Global Manufacturing

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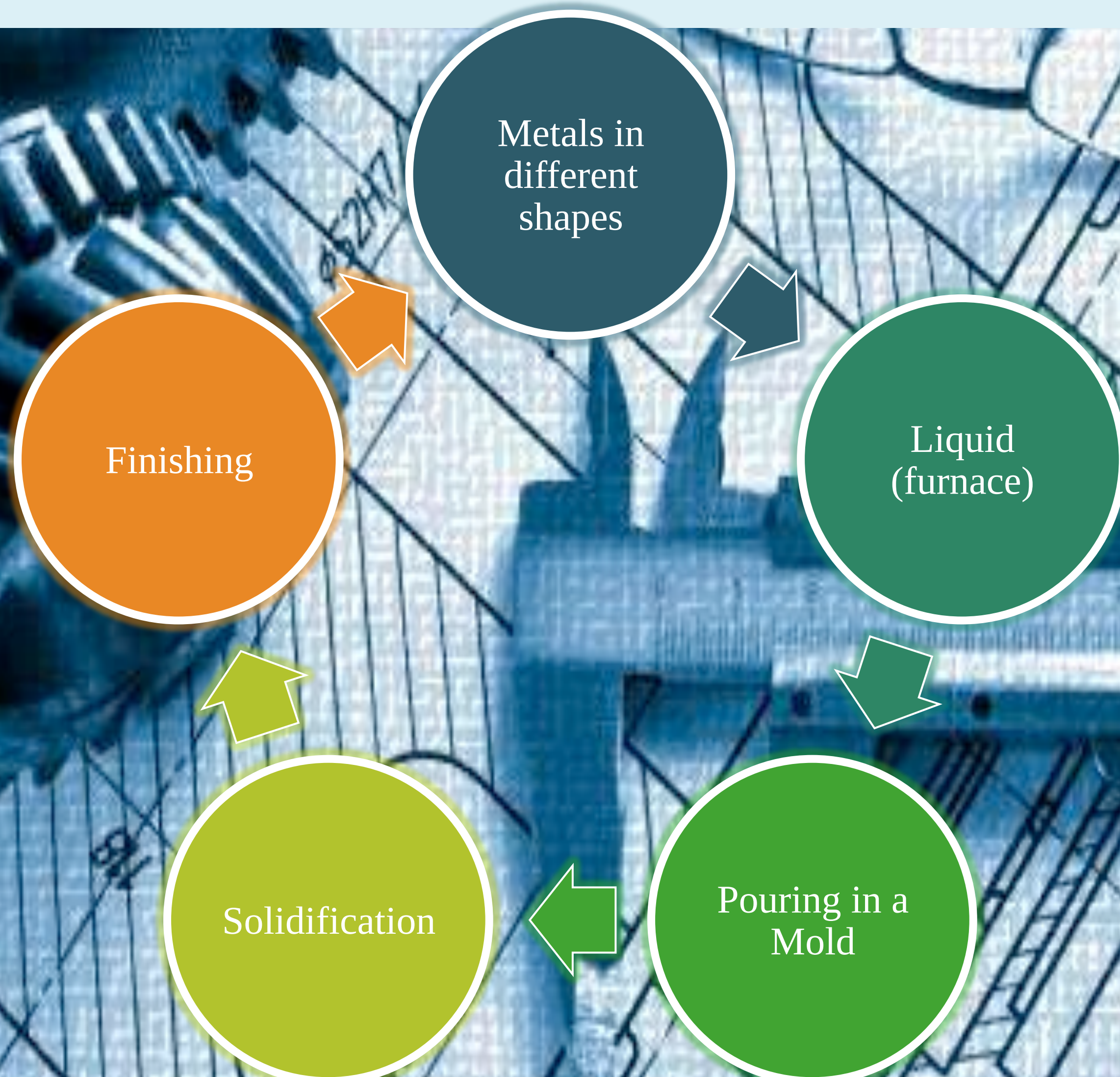
Casting Processes [#4]

Metal Solidification – Casting Processes

- How metal solidifies?
- What are the types of molds?
- What are the types of furnaces?
- How many pieces can be produced by Casting?
- How is the final process like?

"Globalization is the integration and interdependency of world markets and resources in producing consumer goods and services"

Casting – Recycling Process



Heating the Metal

The heat energy required is the sum of:

1. the heat to raise the temperature to the melting point,
2. the heat of fusion to convert it from solid to liquid,
3. the heat to raise the molten metal to the desired temperature for pouring.

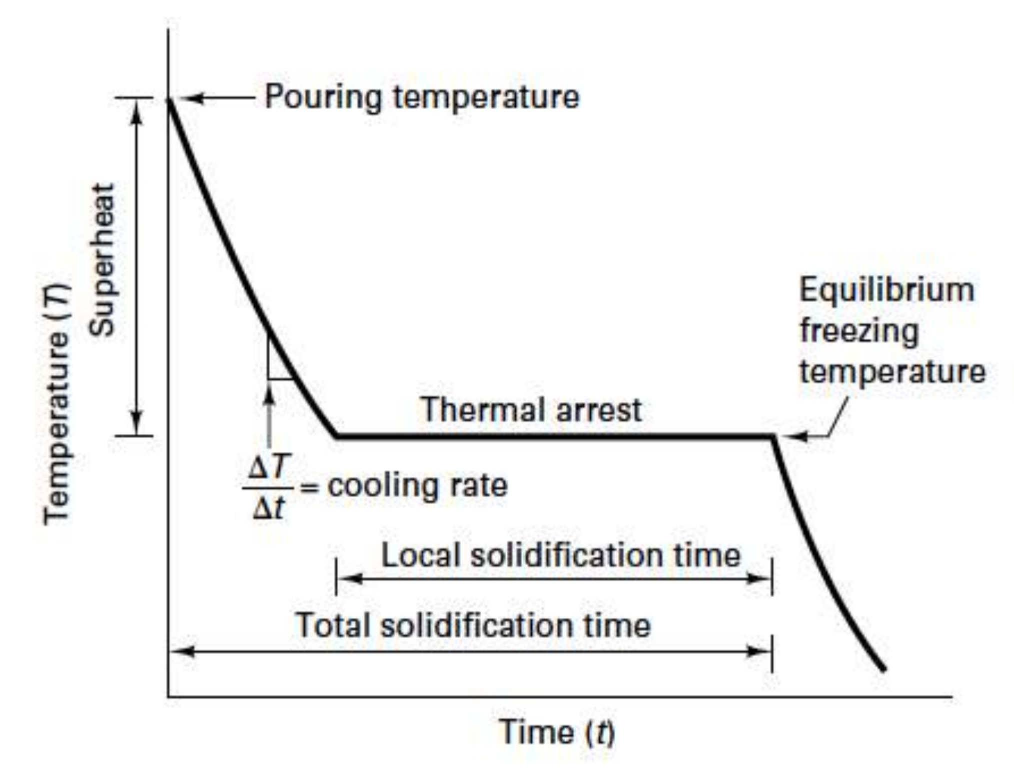
$$H = \rho V \{ C_s (T_m - T_o) + H_f + C_l (T_p - T_m) \}$$

H (Total heat required to raise the temperature of the metal to the pouring temperature), ρ density, Cs . weight specific heat for the solid metal, Tm: melting temperature of the metal; To: starting temperature—usually ambient; Hf . heat of fusion, Cl: weight specific heat of the liquid metal, Tp . pouring temperature, V: volume of metal

Problems in the equation:

(1) Specific heat vary with temperature, especially in phase change.
(2) Most casting metals are alloys, the heat of fusion cannot be applied so simply as indicated above.
(3) The property values required in the equation for a particular alloy are not readily available in most cases.
(4) Heat losses to the environment during heating.

How pure metal solidifies?



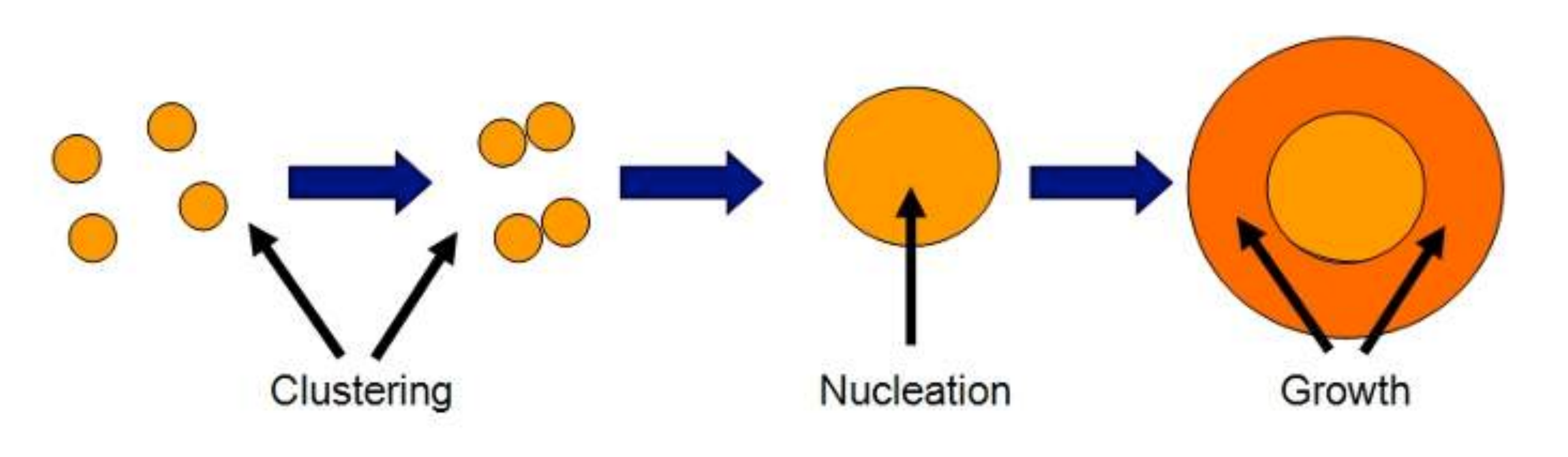
Pouring temperature: the temperature of the liquid metal when it first enters the mold.

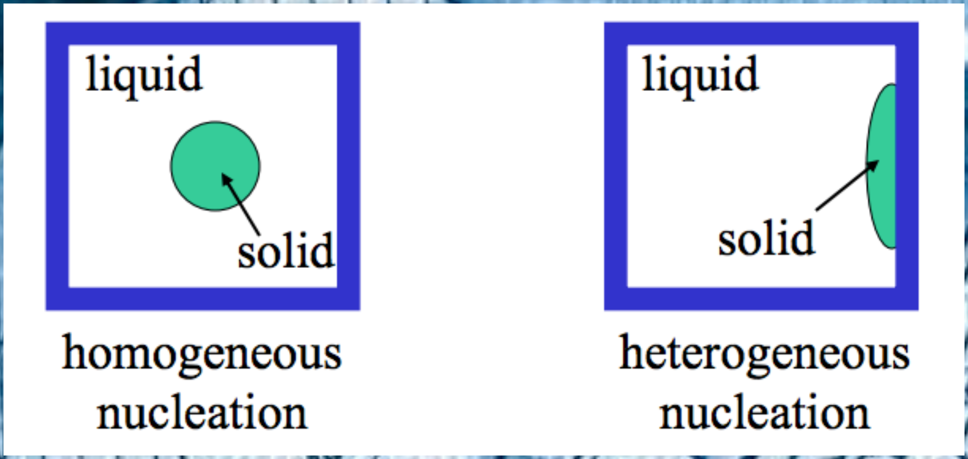
Superheat: is the difference between the pouring temperature and the freezing temperature of the material.

Cooling rate: the rate at which the liquid or solid is cooling and can be viewed as the slope of the cooling curve at any given point.

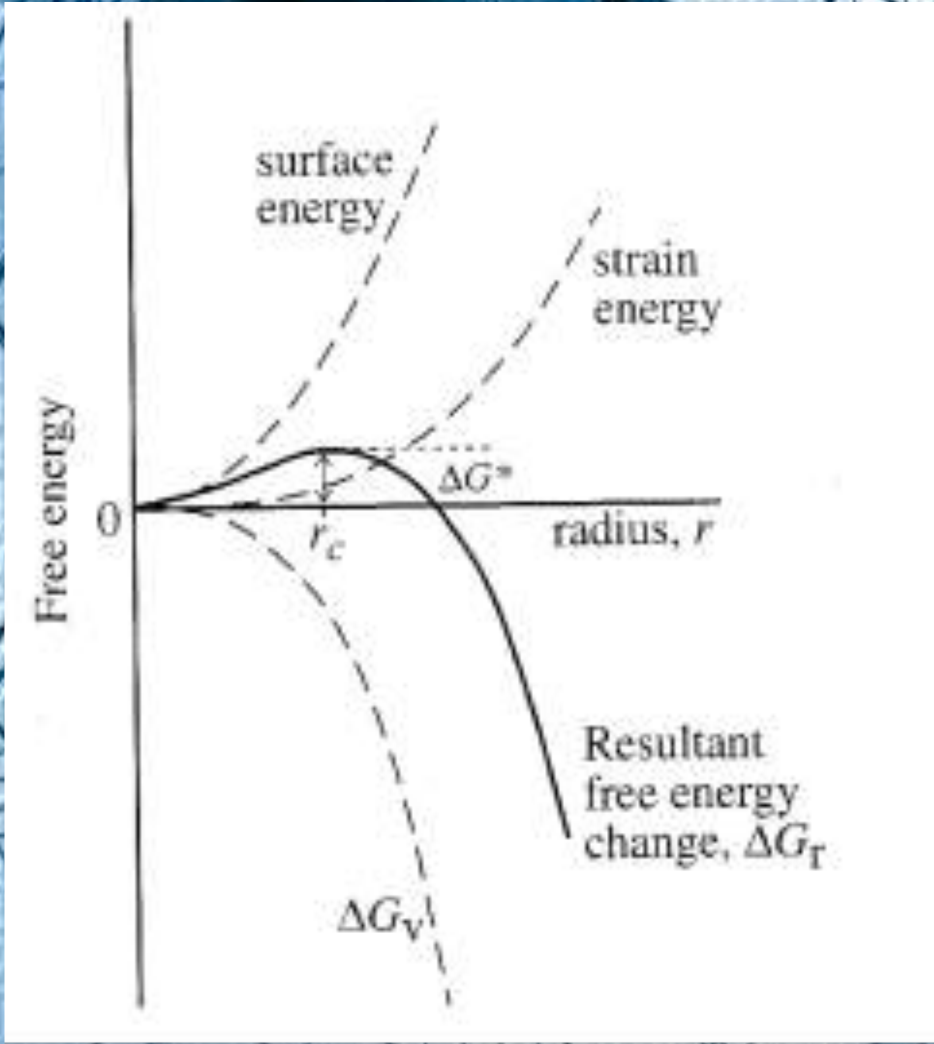
Thermal arrest: is the plateau in the cooling curve that occurs during the solidification of a material with fixed melting point. At this temperature, the energy or heat being removed from the mold comes from the latent heat of fusion that is being released during the solidification process.

Nucleation and Crystal Grow





Nucleation (Gibbs Free Energy)

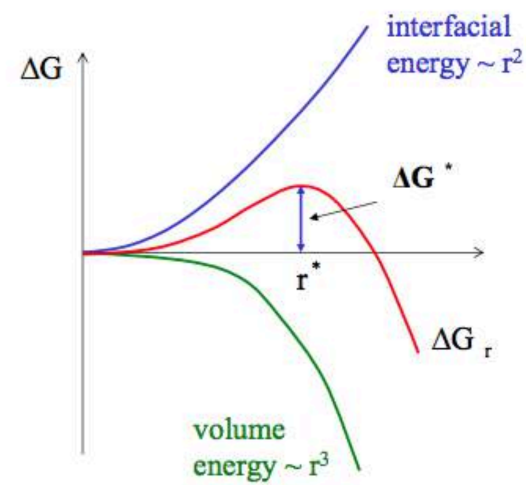


Homogeneous nucleation

$$\Delta G = G_2 - G_1 = -V_S \Delta G_v + A^{SL}\gamma^{SL}$$

For a spherical nucleus with radius r: $\mathbf{V_S = \frac{4}{3}\pi r^3}$

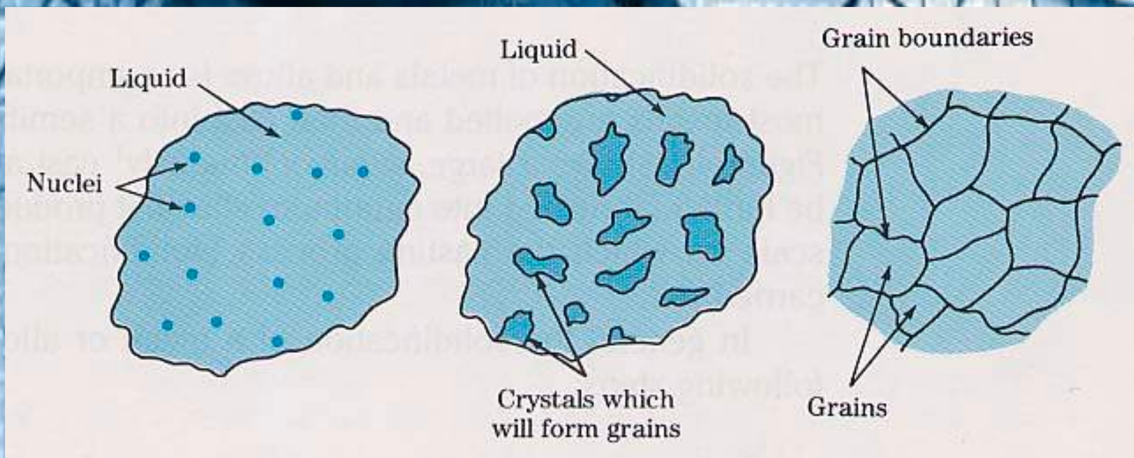
$$\Delta G_r = -\frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma^{SL} \qquad \mathbf{A^{SL} = 4\pi r^2}$$

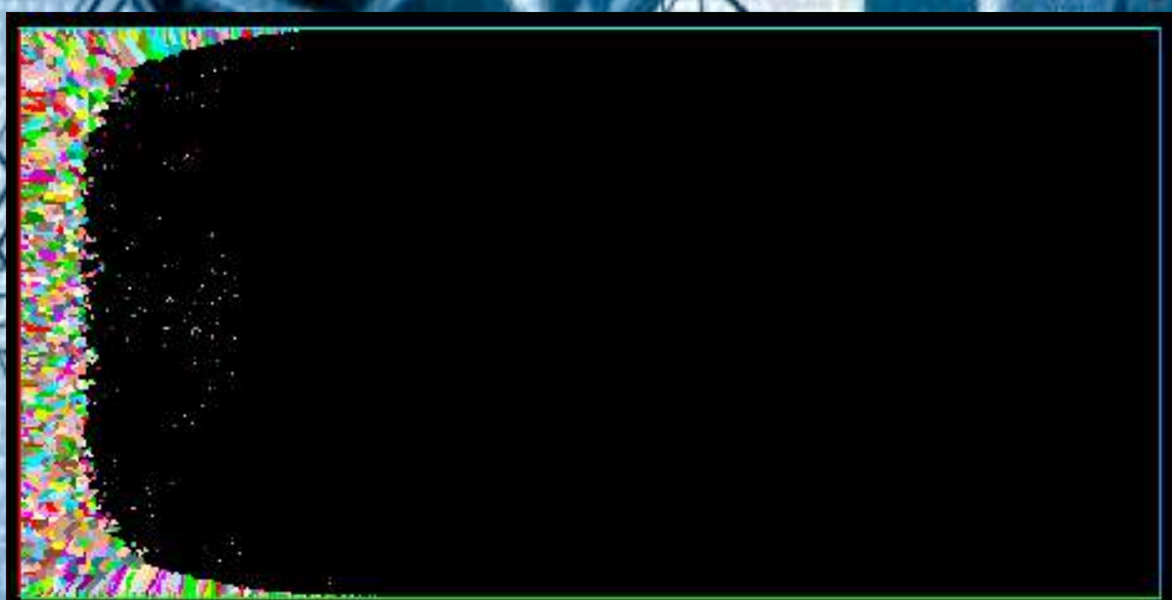


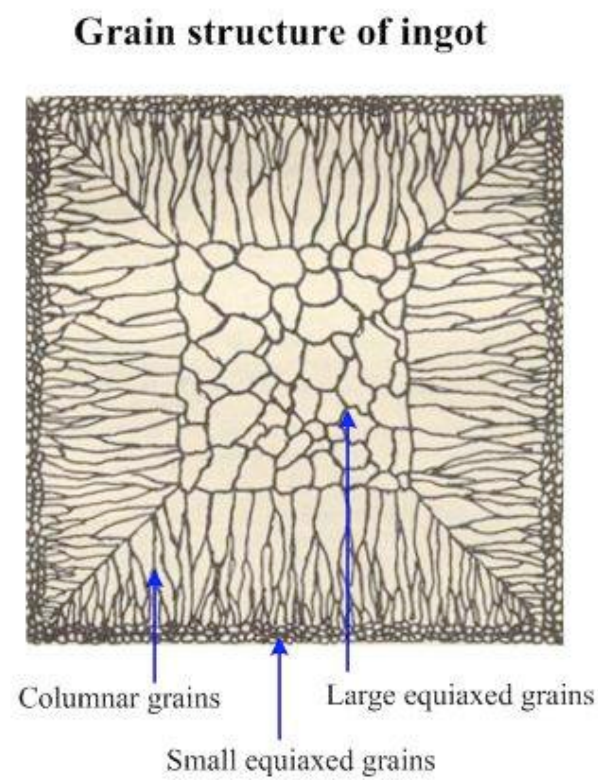
For nucleus with a radius $r > r^*$, the Gibbs free energy will decrease if the nucleus grows. **r^* is the critical nucleus size, ΔG^* is the nucleation barrier.**

MSE 3050, Phase Diagrams and Kinetics, Leonid Zhigilei

Grain Boundaries







(from Bower T.F. and Flemings M.C., Trans. AIME, 239, 1620 (1967))

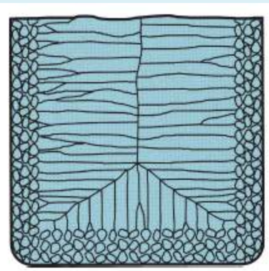


FIGURE 5.3 Characteristic grain structure in a casting of a pure metal, showing randomly oriented grains of small size near the mold wall, and large columnar grains oriented toward the center of the casting. (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)

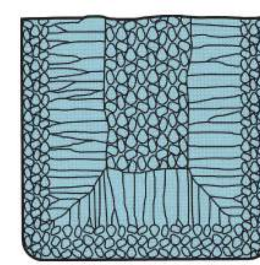
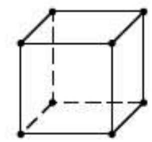
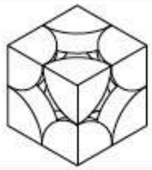
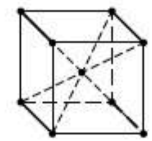
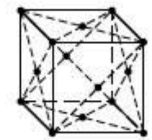
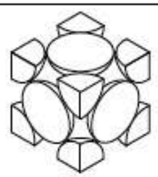
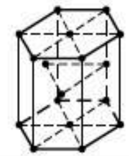


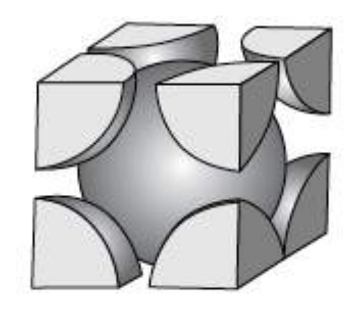
FIGURE 5.5 Characteristic grain structure in an alloy casting, showing segregation of alloying components in the center of casting. (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)

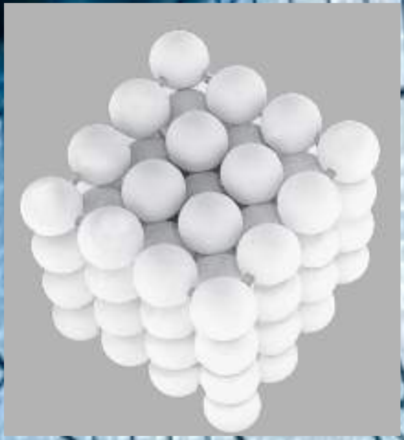
Crystal Structure of Metals

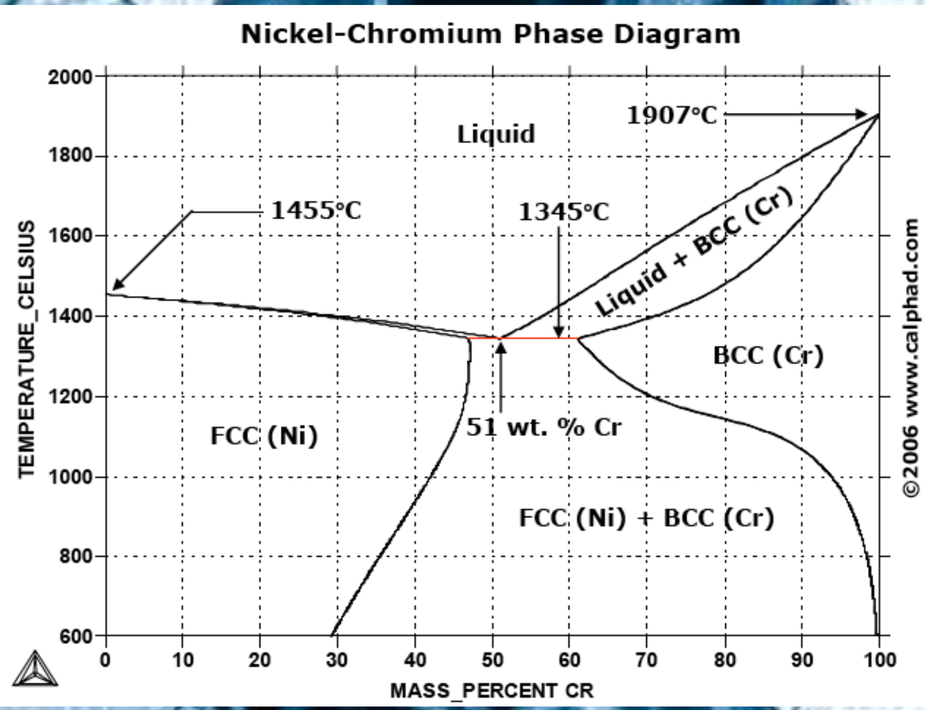
TABLE 4-1 The Type of Crystal Lattice for Common Metals at Room Temperature

Metal	Lattice Type
Aluminum	Face-centered cubic
Copper	Face-centered cubic
Gold	Face-centered cubic
Iron	Body-centered cubic
Lead	Face-centered cubic
Magnesium	Hexagonal
Silver	Face-centered cubic
Tin	Body-centered tetragonal
Titanium	Hexagonal

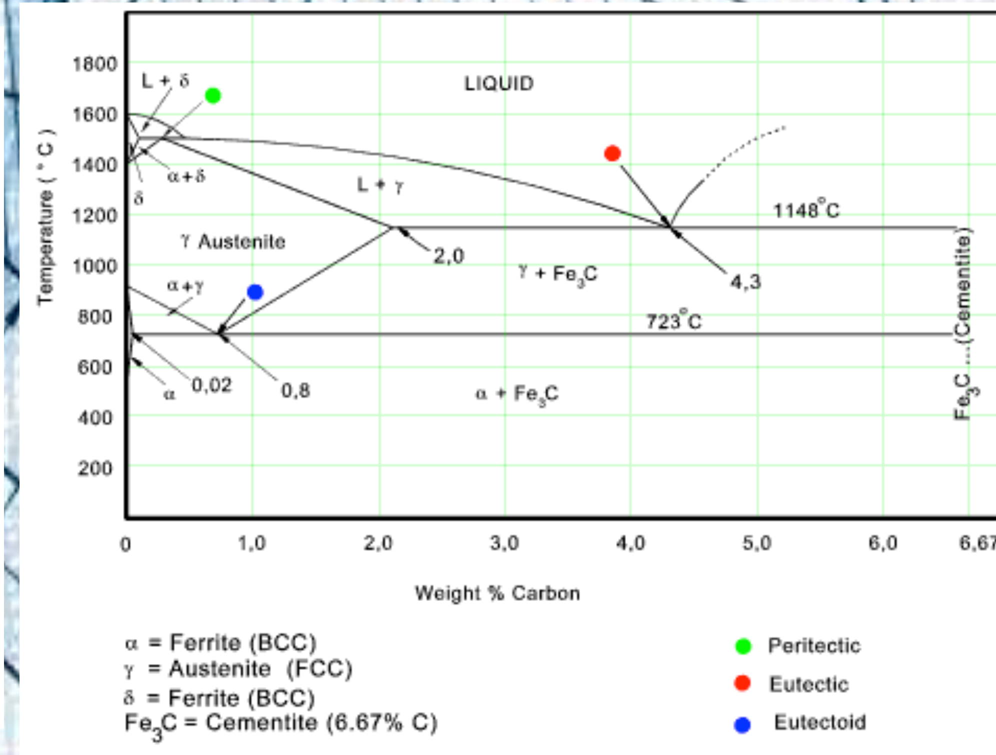
	Lattice structure	Unit cell schematic	Unit cells	Number of nearest neighbors	Packing efficiency	Typical metals
a	Simple cubic			6	52%	None
b	Body-centered cubic			8	68%	Fe, Cr, M Cb, W, Ta Ti, V, Na,
c	Face-centered cubic			12	74%	Fe, Al, Cu Ni, Ca, Au Ag, Pb, P
d	Hexagonal close-packed			12	74%	Be, Cd, Mg, Zn, Zr



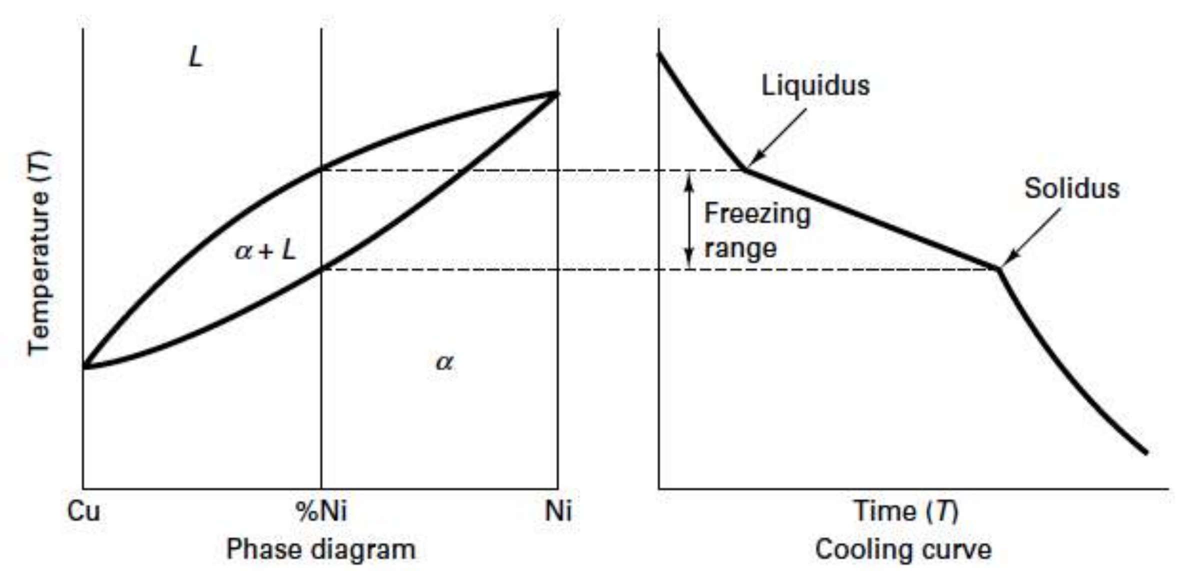




Nickel-Chromium Phase Diagram
Liquid
1907°C
1455°C
1345°C
Liquid + BCC (Cr)
BCC (Cr)
FCC (Ni)
51 wt. % Cr
FCC (Ni) + BCC (Cr)
TEMPERATURE_CELSIUS
MASS_PERCENT CR
©2006 www.calphad.com



L + δ
LIQUID
α+δ
δ
L + γ
1148°C
γ Austenite
2,0
γ + Fe_3C
4,3
α+γ
723°C
0,02
0,8
α
α + Fe_3C
Fe_3C ...(Cementite)
Temperature (°C)
Weight % Carbon
α = Ferrite (BCC)
γ = Austenite (FCC)
δ = Ferrite (BCC)
Fe_3C = Cementite (6.67% C)
Peritectic
Eutectic
Eutectoid



L
α + L
α
Temperature (T)
Cu
%Ni
Ni
Phase diagram
Liquidus
Freezing range
Solidus
Time (T)
Cooling curve

Solidification Time (CHVORINOV'S RULE)

"The amount of heat that must be removed from a casting to cause it to solidify depends on both the amount of superheating and the volume of metal in the casting. Conversely, the ability to remove heat from a casting is directly related to the amount of exposed surface area through which the heat can be extracted and the environment surrounding the molten material".

Solidification time: $t_s = B\,(V/A)^n$ where $n = 1.5$ to 2.0

What is the shape that solidifies faster?

The mold constant, B, incorporates the characteristics of the metal being cast (heat capacity and heat of fusion), the mold material (heat capacity and thermal conductivity), the mold thickness, initial mold temperature, and the amount of superheat.

Shrinkage

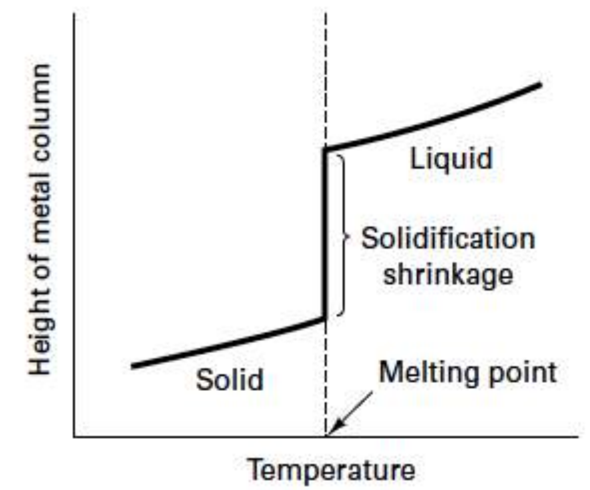
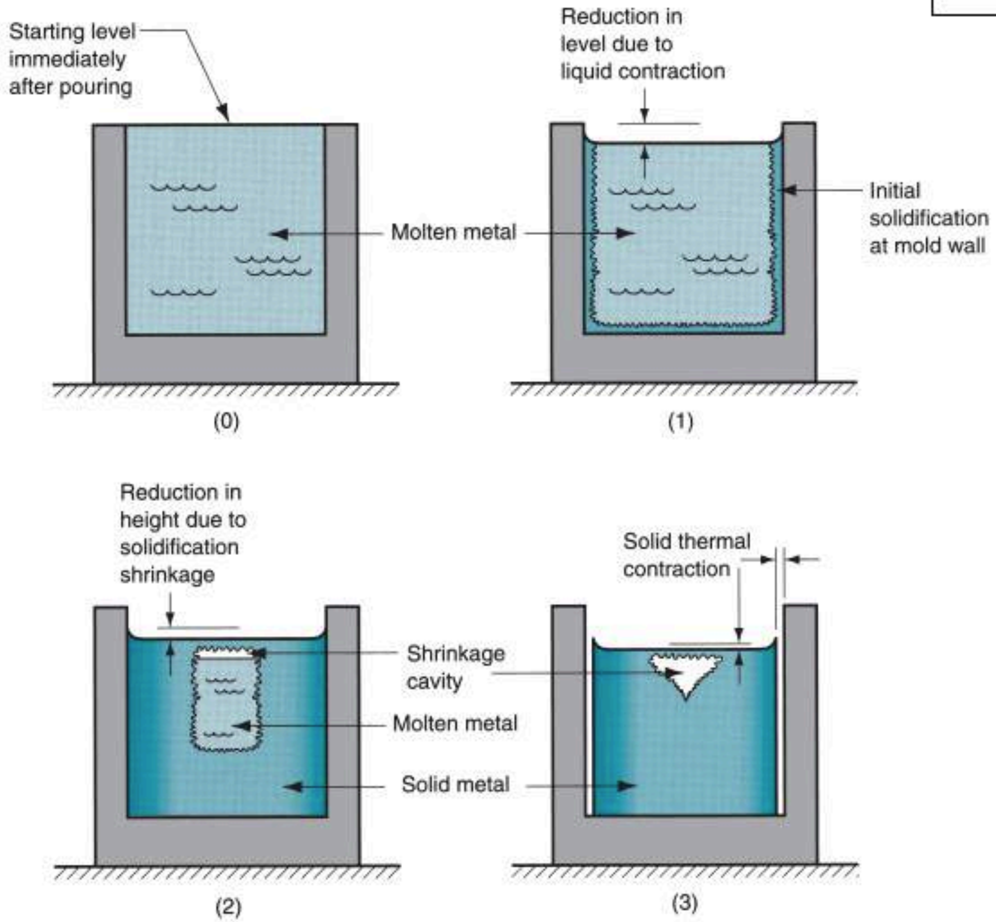


FIGURE 5.6 Shrinkage of a cylindrical casting during solidification and cooling: (0) starting level of molten metal immediately after pouring; (1) reduction in level caused by liquid contraction during cooling; (2) reduction in height and formation of shrinkage cavity caused by solidification shrinkage; and (3) further reduction in height and diameter due to thermal contraction during cooling of the solid metal. For clarity, dimensional reductions are exaggerated in our sketches. (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)



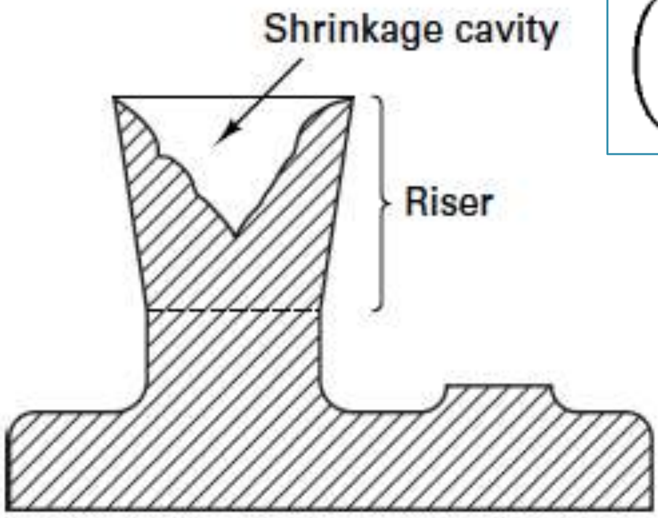
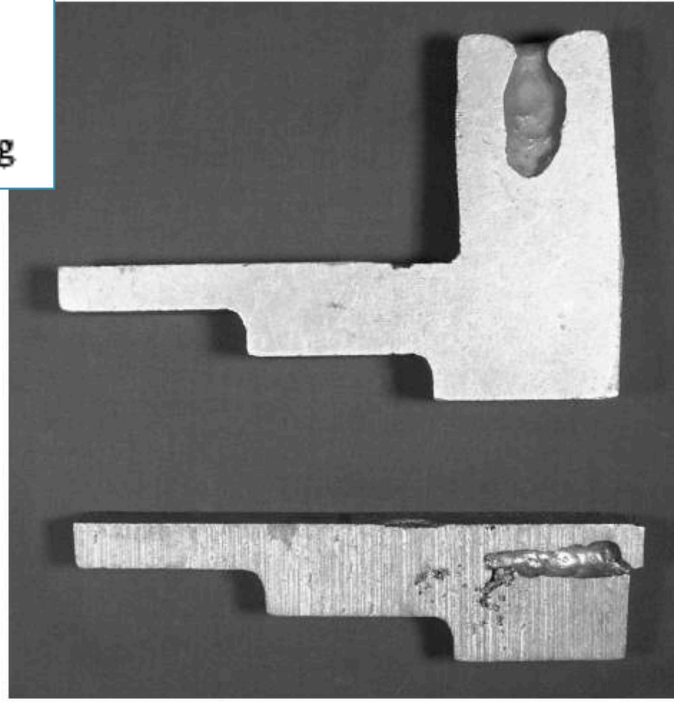
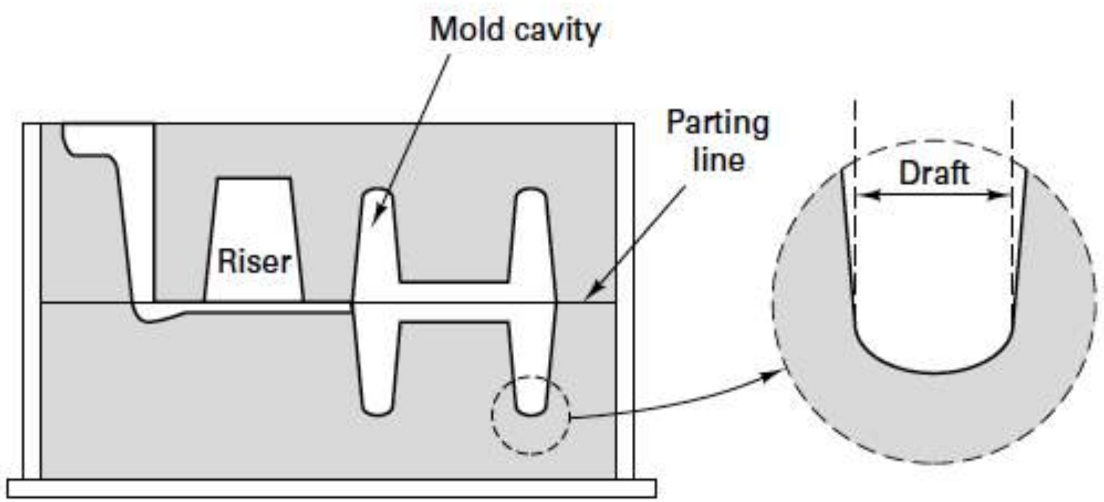


FIGURE 11-22 Attached risers can move the shrinkage cavity external to the actual casting.

$$\left(\frac{V}{A}\right)_{\text{riser}} > \left(\frac{V}{A}\right)_{\text{casting}}$$





Shrinkage

TABLE 5.1 Typical linear shrinkage values for different casting metals due to solid thermal contraction.

Metal	Linear shrinkage	Metal	Linear shrinkage	Metal	Linear shrinkage
Aluminum alloys	1.3%	Magnesium	2.1%	Steel, chrome	2.1%
Brass, yellow	1.3% – 1.6%	Magnesium alloy	1.6%	Tin	2.1%
Cast iron, gray	0.8% – 1.3%	Nickel	2.1%	Zinc	2.6%
Cast iron, white	2.1%	Steel, carbon	1.6% – 2.1%		

How to design a mold?

Directional Solidification / Segregation / Gases

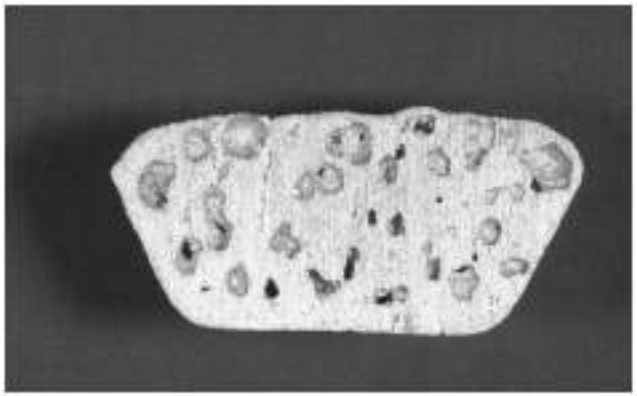
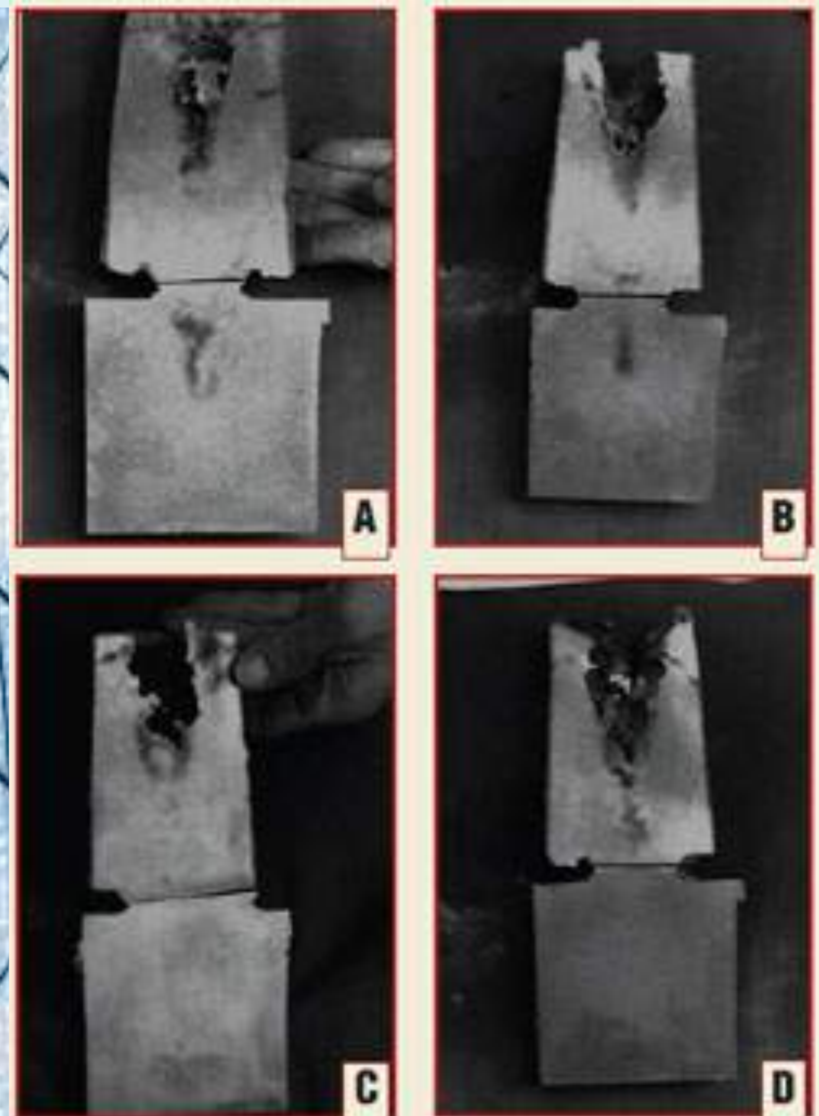


FIGURE 11-8 Demonstration casting made from aluminum that has been saturated in dissolved hydrogen. Note the extensive gas porosity. *(Courtesy Ronald Kohser)*



Rising/Mold Design

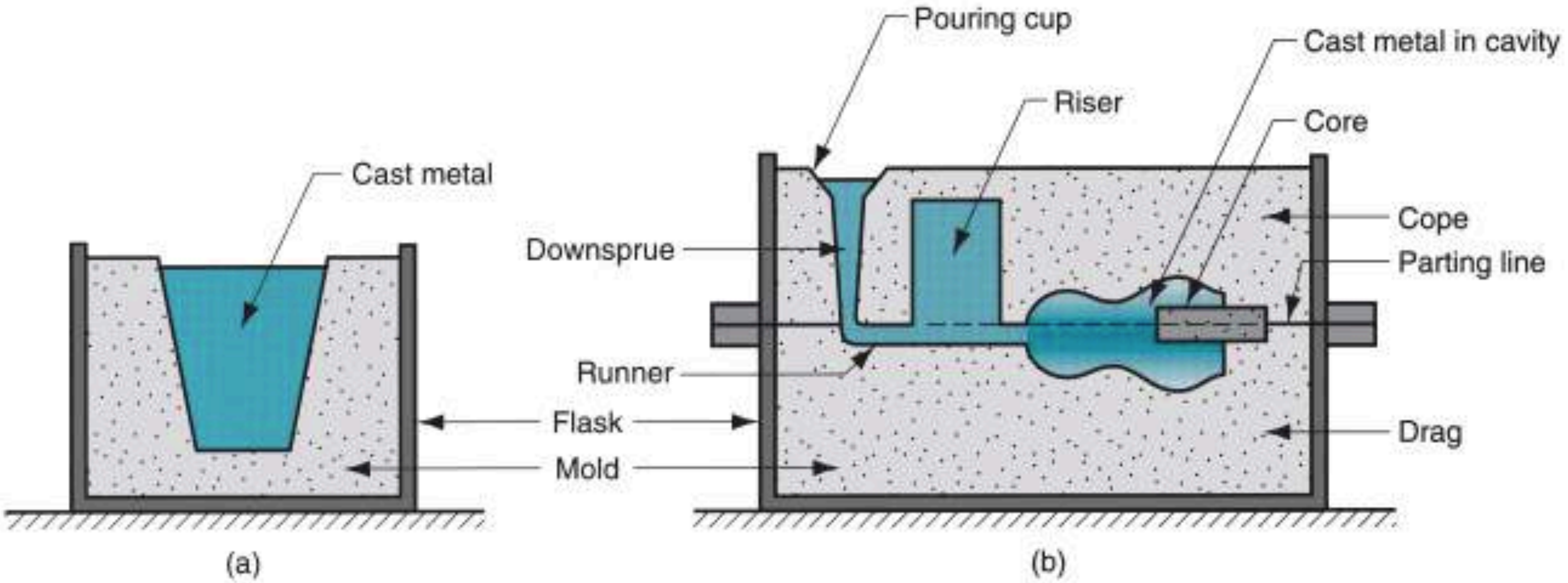
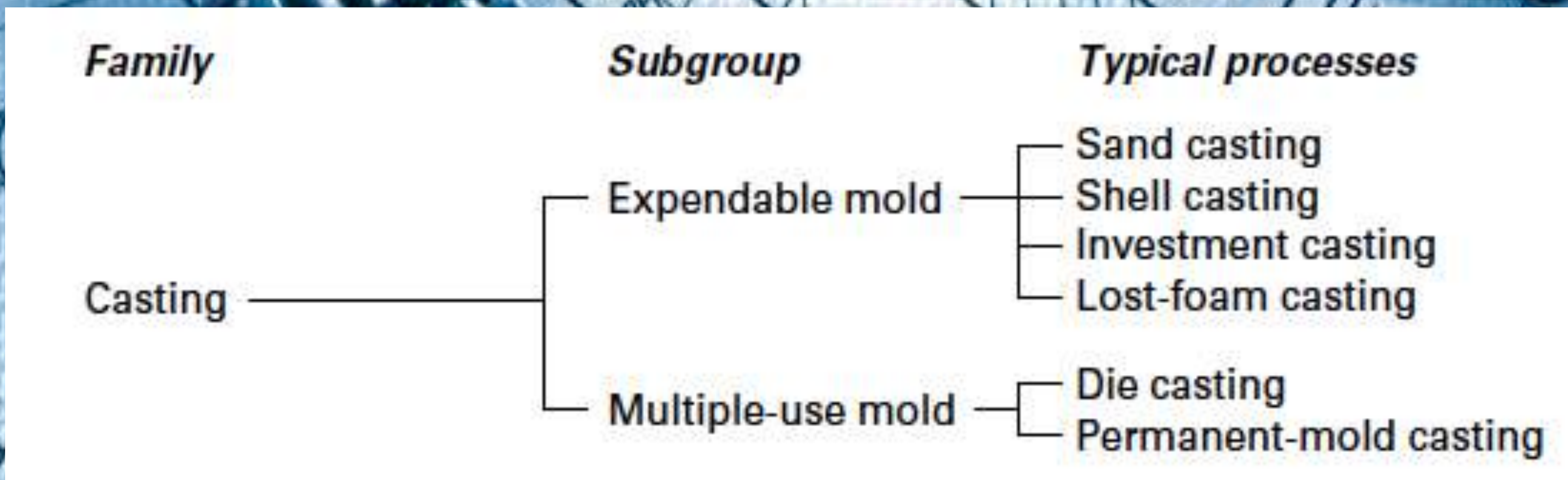


FIGURE 5.1 Two forms of mold: (a) open mold, simply a container in the shape of the desired part; and (b) closed mold, in which the mold geometry is more complex and requires a gating system (passageway) leading into the cavity. (Credit: *Fundamentals of Modern Manufacturing,* 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)

Casting Processes (Classes as a function of mold type)



Capabilities and Advantages of Casting

- Casting can be used to create complex part geometries, including both external and

internal shapes.

- Net Shape / Near Net Shape
- Casting can be used to produce very large parts. (100 tons!)
- The casting process can be performed on any metal that can be heated to the liquid state.
- Some casting methods are quite suited to mass production.

Disadvantages:

- Different disadvantages for different casting methods!
- Mechanical properties, porosity, poor dimensional accuracy and surface finish for some casting processes, safety hazards to humans when processing hot molten metals, and environmental problems.

Sand Casting

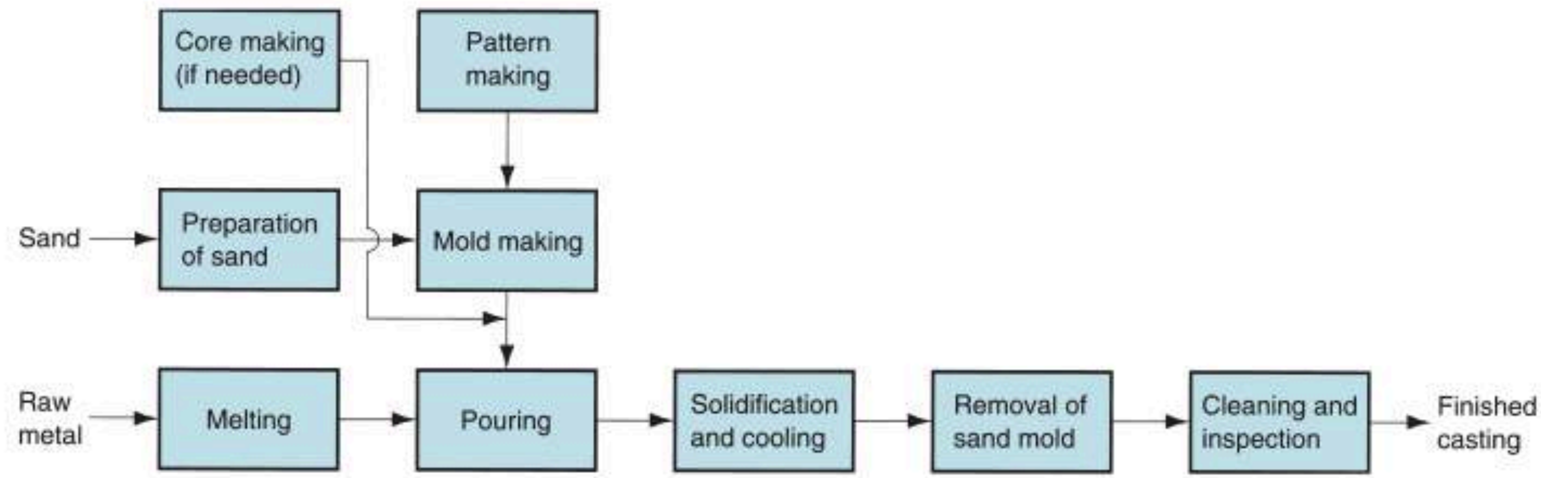


FIGURE 6.1 Steps in the production sequence in sand casting. The steps include not only the casting operation but also pattern making and mold making. (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)

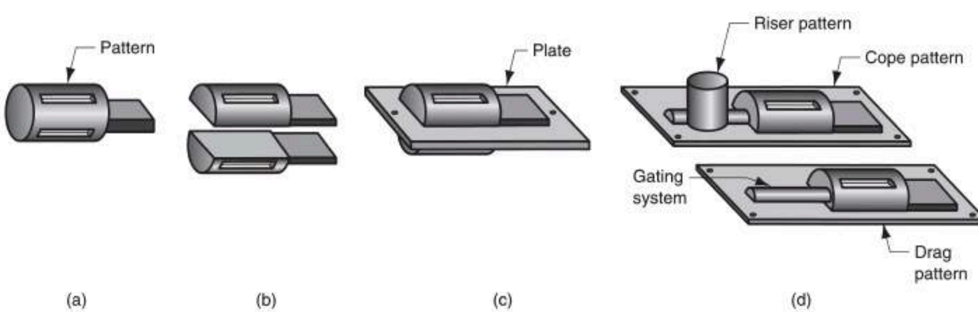
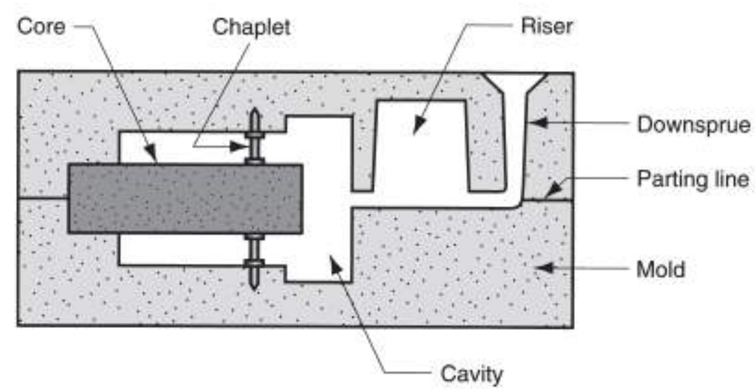
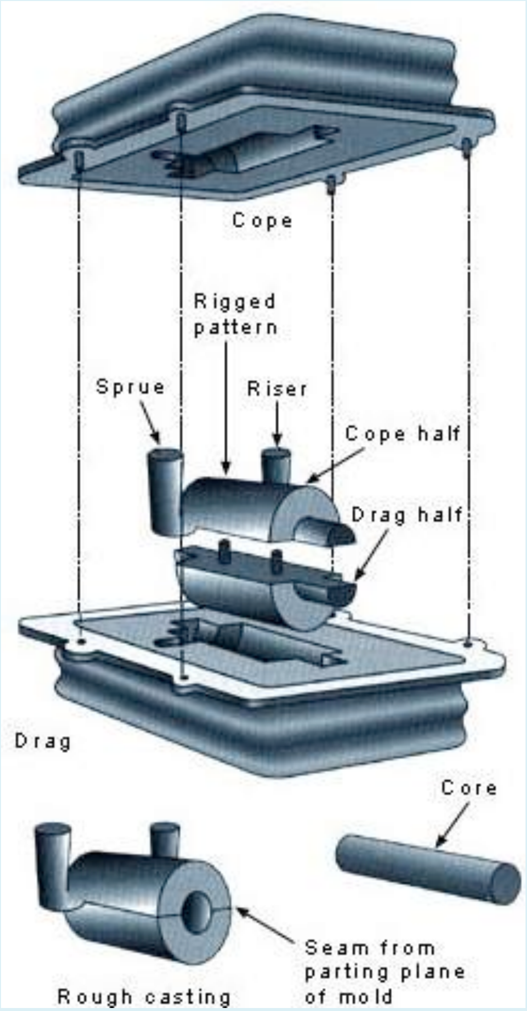


FIGURE 6.2 Types of patterns used in sand casting: (a) solid pattern, (b) split pattern, (c) match-plate pattern, and (d) cope-and-drag pattern. (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)




Cope
Rigged pattern
Sprue
Riser
Cope half
Drag half
Drag
Core
Seam from parting plane of mold
Rough casting

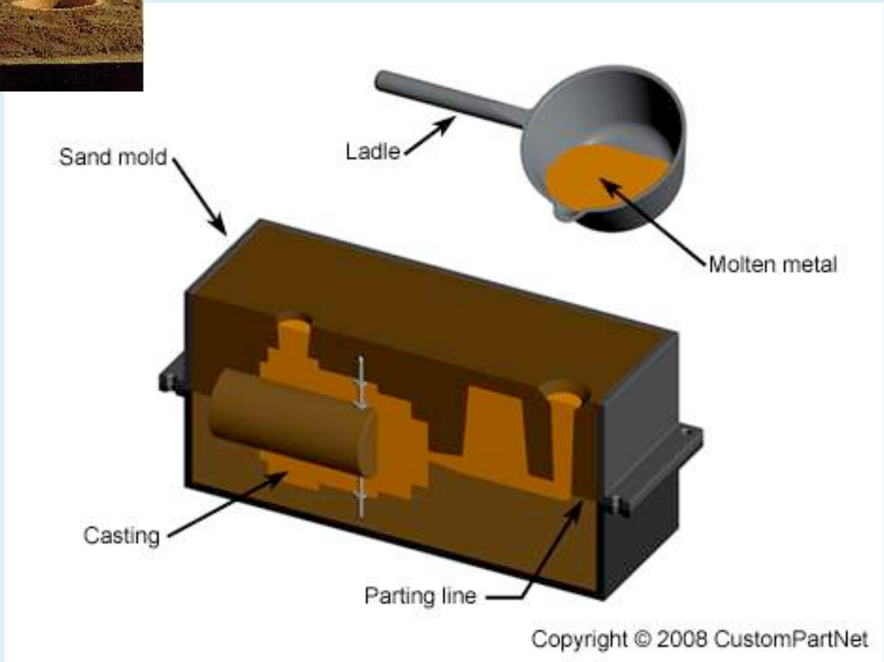
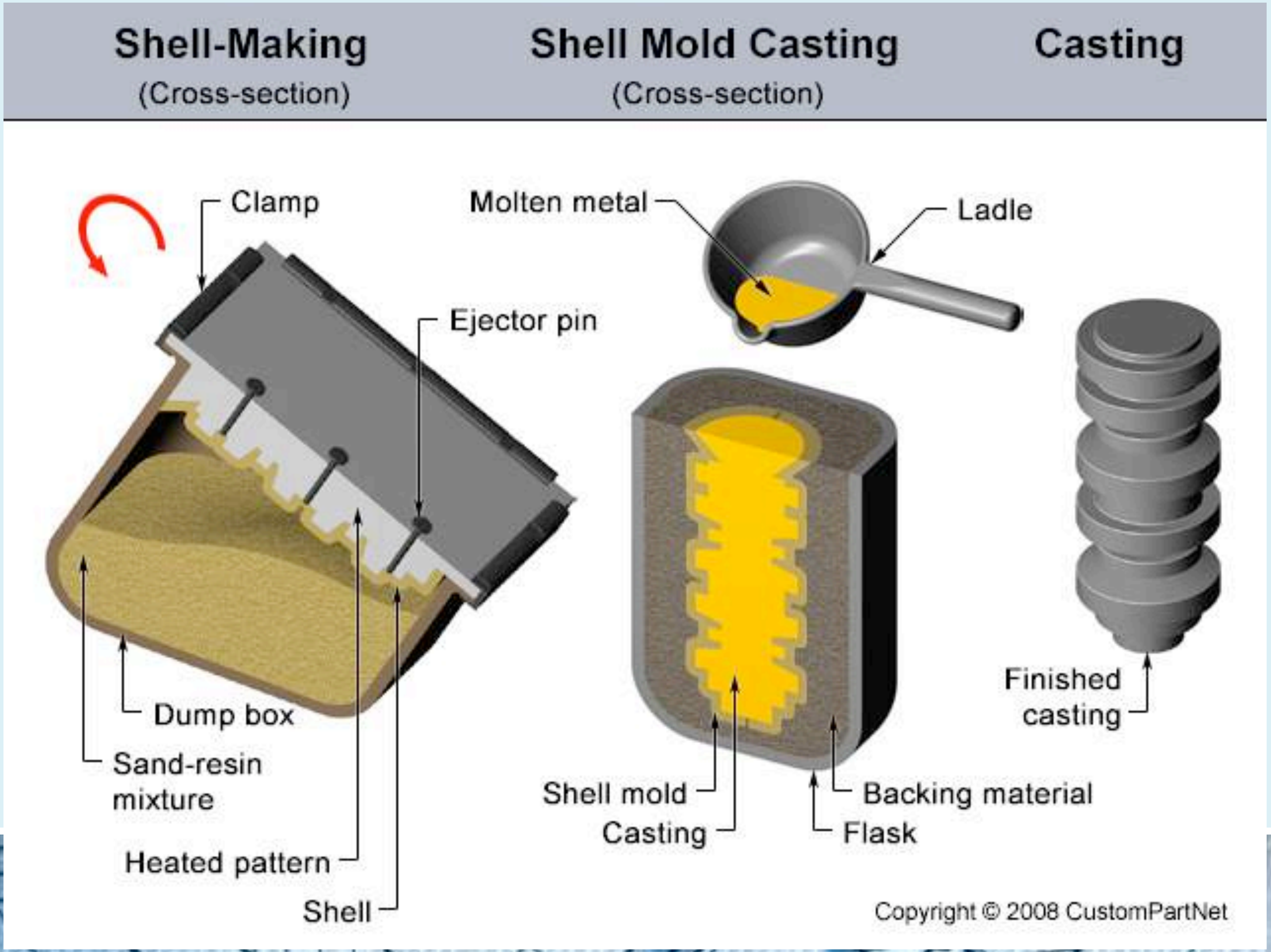
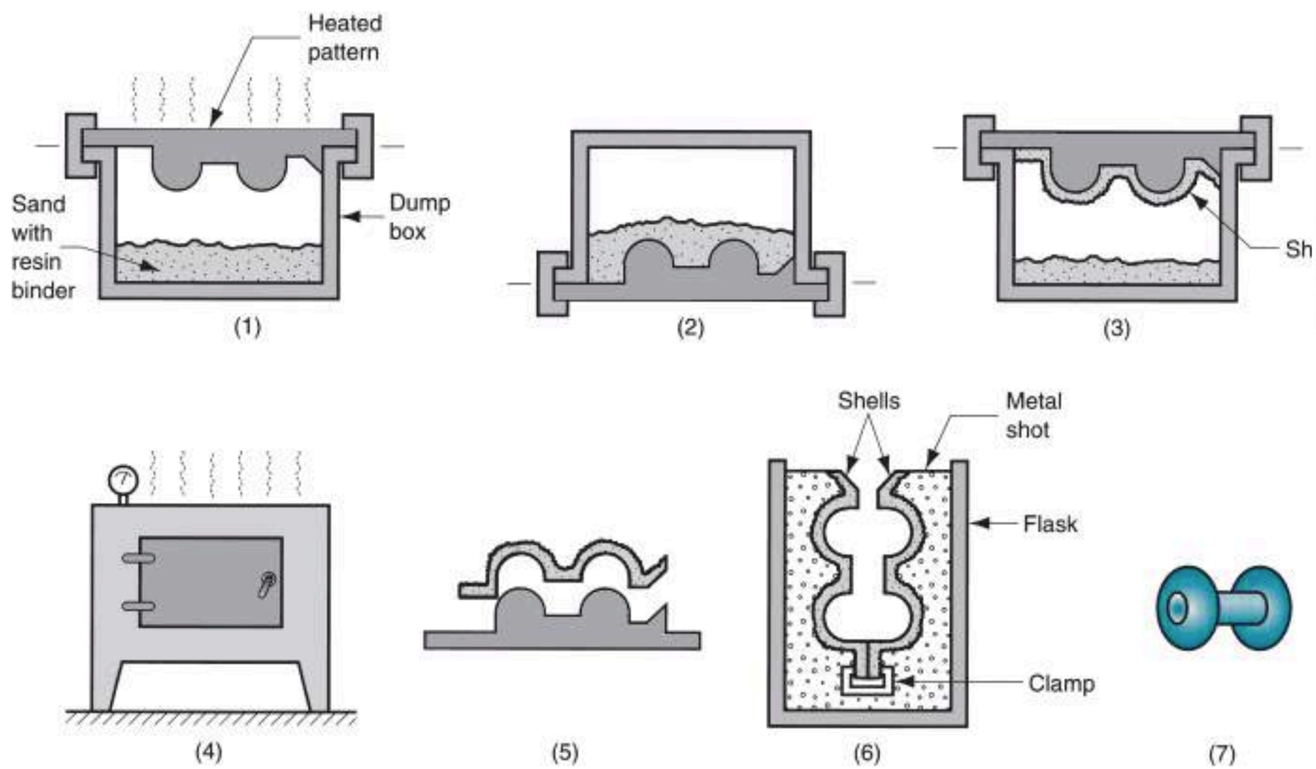

Sand mold
Ladle
Molten metal
Casting
Parting line
Copyright © 2008 CustomPartNet

FIGURE 12-17 A variety of sand cast aluminum parts. *(Courtesy Bodine Aluminum, Inc., St. Louis, MO)*

Shell Molding





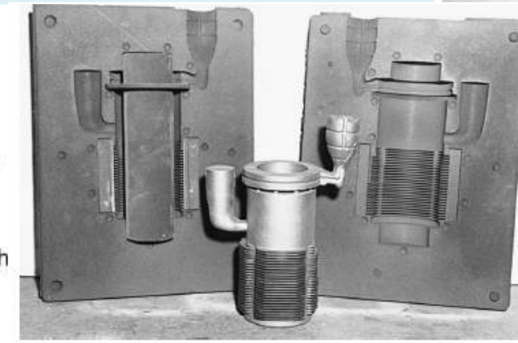
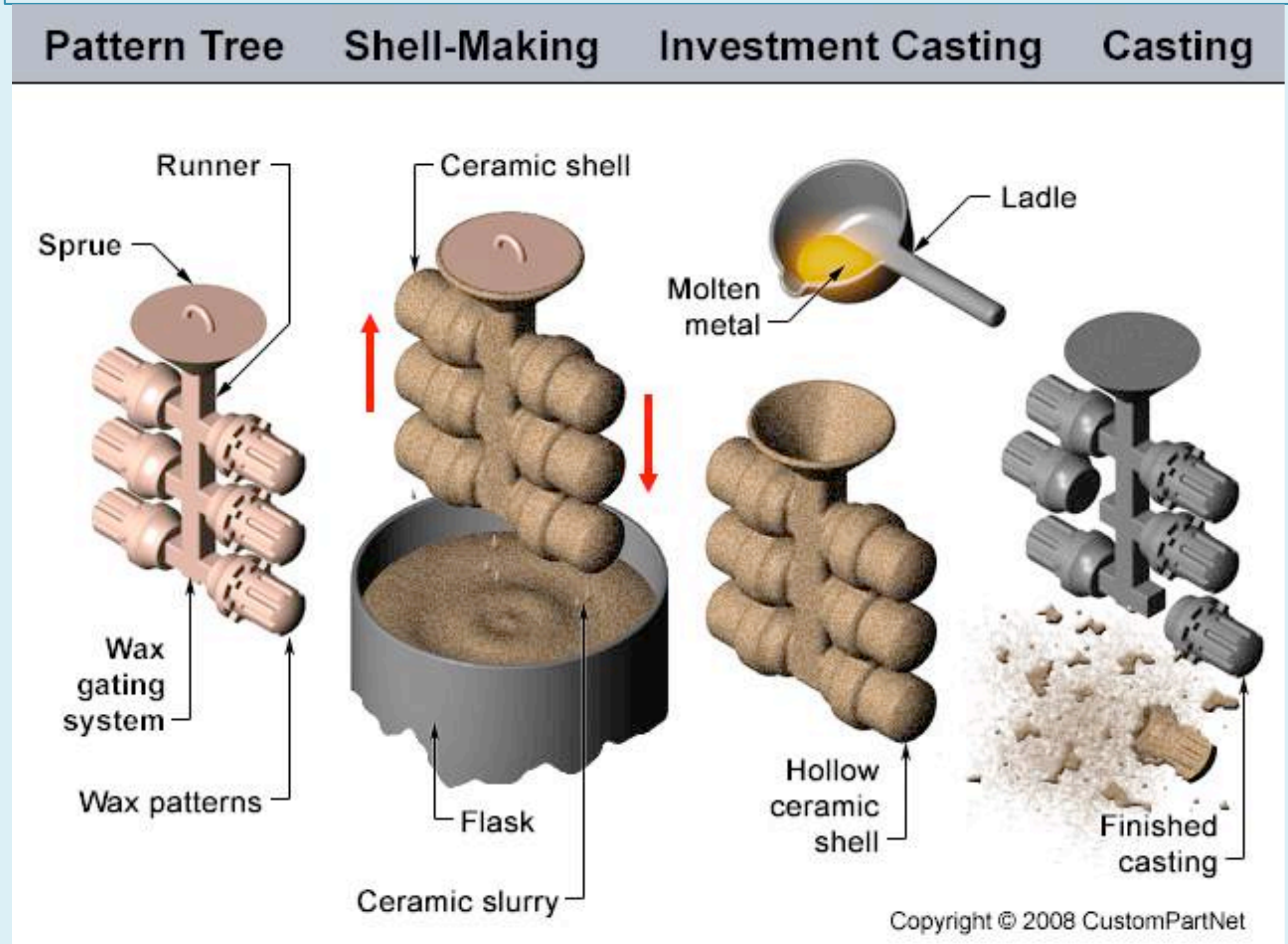
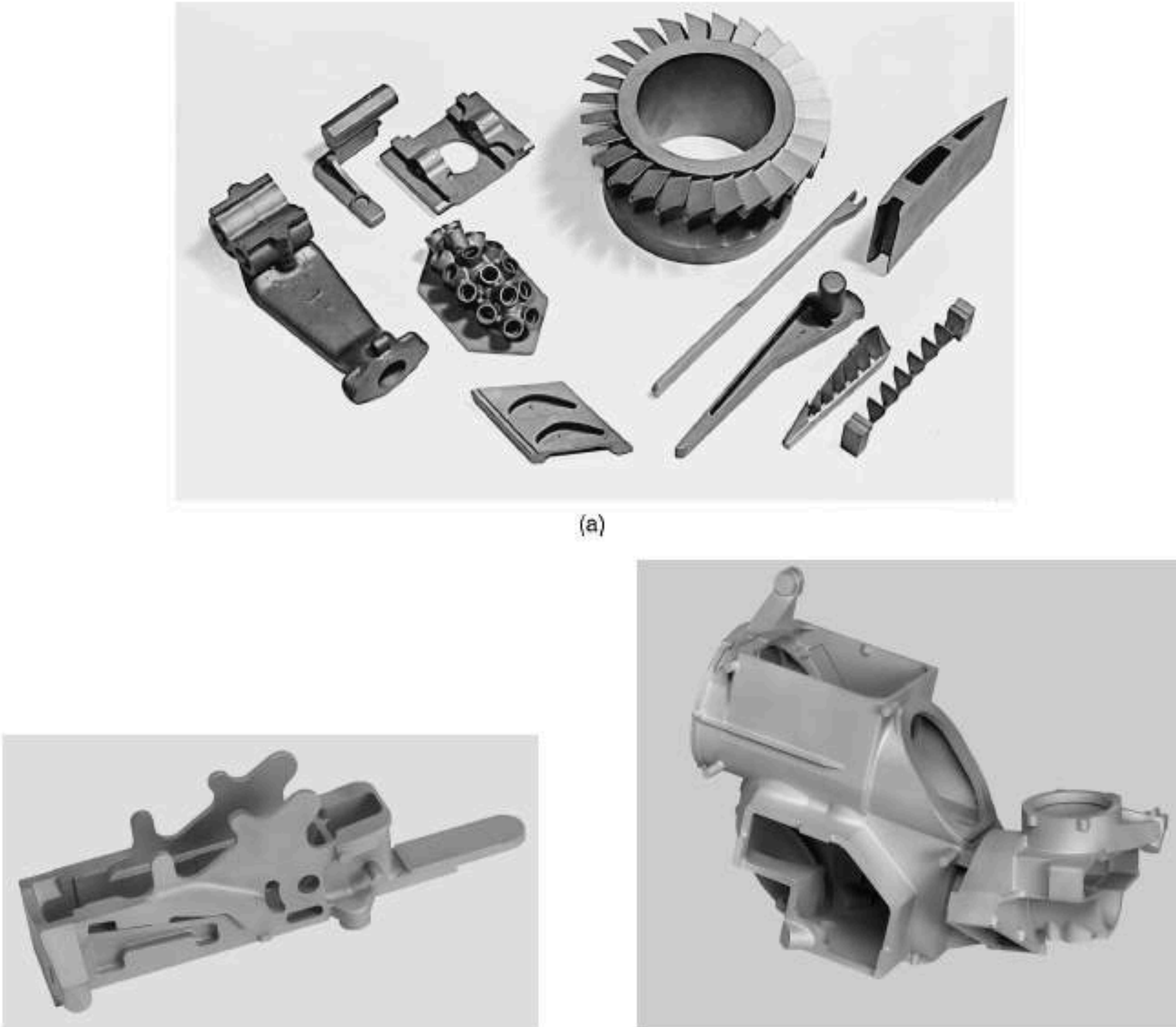


FIGURE 6.4 Steps in shell molding: (1) a match-plate or cope-and-drag metal pattern is heated and placed over a box containing sand mixed with thermosetting resin; (2) box is inverted so that sand and resin fall onto the hot pattern, causing a layer of the mixture to partially cure on the surface to form a hard shell; (3) box is repositioned so that loose, uncured particles drop away; (4) sand shell is heated in oven for several minutes to complete curing; (5) shell mold is stripped from the pattern; (6) two halves of the shell mold are assembled, supported by sand or metal shot in a box, and pouring is accomplished. The finished casting with sprue removed is shown in (7). (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)

Investiment Casting





(a)

(b)

(c)

FIGURE 12-29 Typical parts produced by investment casting: (a) nickel and cobalt superalloys; (b) copper alloy; (c) aluminum alloy. *[(a) Haynes International Inc.; (b and c) O'Fallon Casting]*

Evaporative pattern (full-mold and lost-foam) casting

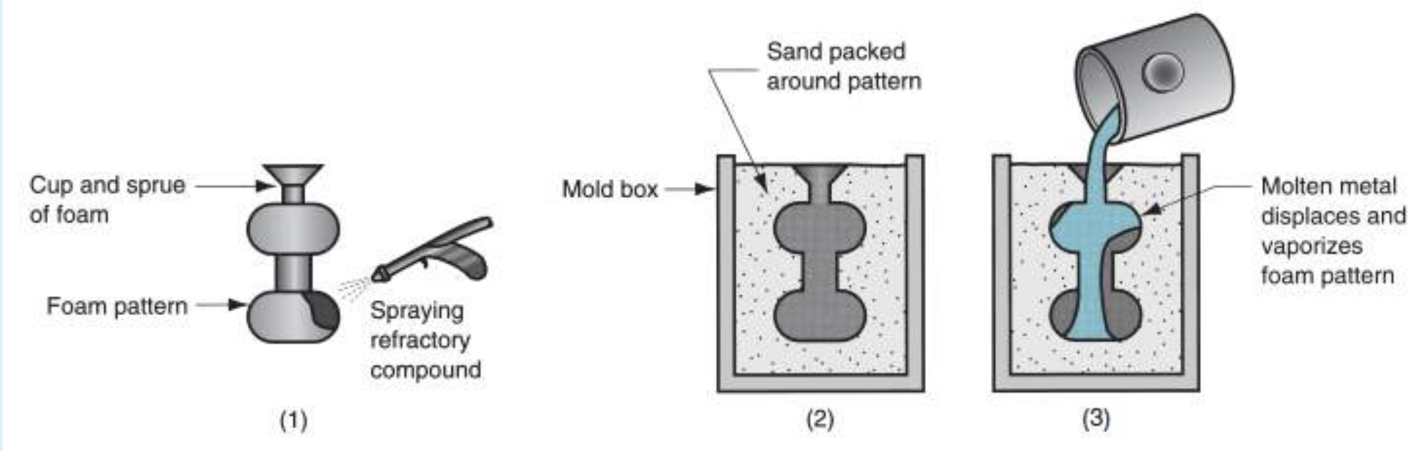


FIGURE 6.5 Expanded polystyrene casting process: (1) pattern of polystyrene is coated with refractory compound; (2) foam pattern is placed in mold box, and sand is compacted around the pattern; and (3) molten metal is poured into the portion of the pattern that forms the pouring cup and sprue. As the metal enters the mold, the polystyrene foam is vaporized ahead of the advancing liquid, thus allowing the resulting mold cavity to be filled. (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)

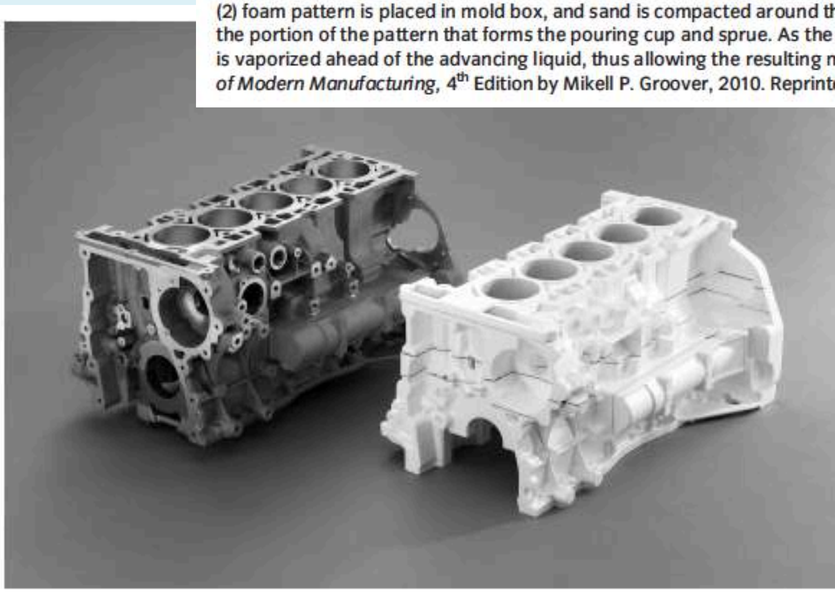
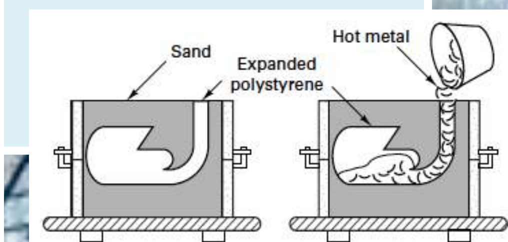
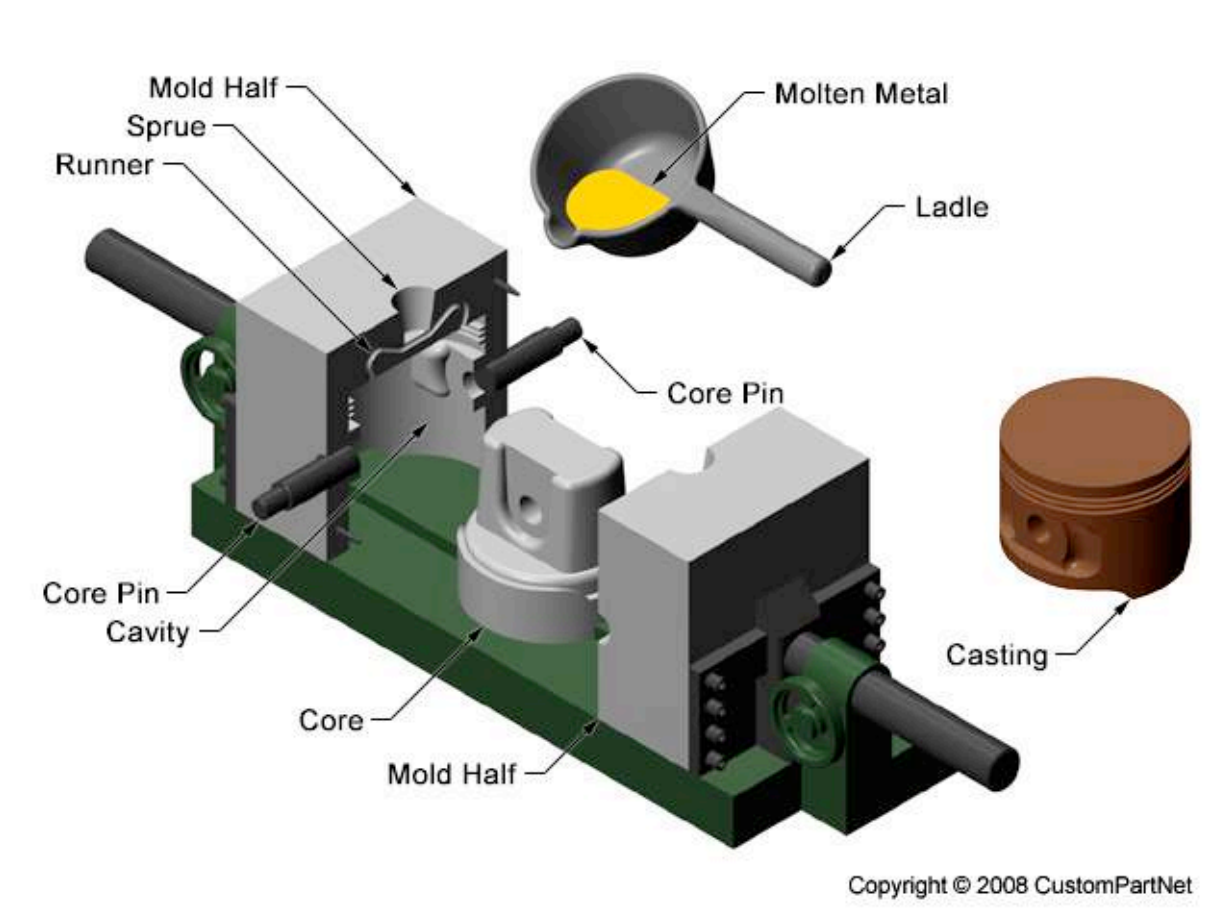


FIGURE 12-32 The Styrofoam pattern and the finished casting of a five-cylinder engine block produced by lost foam casting. *(Courtesy General Motors Corporation, Detroit, MI)*



The basic permanent-mold process



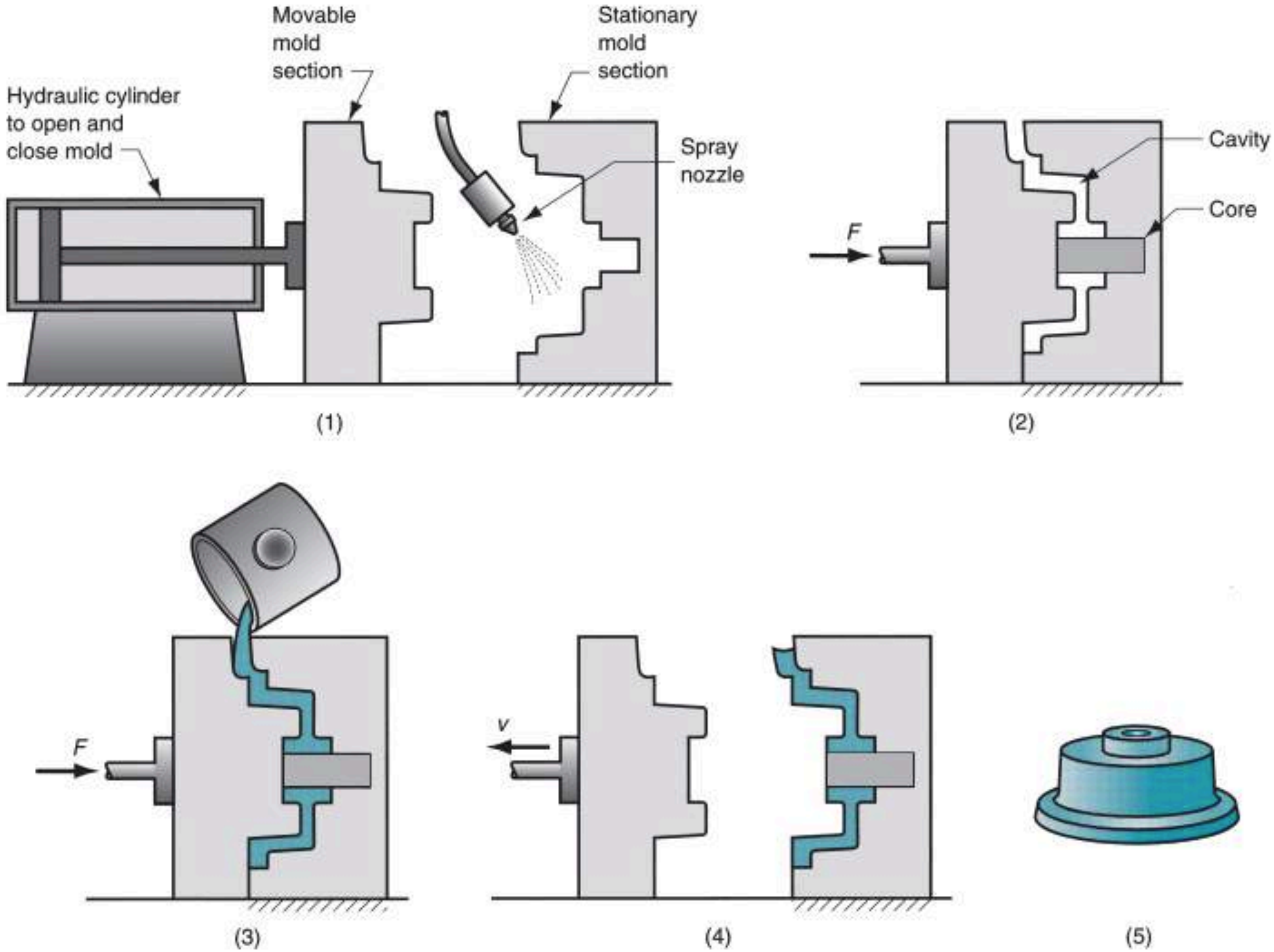
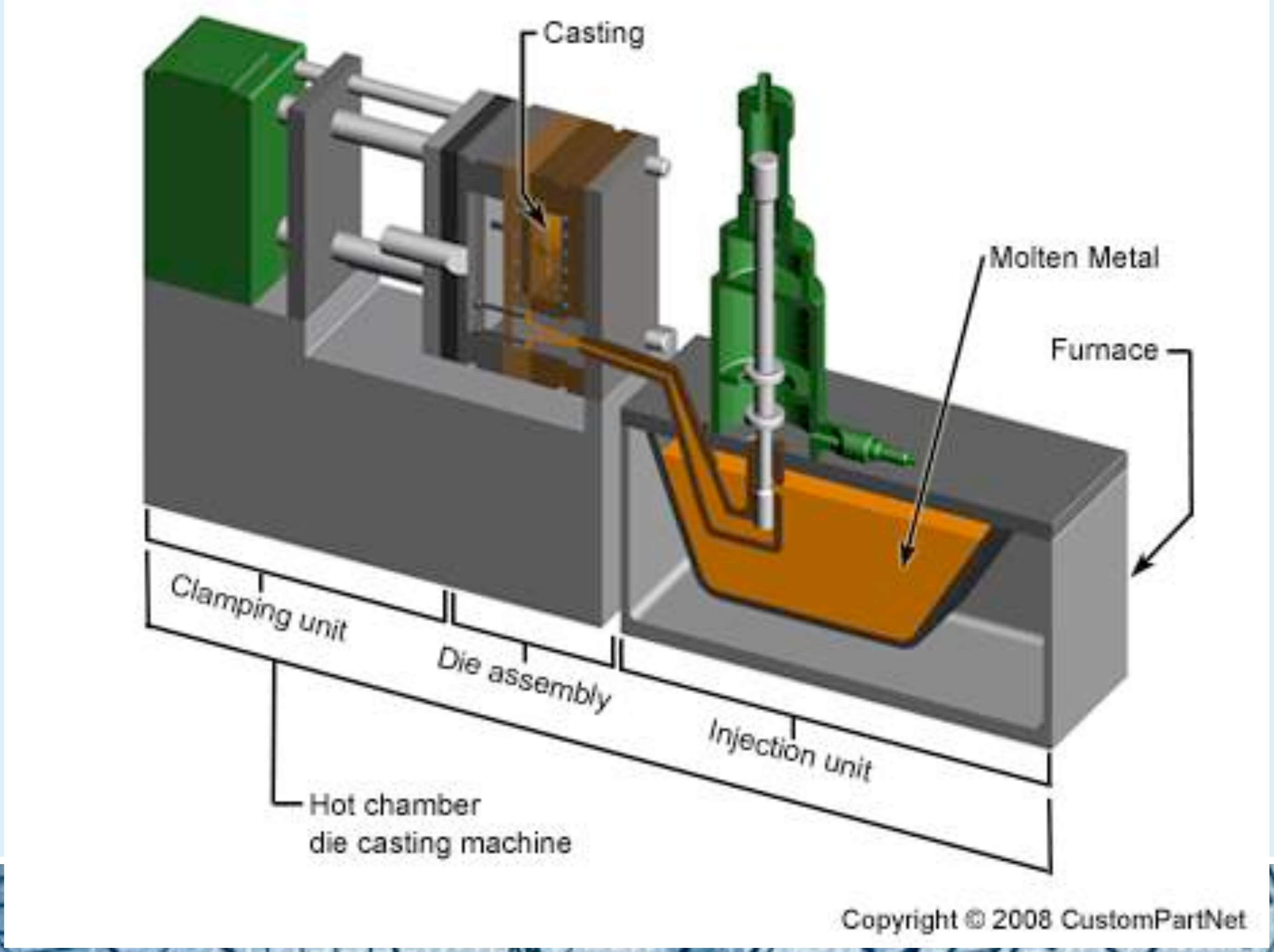
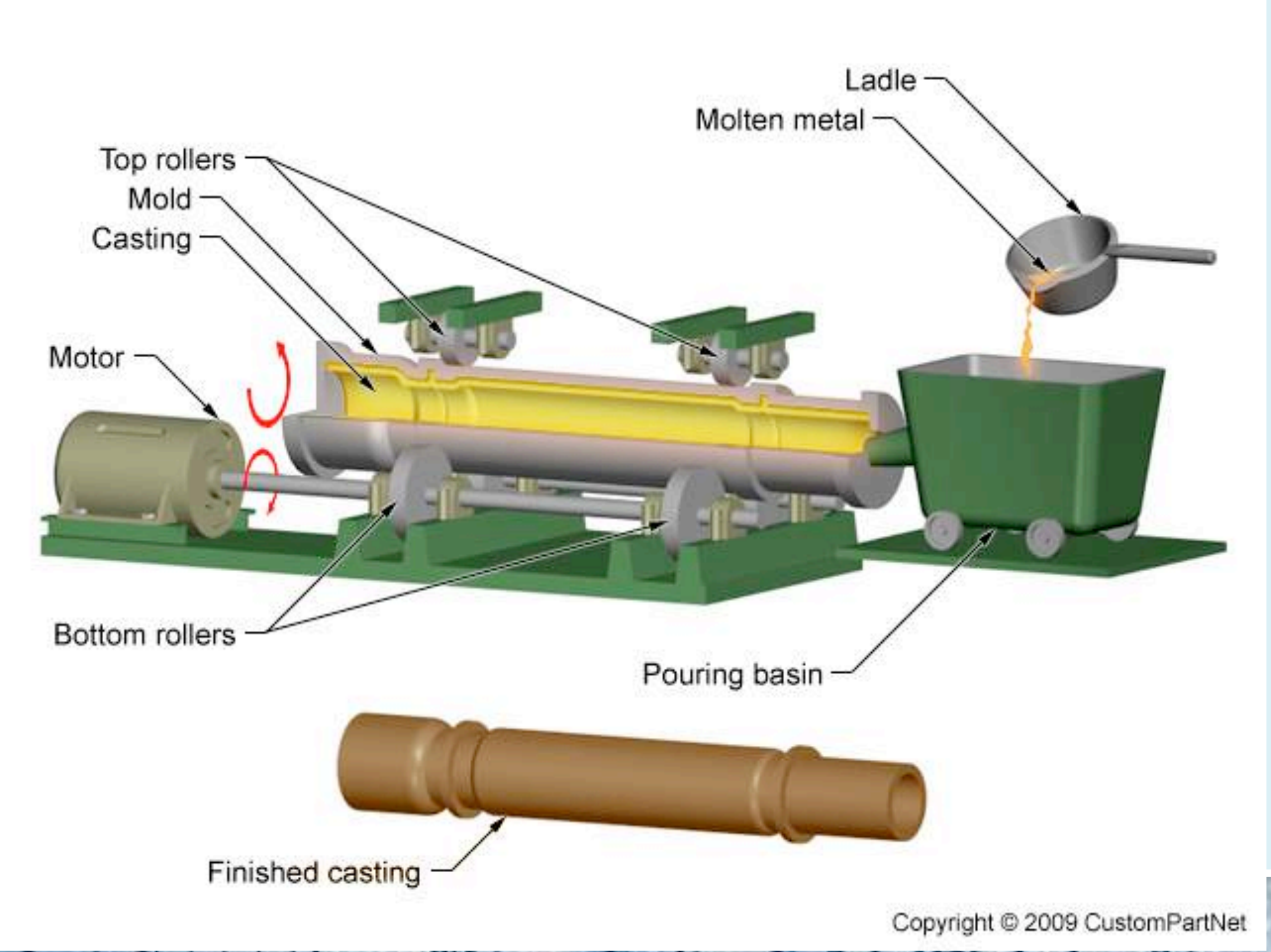


FIGURE 6.8 Steps in permanent-mold casting: (1) Mold is preheated and coated; (2) cores (if used) are inserted, and mold is closed; (3) molten metal is poured into the mold; and (4) mold is opened. Finished part is shown in (5). (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)

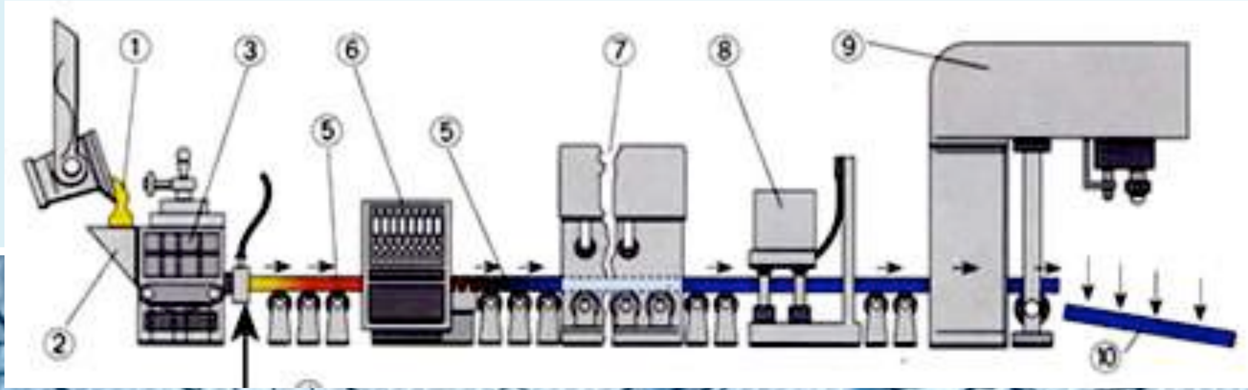
Die Casting (fundição por pressão)



Centrifugal Casting



Continuous Casting



Furnaces

The types of furnaces most commonly used in foundries are:

1. Cupolas,
2. Direct fuelfired furnaces,
3. crucible furnaces,
4. electric-arc furnaces, and
5. induction furnaces.

1. Cupola

Cupolas are used only for melting cast irons, the largest tonnage of cast iron is melted in cupolas.

It consists of a large shell of steel plate lined with refractory.

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

The iron is usually a mixture of pig iron and scrap (including risers, runners, and sprues left over from previous castings).

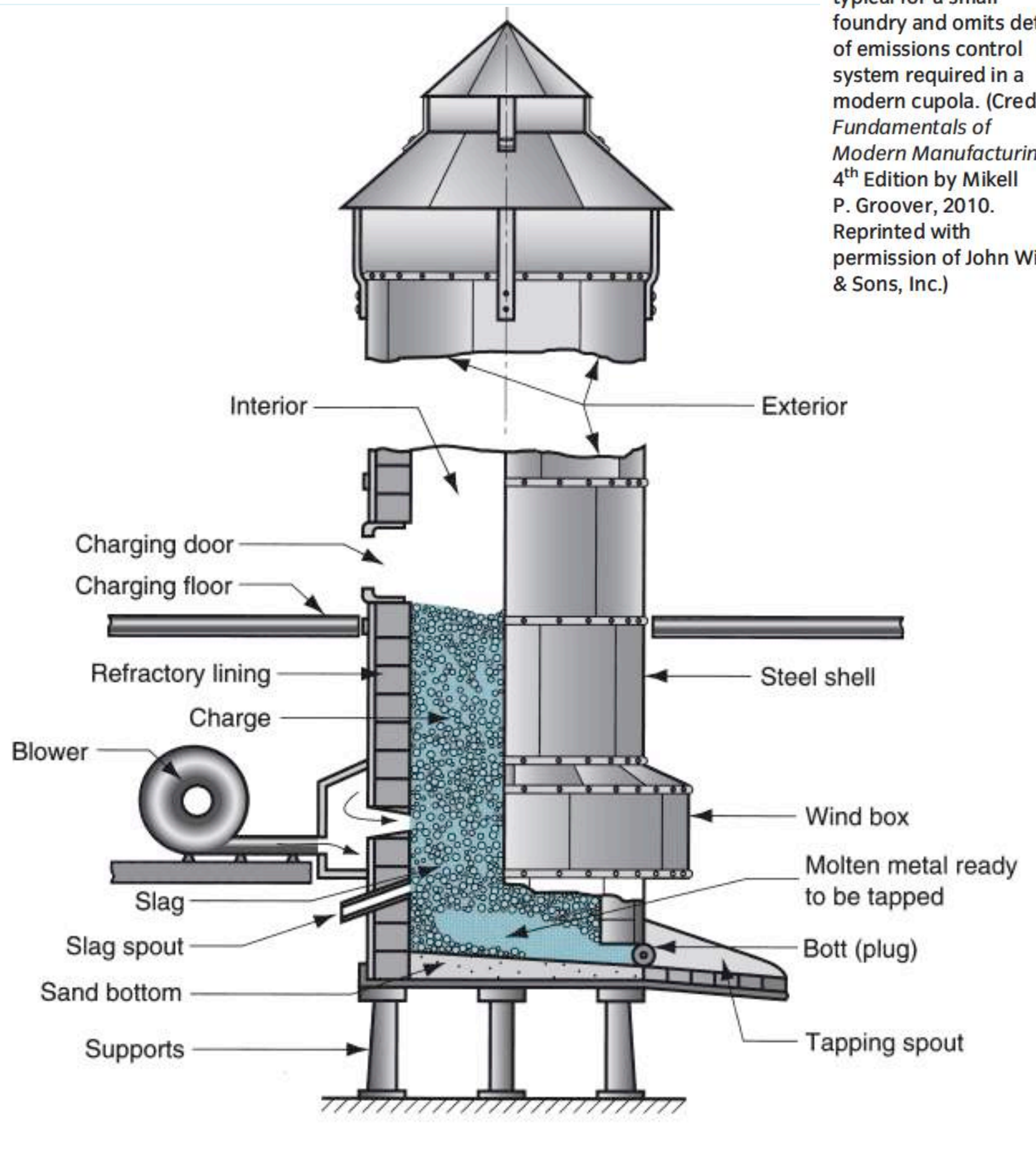
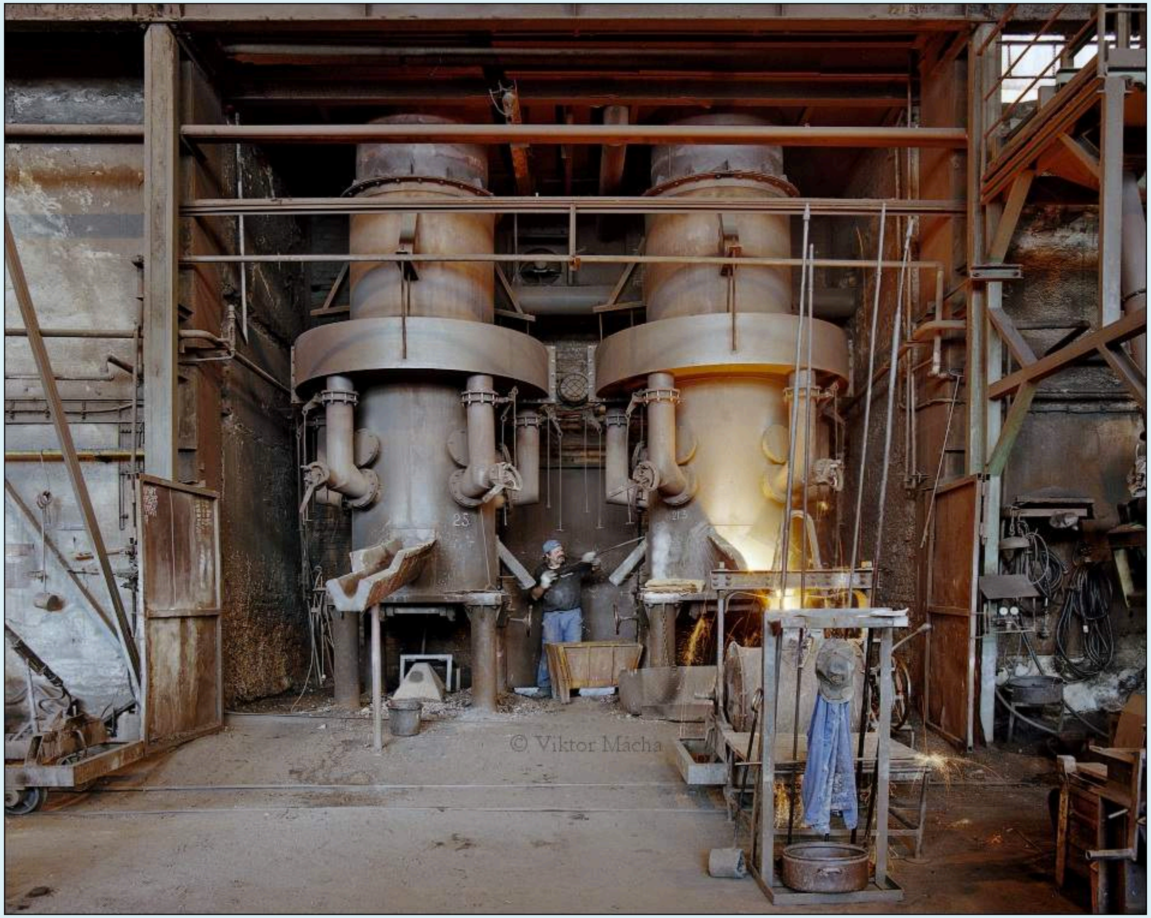


FIGURE 6.14 Cupola used for melting cast iron. Furnace shown is typical for a small foundry and omits details of emissions control system required in a modern cupola. (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)


© Viktor Macha

2. Direct Fuel-Fired Furnaces

“A direct fuel-fired furnace contains a small open hearth, in which the metal charge is heated by fuel burners located on the side of the furnace. roof of the furnace assists the heating action by reflecting the flame down against the charge. Typical fuel is natural gas, and the combustion products exit the furnace through a stack. At the bottom of the hearth is a tap hole to release the molten metal. Direct fuelfired furnaces are generally used in casting for melting nonferrous metals such as copperbase alloys and aluminum.”

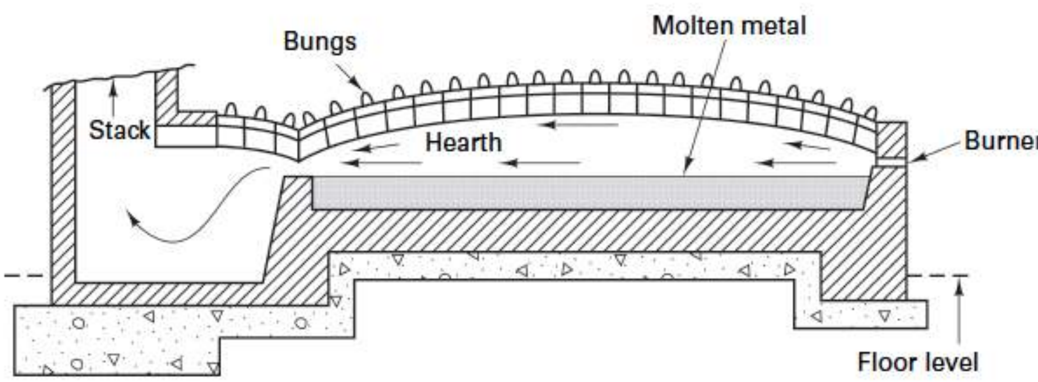


FIGURE 13-15 Cross section of a direct fuel-fired furnace. Hot combustion gases pass across the surface of a molten metal pool.

3. Crucible Furnaces (Indirect Fuel-fired furnaces)

These furnaces melt the metal without direct contact with a burning fuel mixture.

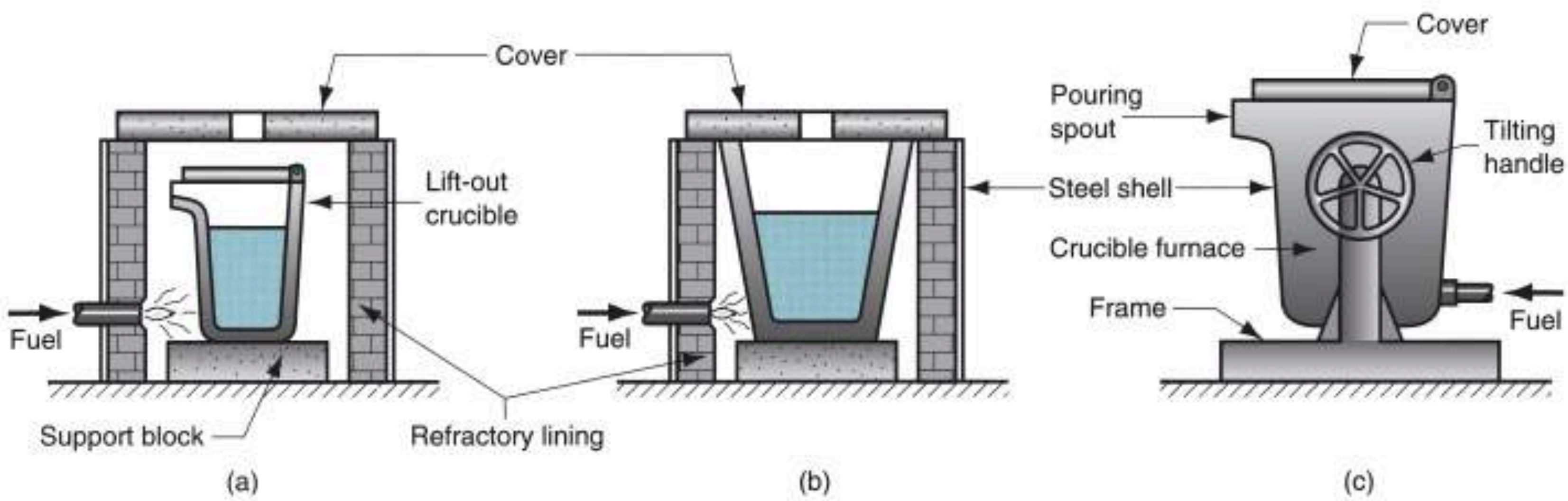
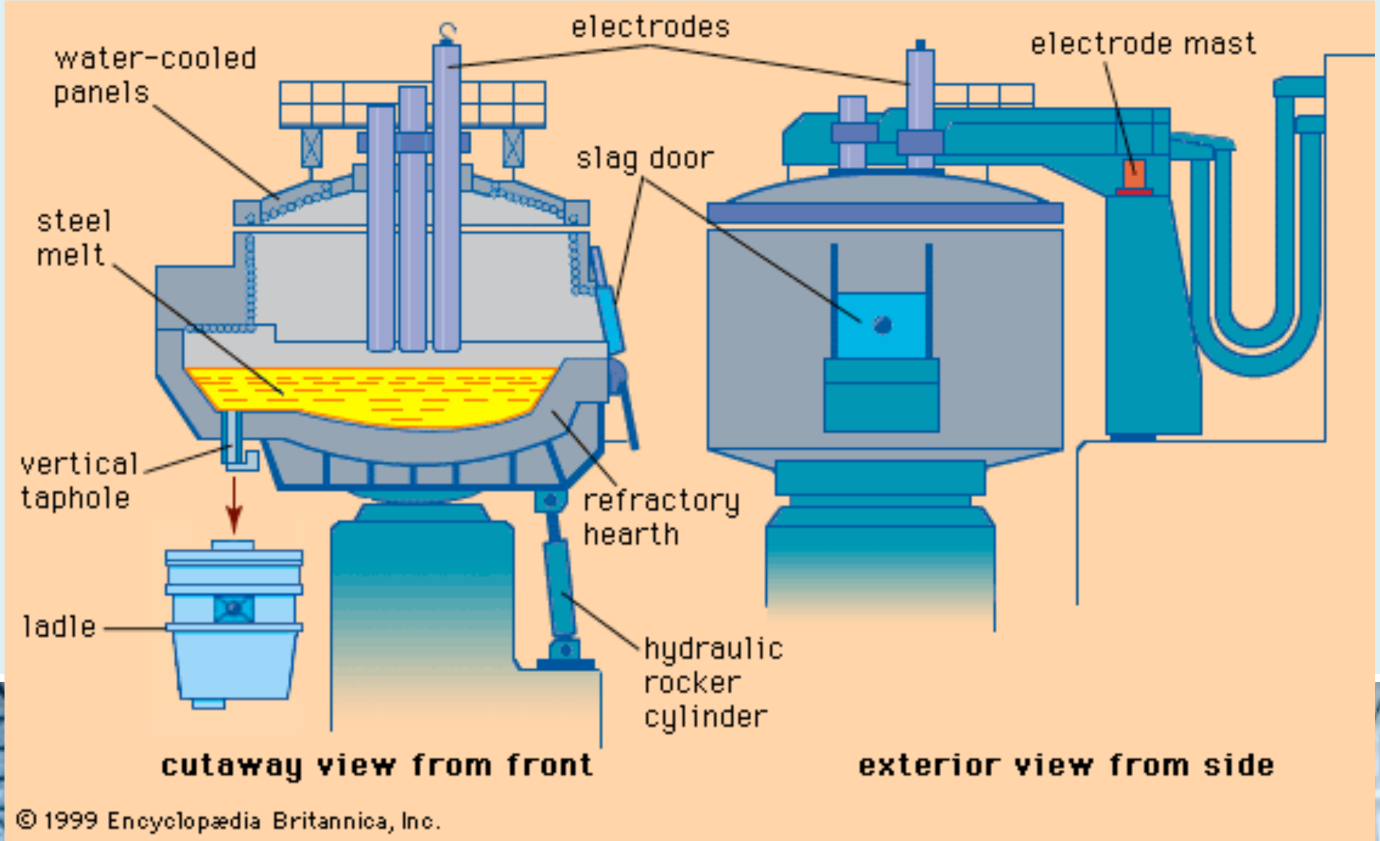


FIGURE 6.15 Three types of crucible furnaces: (a) lift-out crucible, (b) stationary pot, and (c) tilting-pot furnace. (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)

4. Electric Arc Furnace - Forno a arco elétrico

In this furnace type, the charge is melted by heat generated from an electric arc that flows between two or three electrodes and the charge metal.

Power consumption is high, but electric-arc furnaces can be designed for high melting capacity (23,000 to 45,000 kg/hr or 25 to 50 tons/hr), and they are used primarily for casting steel.



5. Induction Furnace

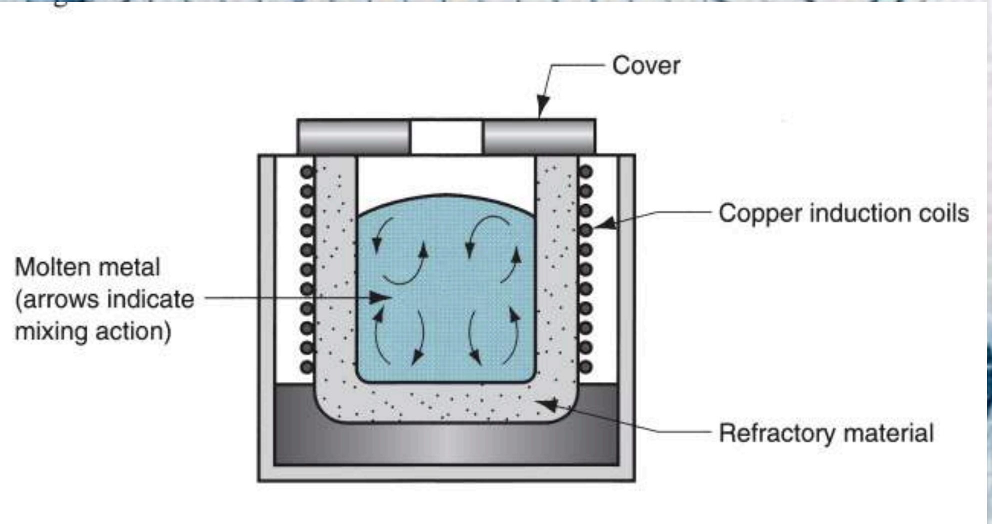
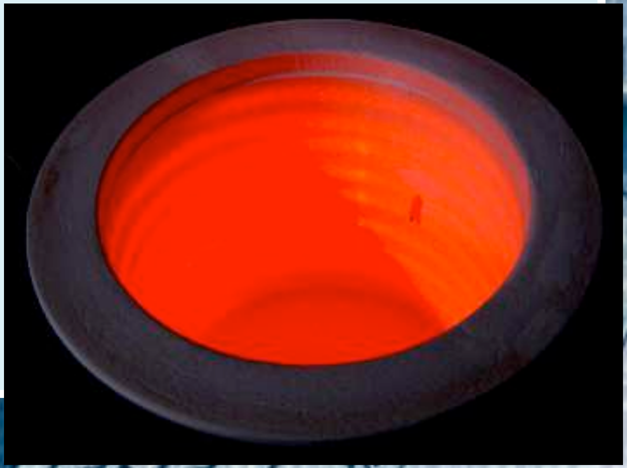


FIGURE 6.16 Induction furnace. (Credit: *Fundamentals of Modern Manufacturing*, 4th Edition by Mikell P. Groover, 2010. Reprinted with permission of John Wiley & Sons, Inc.)



How is the final process like?

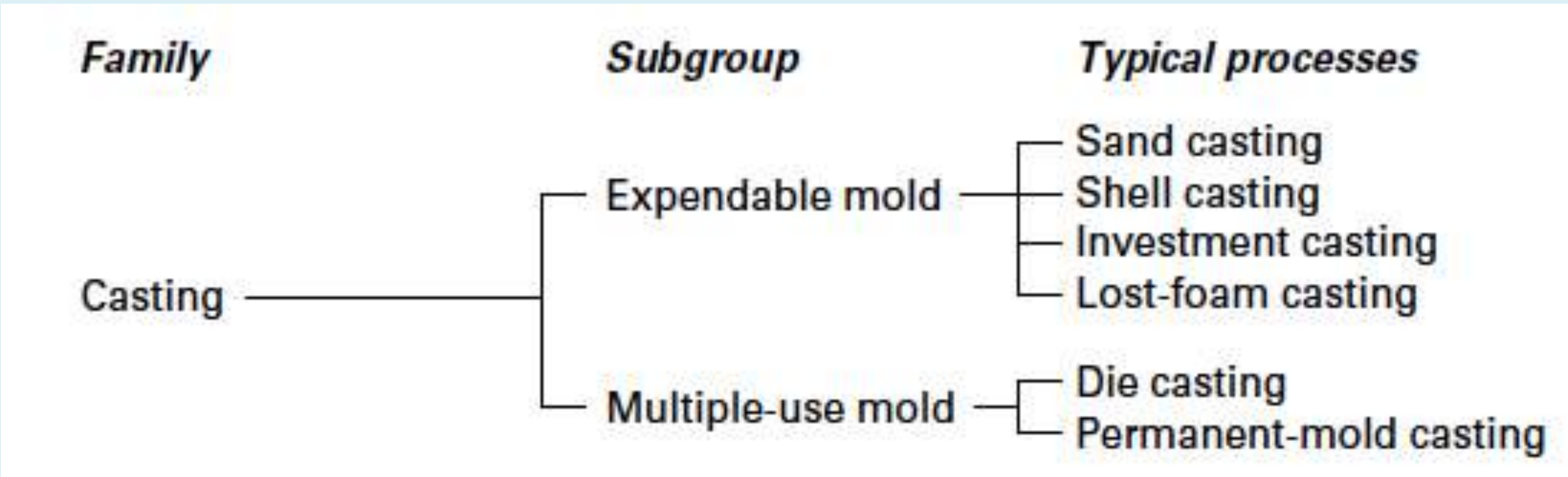
TABLE 6.1 Typical dimensional tolerances for various casting processes and metals

Casting Process	Part Size	Tolerance mm	Tolerance in	Casting Process	Part Size	Tolerance mm	Tolerance in
Sand casting				Permanent mold			
Aluminum[a]	Small	±0.5	±0.020	Aluminum[a]	Small	±0.25	±0.010
Cast iron	Small	±1.0	±0.040	Cast iron	Small	±0.8	±0.030
	Large	±1.5	±0.060	Copper alloys	Small	±0.4	±0.015
Copper alloys	Small	±0.4	±0.015	Steel	Small	±0.5	±0.020
Steel	Small	±1.3	±0.050	Die casting			
	Large	±2.0	±0.080	Aluminum[a]	Small	±0.12	±0.005
Shell molding				Copper alloys	Small	±0.12	±0.005
Aluminum[a]	Small	±0.25	±0.010	Investment			
Cast iron	Small	±0.5	±0.020	Aluminum[a]	Small	±0.12	±0.005
Copper alloys	Small	±0.4	±0.015	Cast iron	Small	±0.25	±0.010
Steel	Small	±0.8	±0.030	Copper alloys	Small	±0.12	±0.005
Plaster mold	Small	±0.12	±0.005	Steel	Small	±0.25	±0.010
	Large	±0.4	±0.015				

Compiled from [7], [14], and other sources.

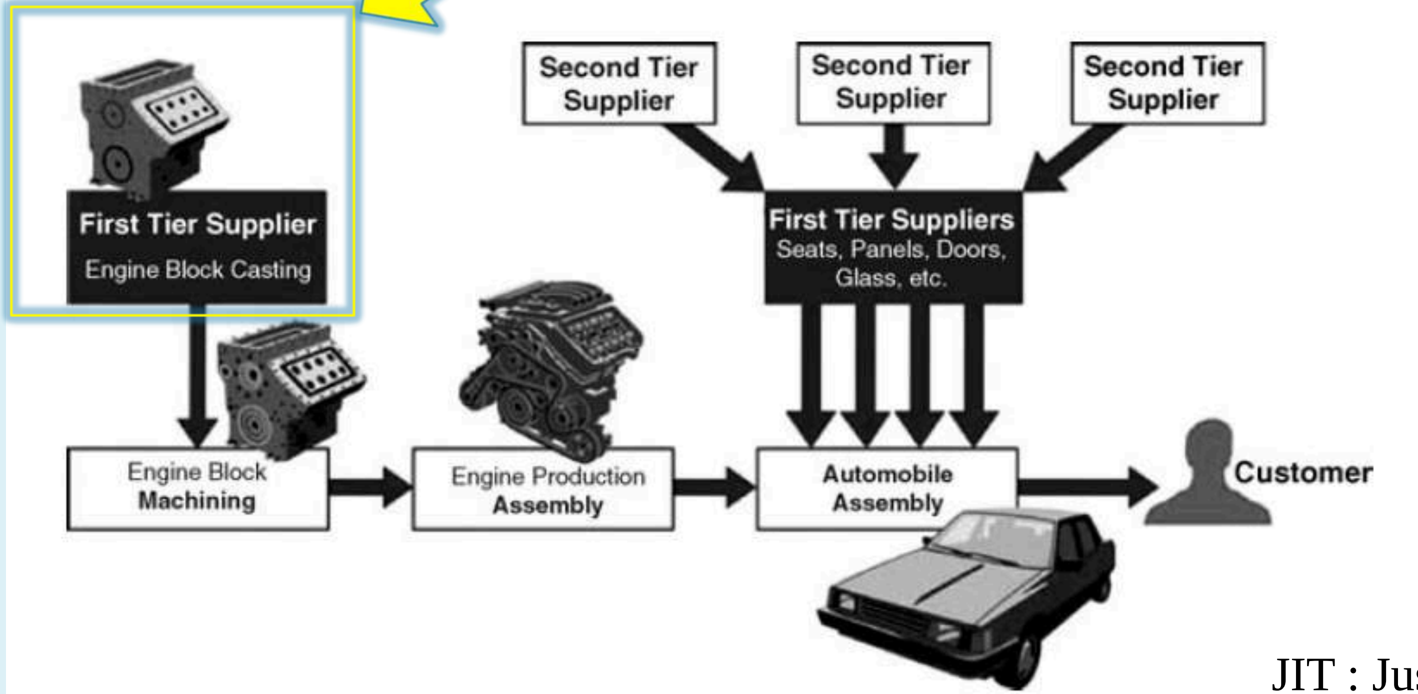
[a]Values for aluminum also apply to magnesium.

How many pieces can be produced by Casting?



Global Manufacturing – Casting Process

Molds? Suppliers? World Dependance? Logistic?



JIT : Just In Time

Figure 4.7 JIT is applied both inside the company and in its supply chain.

Mass Customization
Production of a wide product variety of customized products at mass production efficiencies as a strategy that generates competitive advantage. A wider product variety increases demand and sales.

Figure 5.2 Three part families.

Home Work #2 – Casting

- Answer questions from class #2 applied to Casting in group of 2 students.
- Local Suppliers of Casting parts in your home country

Addictional activities in class:

- Visit to a COPPE Laboratory