal Casting

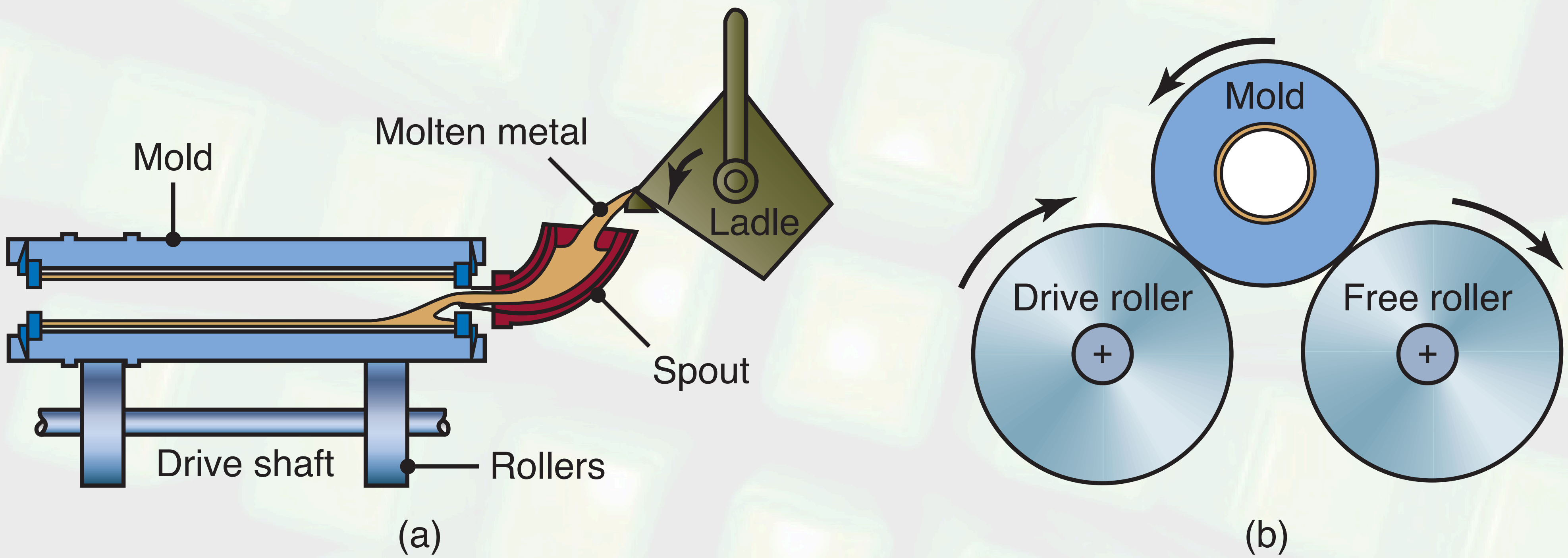

FIGURE 5.26 Schematic illustration of the centrifugal casting process. Pipes, cylinder liners, and similarly shaped hollow parts can be cast by this process.

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Semicentrifugal Casting

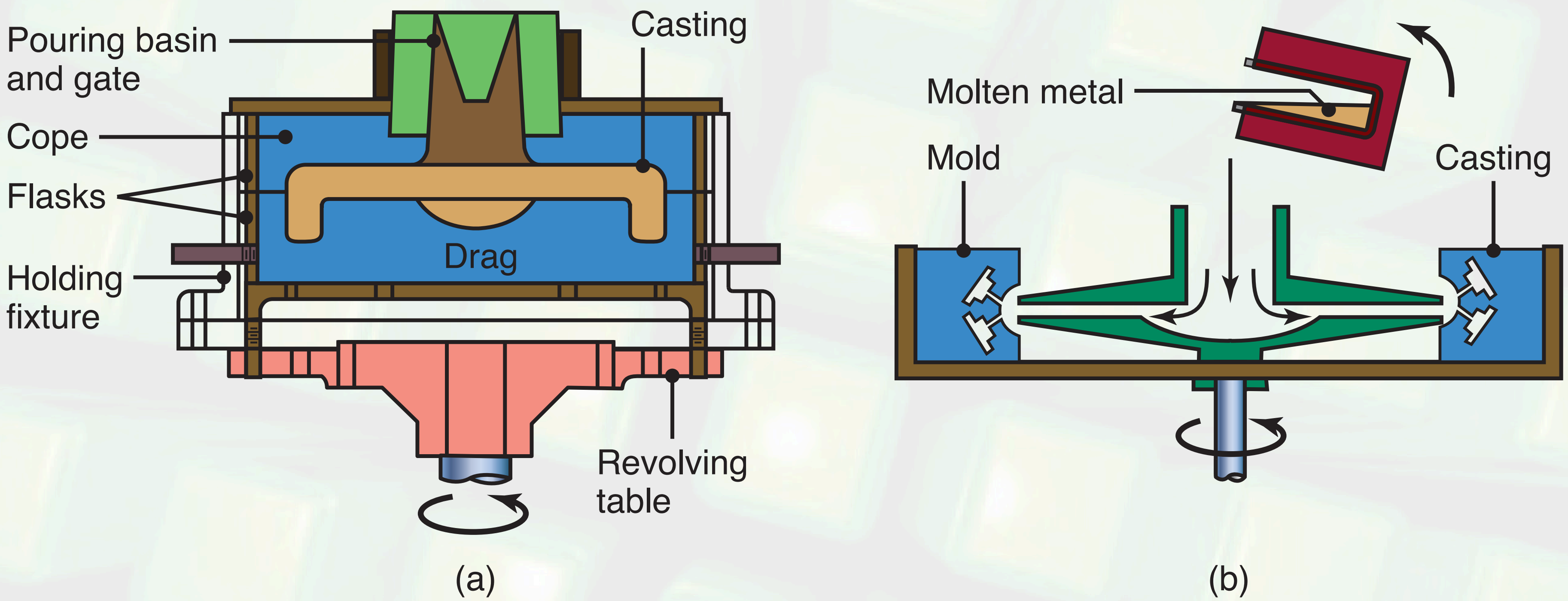

FIGURE 5.27 (a) Schematic illustration of the semicentrifugal casting process. Wheels with spokes can be cast by this process. (b) Schematic illustration of casting by centrifuging. The molds are placed at the periphery of the machine, and the molten metal is forced into the molds by centrifugal forces.

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Squeeze-Casting

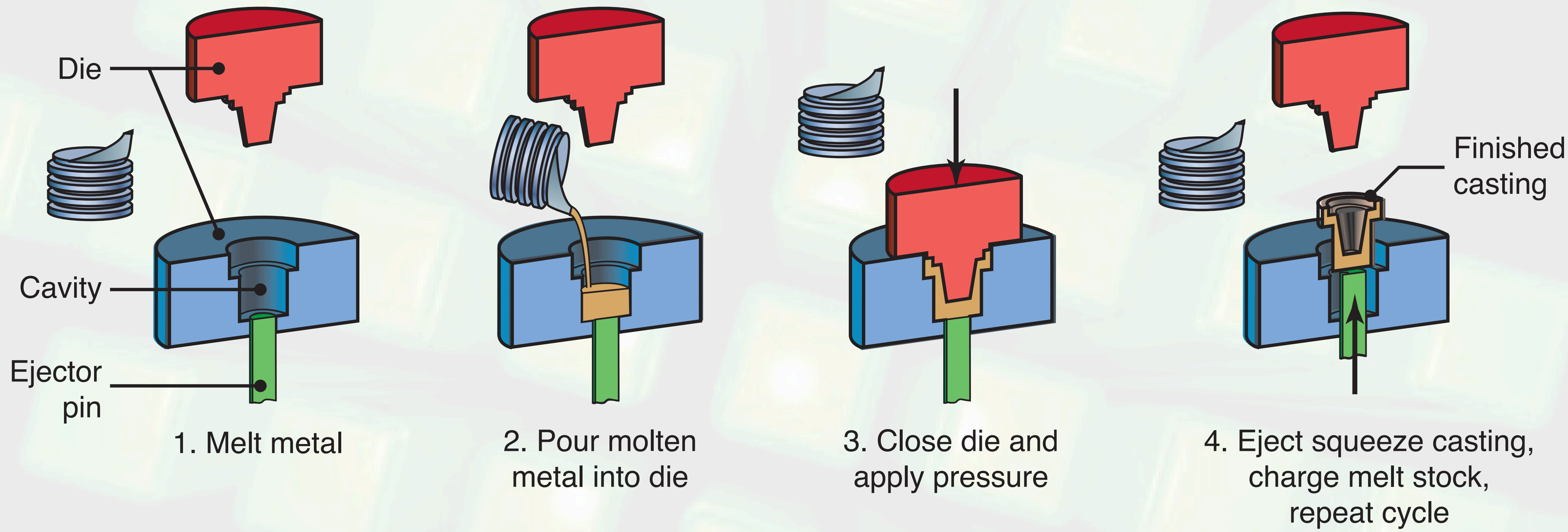

FIGURE 5.28 Sequence of operations in the squeeze-casting process. This process combines the advantages of casting and forging.

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Turbine Blade Casting

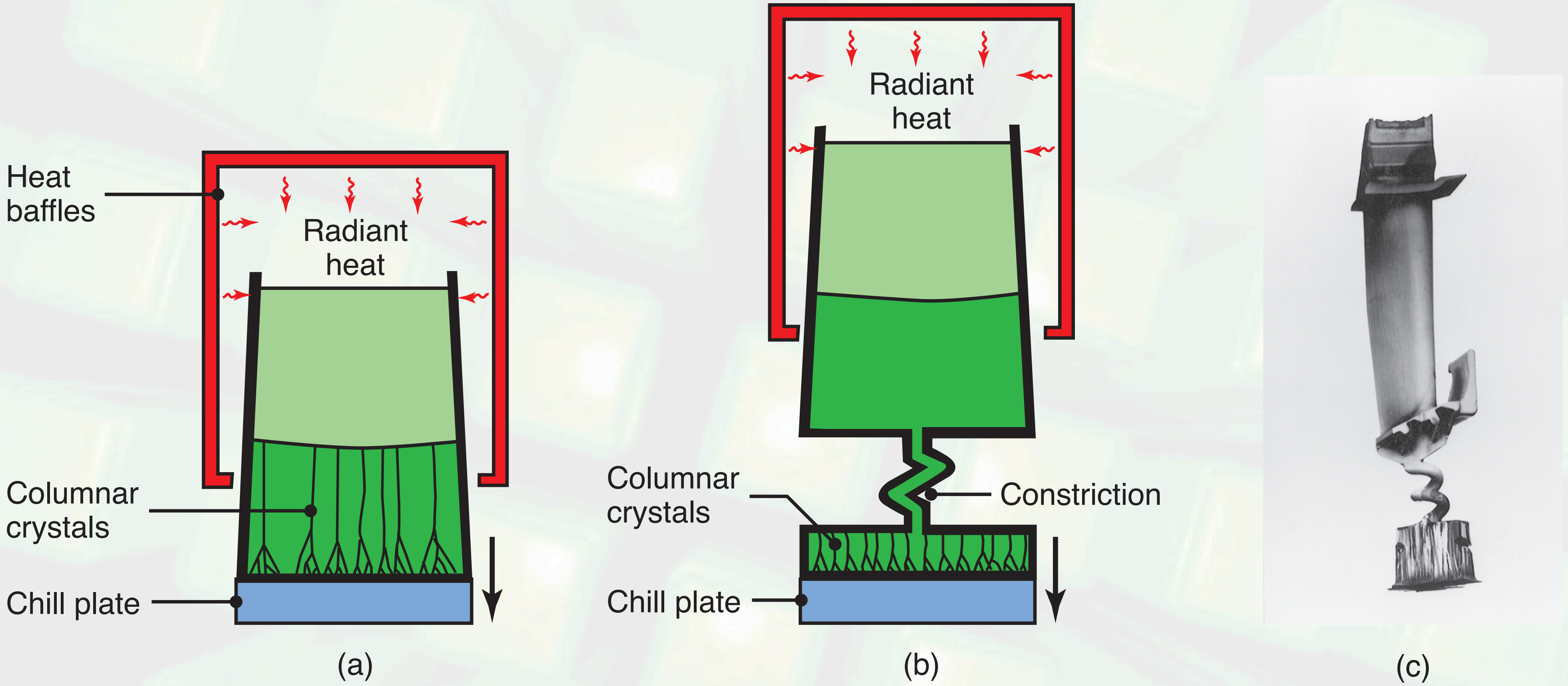

FIGURE 5.29 Methods of casting turbine blades: (a) directional solidification; (b) method to produce a single-crystal blade; and (c) a single-crystal blade with the constriction portion still attached. *Source:* (a) and (b) After B.H. Kear, (c) Courtesy of ASM International.

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Melt-Spinning Process

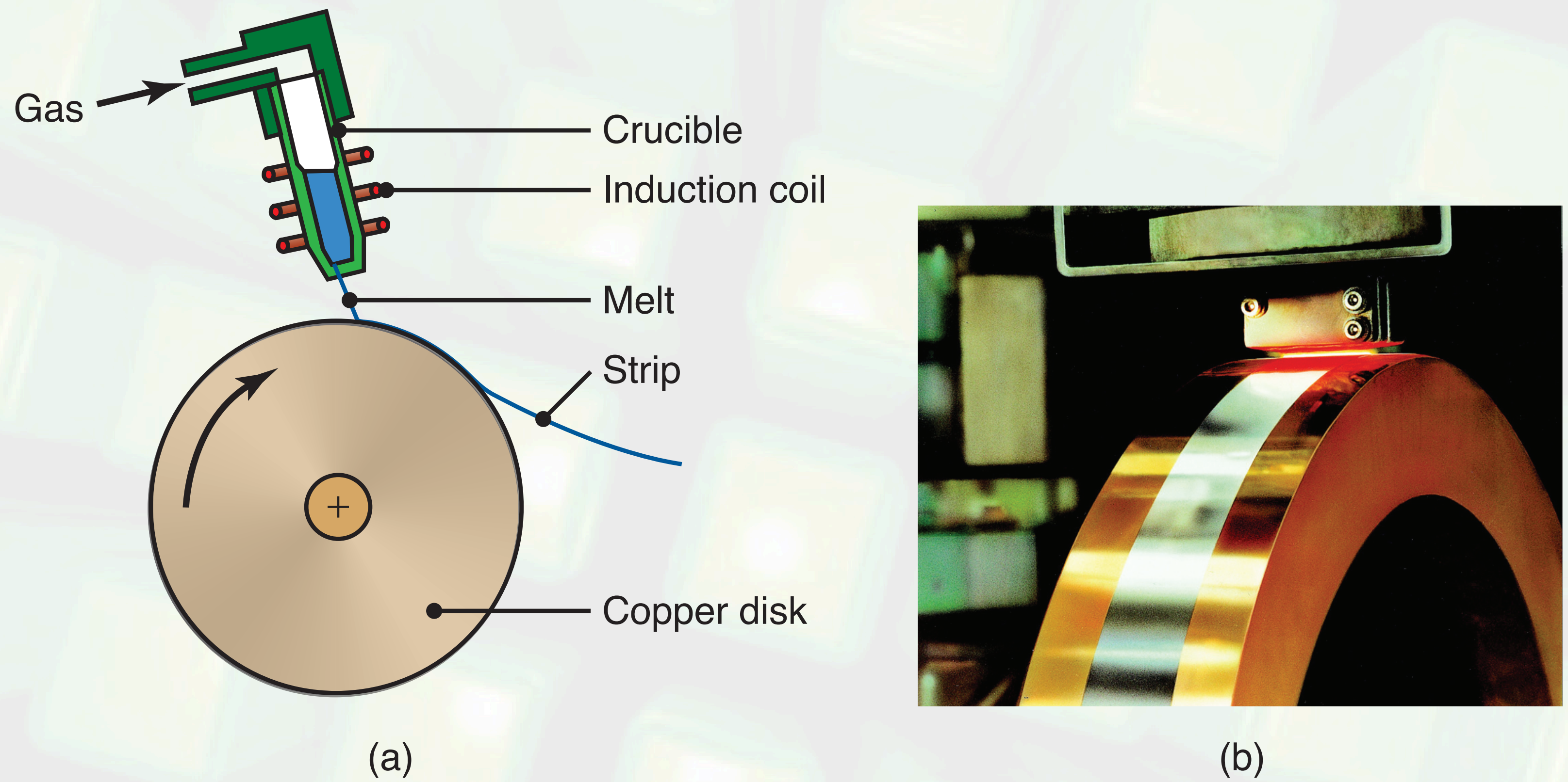

FIGURE 5.31 (a) Schematic illustration of the melt-spinning process to produce thin strips of amorphous metal. (b) Photograph of nickel-alloy production through melt-spinning. *Source:* Courtesy of Siemens AG.

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Chills

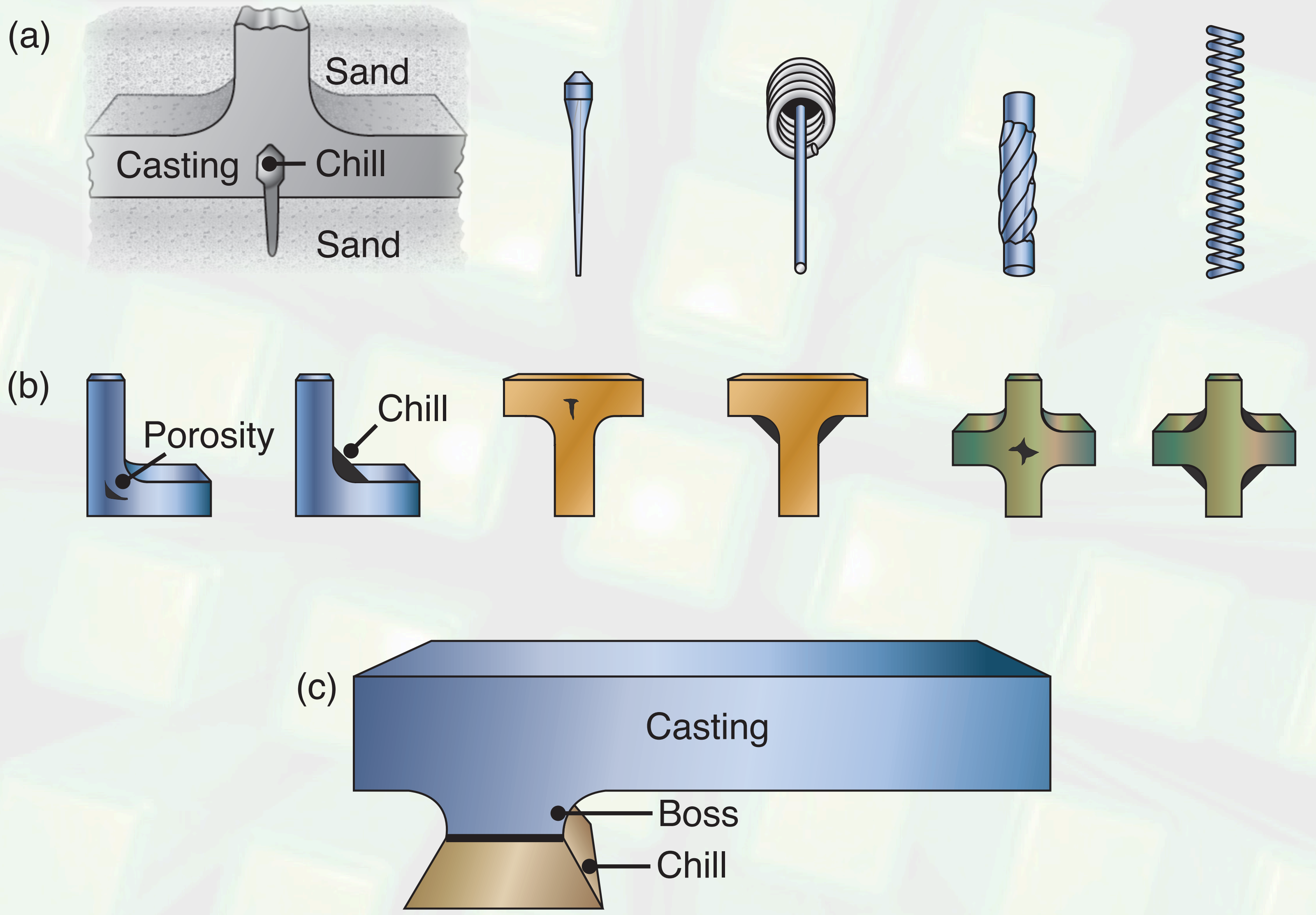

FIGURE 5.35 Various types of (a) internal and (b) external chills (dark areas at corners), used in castings to eliminate porosity caused by shrinkage. Chills are placed in regions where there is a larger volume of metal, as shown in (c).

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Hydrogen Solubility in Aluminum

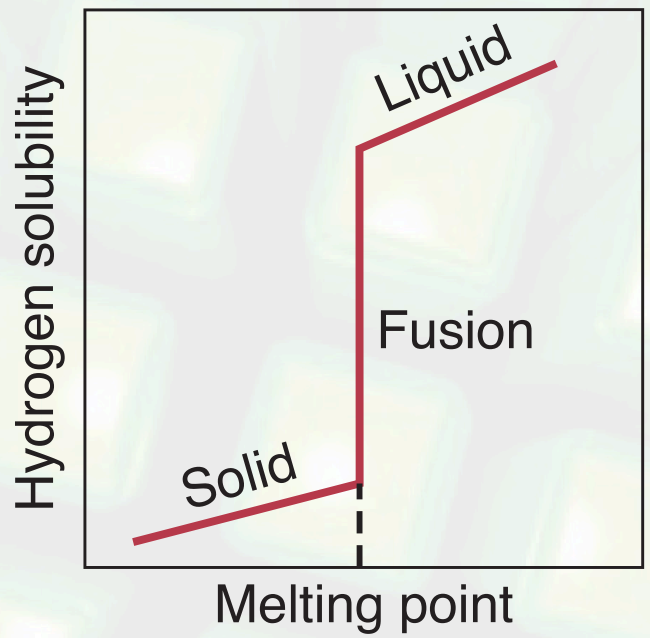

FIGURE 5.36 Solubility of hydrogen in aluminum. Note the sharp decrease in solubility as the molten metal begins to solidify.

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Elimination of Porosity in Castings

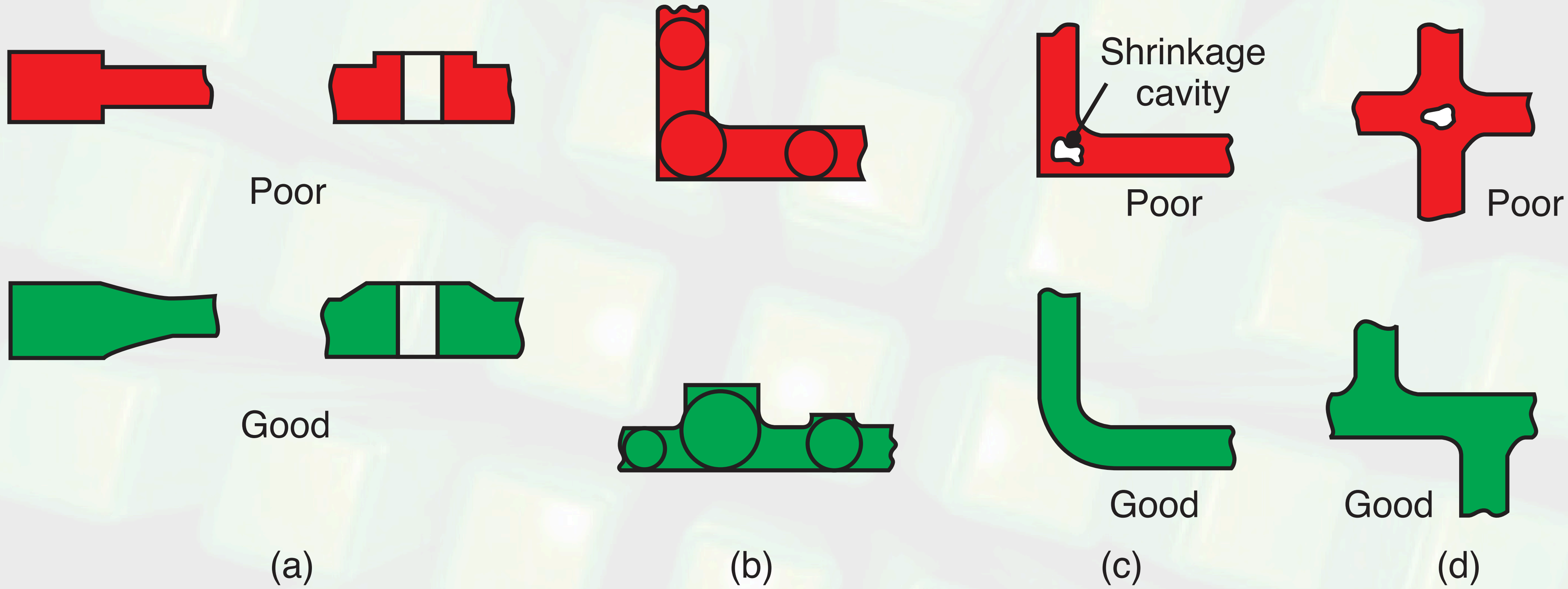

FIGURE 5.37 (a) Suggested design modifications to avoid defects in castings. Note that sharp corners are avoided to reduce stress concentrations; (b, c, d) examples of designs showing the importance of maintaining uniform cross-sections in castings to avoid hot spots and shrinkage cavities.

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Design Modifications

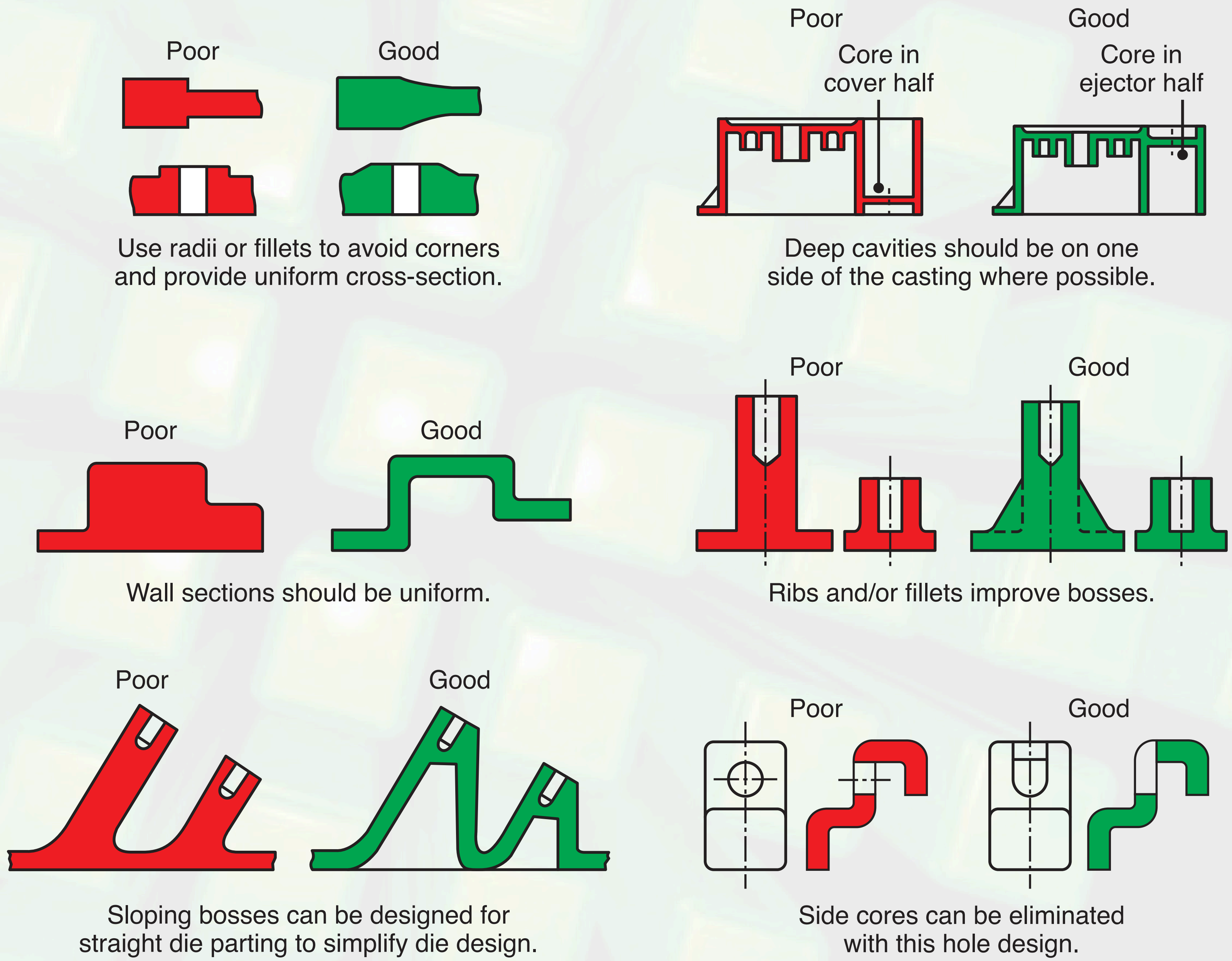

FIGURE 5.38 Suggested design modifications to avoid defects in castings. *Source:* Courtesy of The North American Die Casting Association.

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Economics of Casting

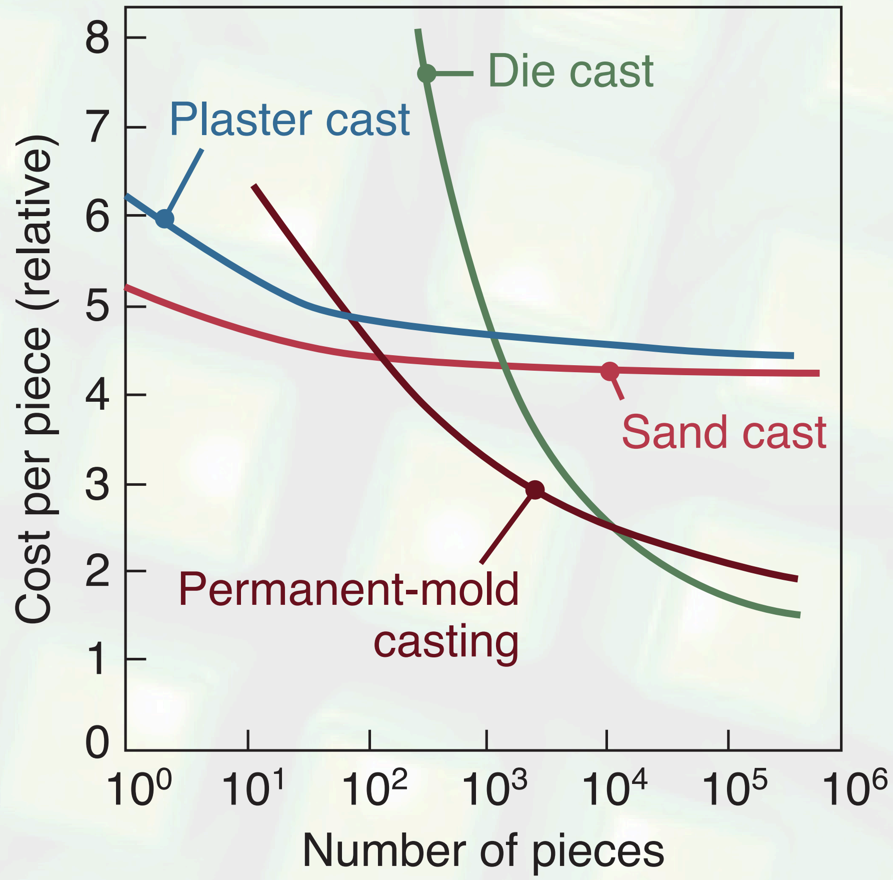

FIGURE 5.39 Economic comparison of making a part by two different casting processes. Note that because of the high cost of equipment, die casting is economical mainly for large production runs. *Source:* The North American Die Casting Association.

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Furnaces for Casting Processes

Furnaces most commonly used in foundries:

- Cupolas
- Direct fuel-fired furnaces
- Crucible furnaces
- Electric-arc furnaces
- Induction furnaces

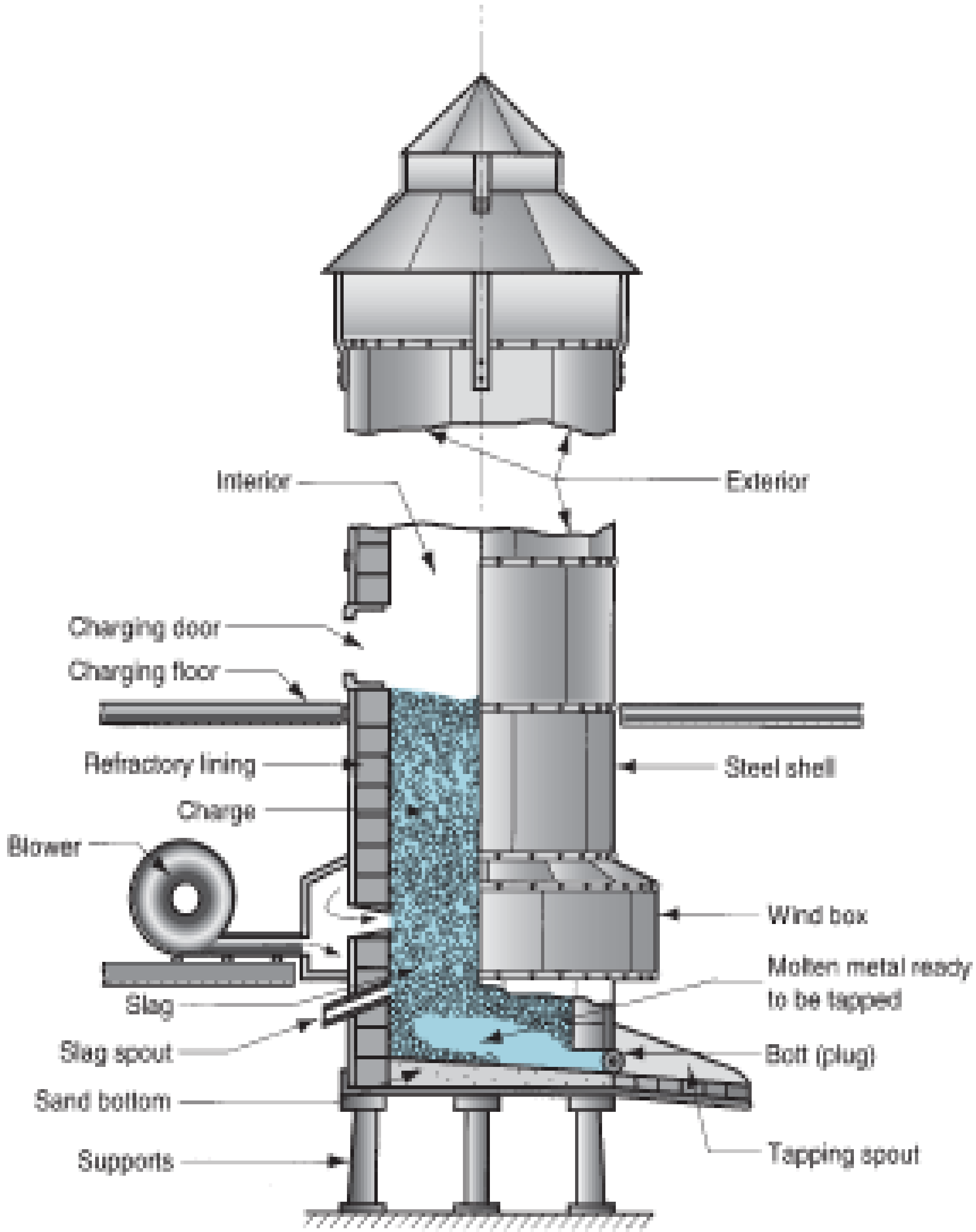
Cupolas

Vertical cylindrical furnace equipped with tapping spout near base

Used only for cast irons

- Although other furnaces are also used, the largest tonnage of cast iron is melted in cupolas

The "charge," consisting of iron, coke, flux, and possible alloying elements, is loaded through a charging door located less than halfway up height of cupola


Interior
Exterior
Charging door
Charging floor
Refractory lining
Steel shell
Charge
Blower
Wind box
Molten metal ready
to be tapped
Slag
Slag spout
Bott (plug)
Sand bottom
Supports
Tapping spout

Direct Fuel-Fired Furnaces

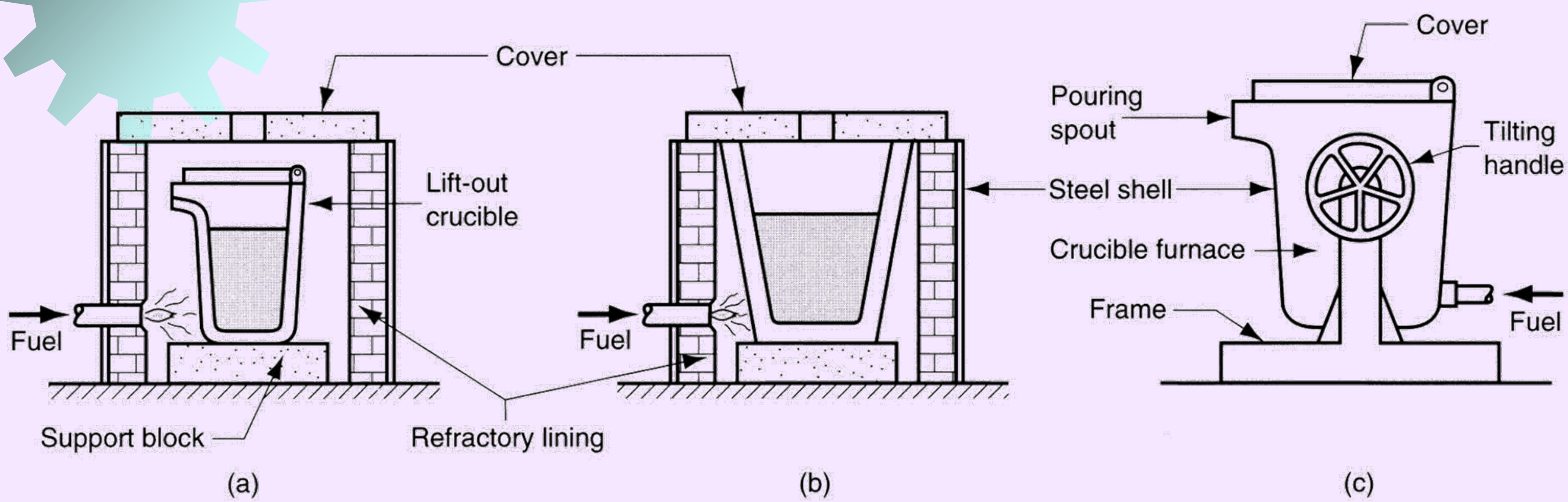
- Small open-hearth in which charge is heated by natural gas fuel burners located on side of furnace
- Furnace roof assists heating action by reflecting flame down against charge
- At bottom of hearth is a tap hole to release molten metal
- Generally used for nonferrous metals such as copper-base alloys and aluminum

Crucible Furnaces

- Metal is melted without direct contact with burning fuel mixture
- Sometimes called *indirect fuel-fired furnaces*
- Container (crucible) is made of refractory material or high-temperature steel alloy
- Used for nonferrous metals such as bronze, brass, and alloys of zinc and aluminum
- Three types used in foundries: (a) lift-out type, (b) stationary, (c) tilting

Crucible Furnaces

Figure 11.19 Three types of crucible furnaces: (a) lift-out crucible, (b) stationary pot, from which molten metal must be ladled, and (c) tilting-pot furnace.



Electric-Arc Furnaces

- Charge is melted by heat generated from an electric arc
- High power consumption, but electric-arc furnaces can be designed for high melting capacity
- Used primarily for melting steel

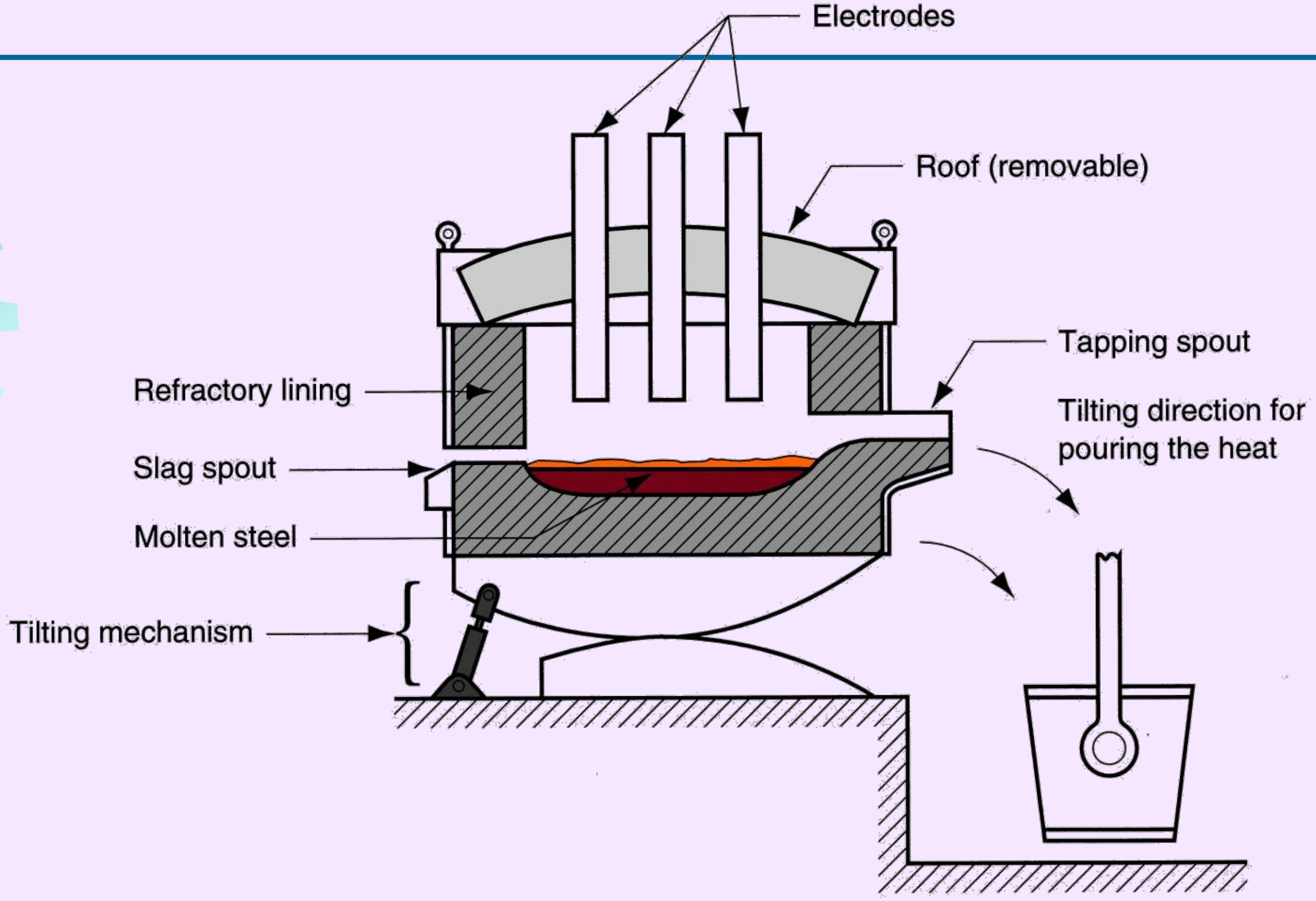


Figure 6.9 Electric arc furnace for steelmaking

Induction Furnaces

- Uses alternating current passing through a coil to develop magnetic field in metal
- Induced current causes rapid heating and melting
- Electromagnetic force field also causes mixing action in liquid metal
- Since metal does not contact heating elements, environment can be closely controlled to produce molten metals of high quality and purity
- Melting steel, cast iron, and aluminum alloys are common applications in foundry work

Induction Furnace

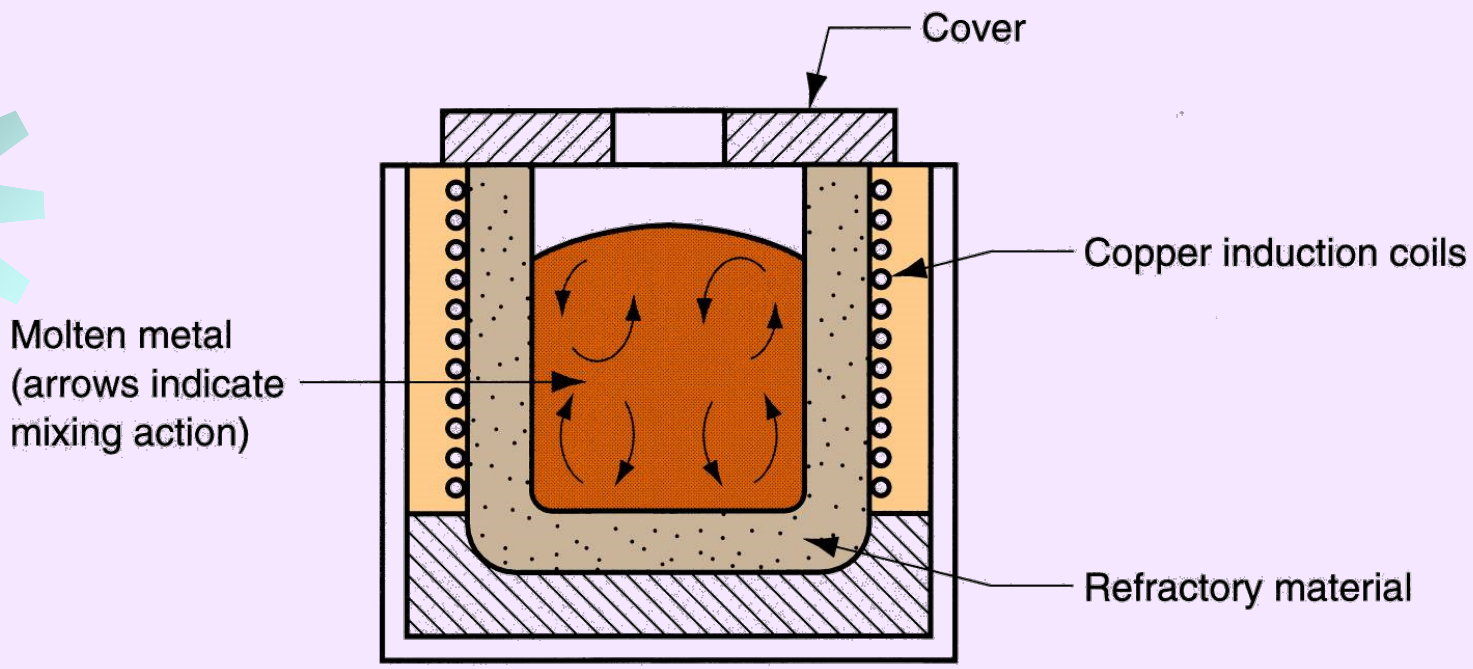


Figure 11.20 Induction furnace

Ladles

Last slide of students' presentations

Moving molten metal from melting furnace to mold is sometimes done using crucibles

More often, transfer is accomplished by *ladles*

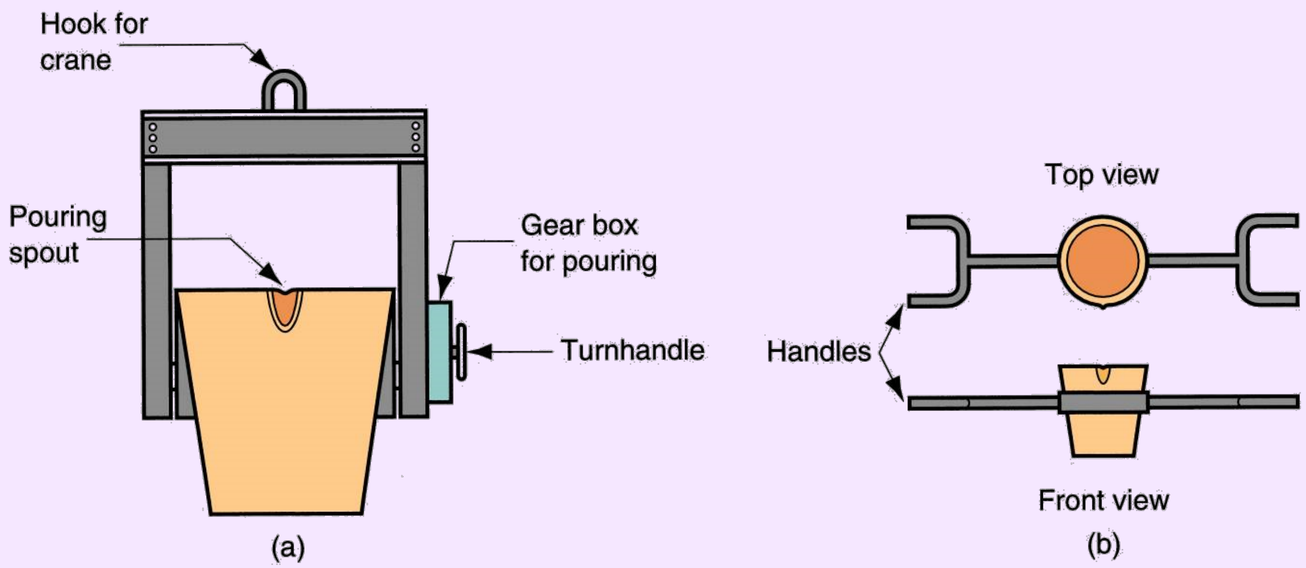


Figure 11.21 Two common types of ladles: (a) crane ladle, and (b) two-man ladle.