446.305A MANUFACTURING PROCESSES

Chapter 5. Metal-Casting Processes and Equipment; Heat Treatment

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Casting

- **Casting is a manufacturing process by which a molten material such as metal or plastic is introduced into a mold made of sand or metal, allowed to solidify within the mold, and then ejected or broken out to make a fabricated part.**

- **Advantages**
  - Making parts of complex shape in a single piece.
  - Producing large number of identical castings within specified tolerances.
  - Good bearing qualities and jointless product.

- **Disadvantages**
  - Limitations of mechanical properties because of the polycrystalline grain structure.
  - Poor dimensional accuracy due to shrinkage of metal during solidification.
  - If the number of parts cast is relatively small, the cost per casting increases rapidly.

- **Fundamental aspects in casting operations**
  - Solidification of the metal from its molten state.
  - Flow of the molten metal into the mold cavity.
  - Heat transfer during solidification and cooling of the metal in the mold.
  - Mold material and its influence on the casting process.

Solidification of Metals

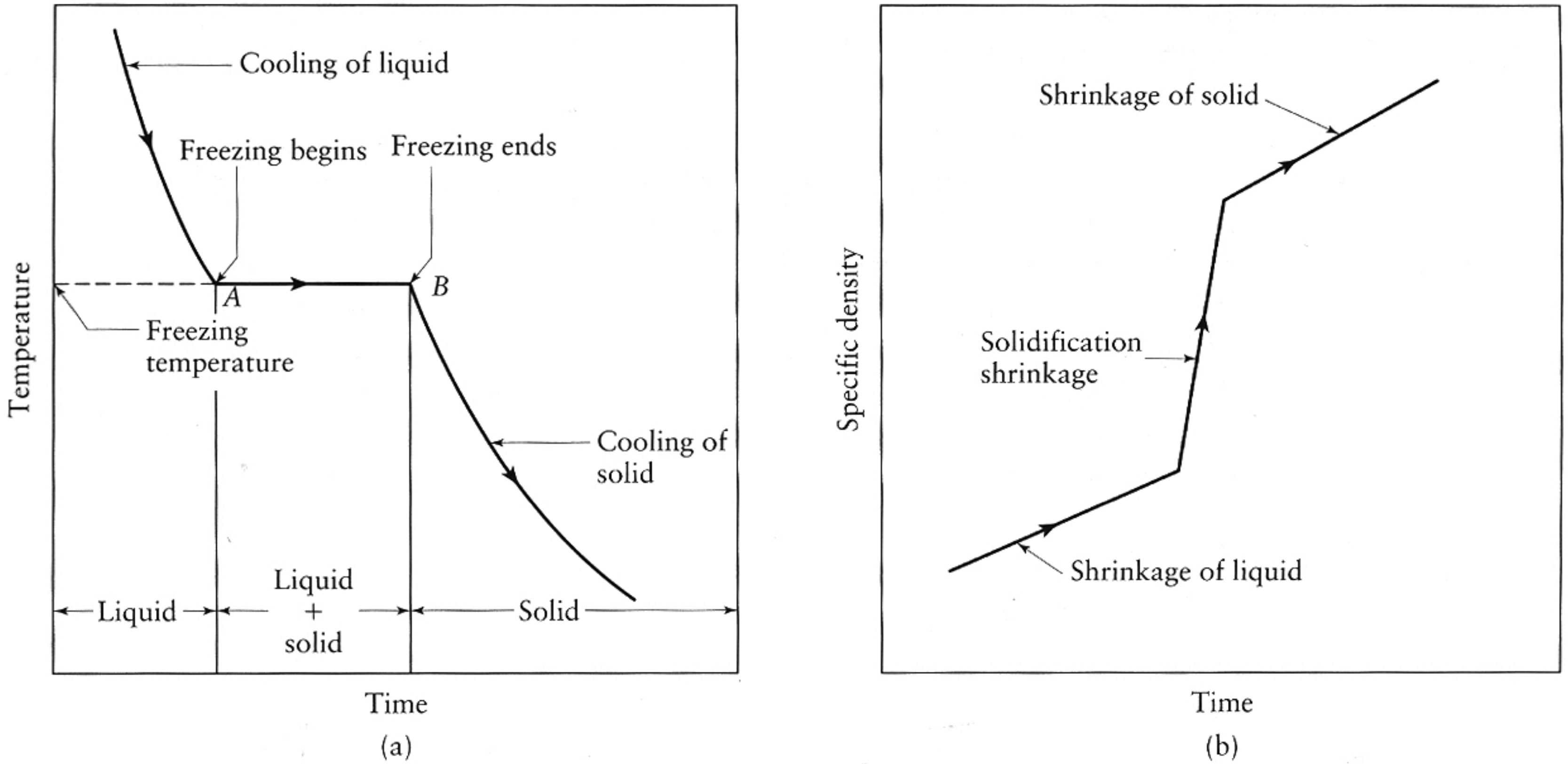


FIGURE 5.1 (a) Temperature as a function of time for the solidification of pure metals. Note that freezing takes place at a constant temperature. (b) Density as a function of time.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", $3^{rd}/4^{th}$ ed. Addison Wesley

Solid solution

- **Solute(용질)**
- **Solvent(용매)**

- **When the particular crystal structure of the solvent is maintained during alloying, the alloy is called *solid solution*.**
  - Substitutional solid solution(치환 고용체)
  - Interstitial solid solution(침입 고용체)

- **5.2.2 Intermetallic compound(금속간 화합물)**
  - Complex structures in which solute atoms are present among solvent atoms in certain specific proportions.

- **5.2.3 Two-phase system(이상계)**
  - Phase: a homogeneous portion of a system that has uniform physical and chemical characteristics

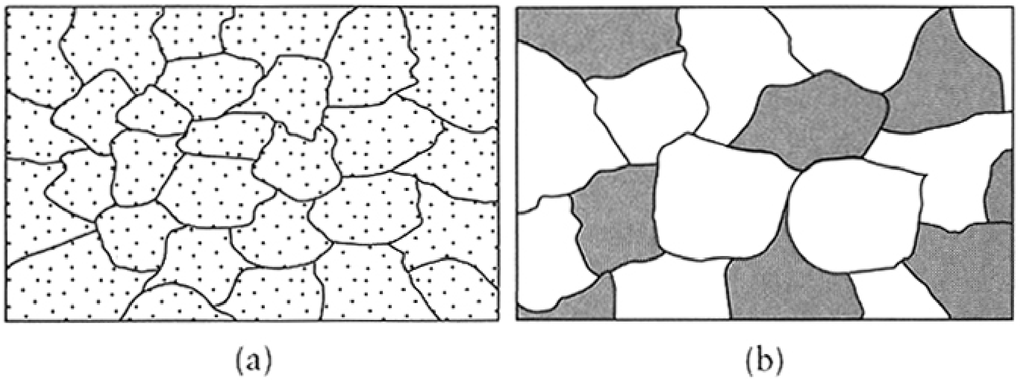
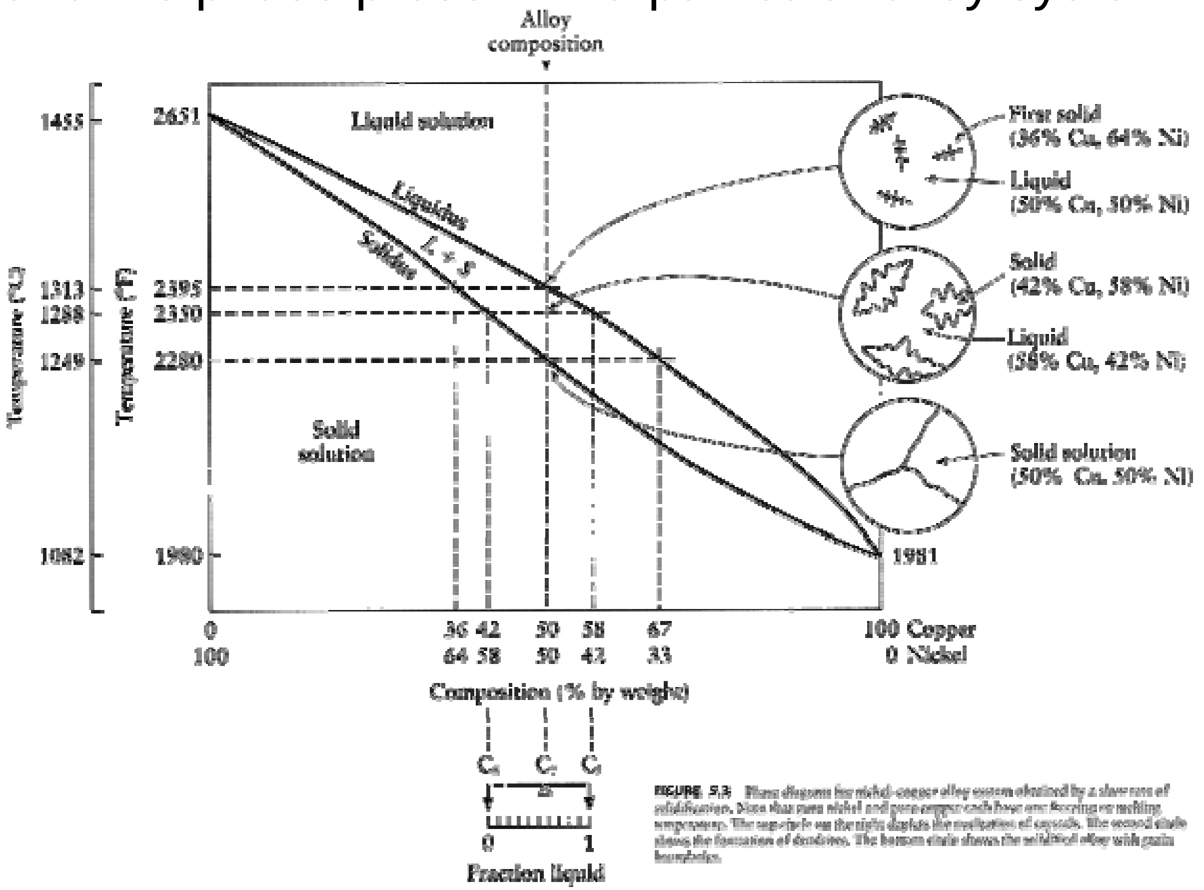


FIGURE 5.2 (a) Schematic illustration of grains, grain boundaries, and particles dispersed throughout the structure of a two-phase system, such as lead–copper alloy. The grains represent lead in a solid solution of copper, and the particles are lead as a second phase. (b) Schematic illustration of a two-phase system consisting of two sets of grains: dark and light. Dark and light grains have their own compositions and properties.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Phase diagram (평형상태도)

Graphically illustrates the relationships among temperature, composition, and the phase present in a particular alloy system.



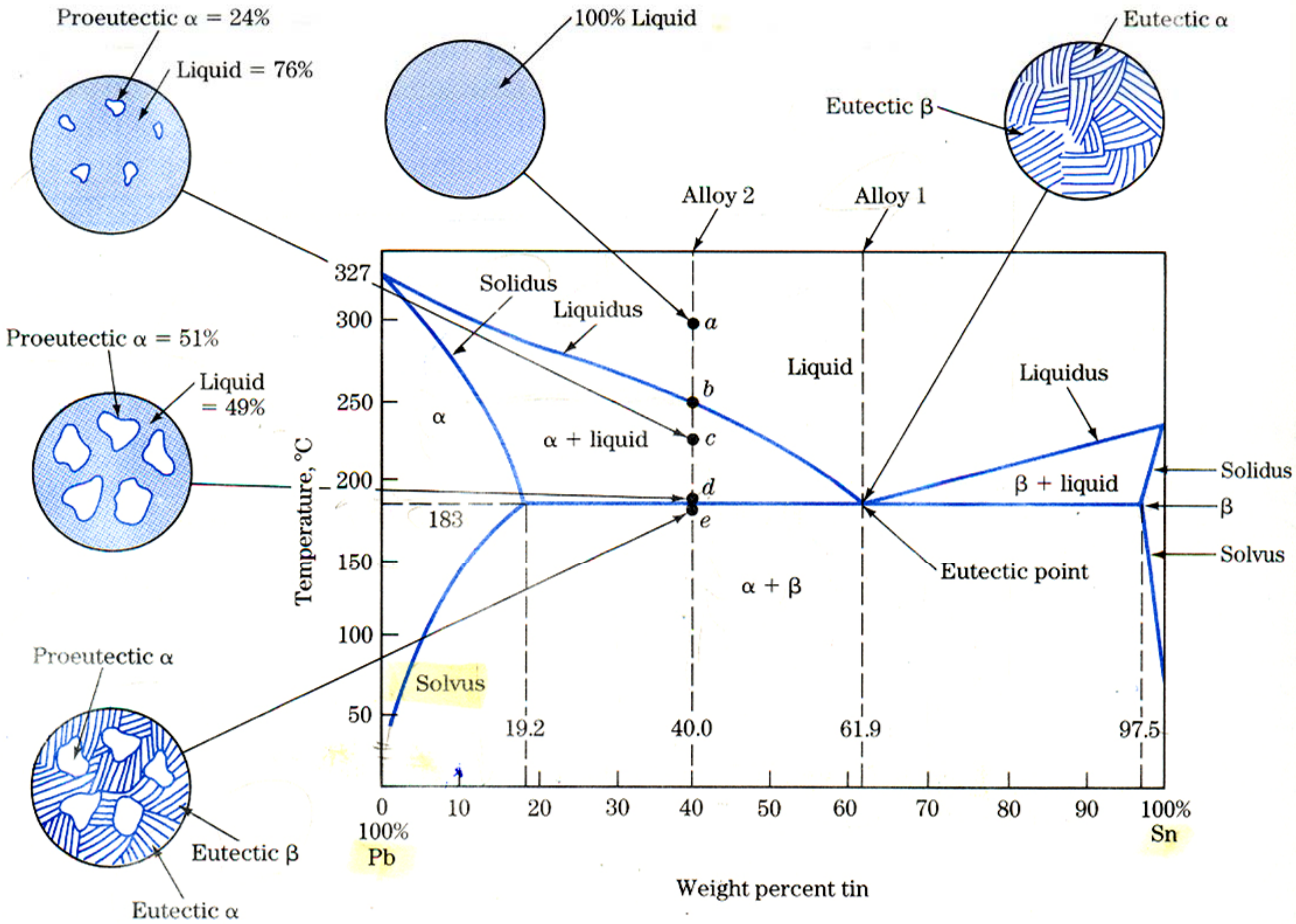
Lever Rule

$$\frac{S}{S+L} = \frac{C_O - C_L}{C_S - C_L}$$

$$\frac{L}{S+L} = \frac{C_S - C_O}{C_S - C_L}$$

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

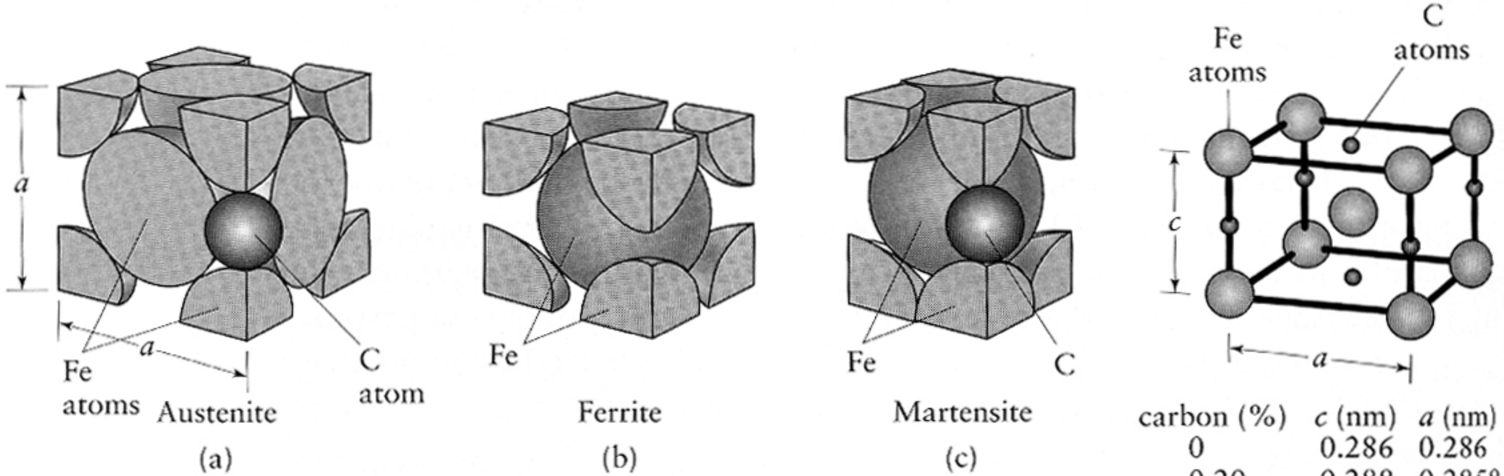
Eutectic system, Pb-Sn



Ref.
William D. Callister, Jr, "Fundamentals of Materials Science and Engineering", 2nd ed. Wiley

Iron-carbon system (1)

- **Pure iron(순철) : 0.008% C**
- **Steels(강) : 2.11% C**
- **Cast irons(주철) : ~6.67% C**
- **α-ferrite(페라이트): BCC, soft and ductile**
- **δ-ferrite: BCC, stable only at very high temperatures**
- **Austenite(오스테나이트) : FCC, ductile**
- **Cementite(세멘타이트): Fe_3C, C 6.67%, iron carbide(탄화철), brittle**



carbon (%)	c (nm)	a (nm)
0	0.286	0.286
0.20	0.288	0.2858
0.40	0.291	0.2856

(d)

FIGURE 5.5 The unit cell for (a) austenite, (b) ferrite, and (c) martensite. The effect of the percentage of carbon (by weight) on the lattice dimensions for martensite is shown in (d). Note the interstitial position of the carbon atoms (see also Fig. 3.8) and the increase in dimension *c* with increasing carbon content. Thus, the unit cell of martensite is in the shape of a rectangular prism.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Iron-carbon system (2)

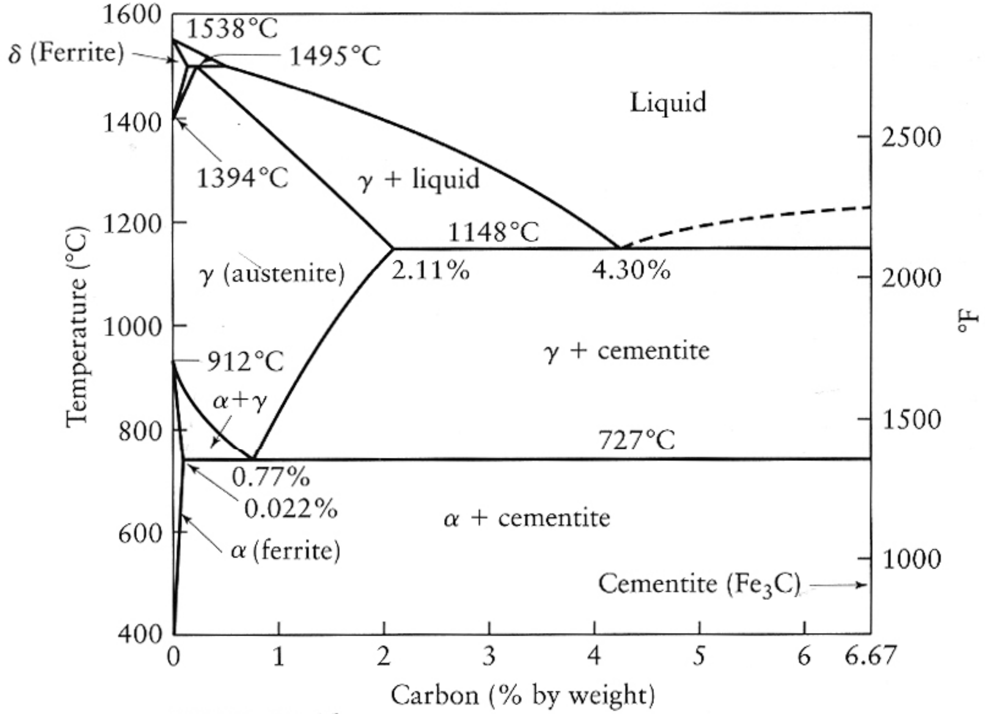


FIGURE 5.4 The iron–iron-carbide phase diagram. Because of the importance of steel as an engineering material, this diagram is one of the most important phase diagrams.

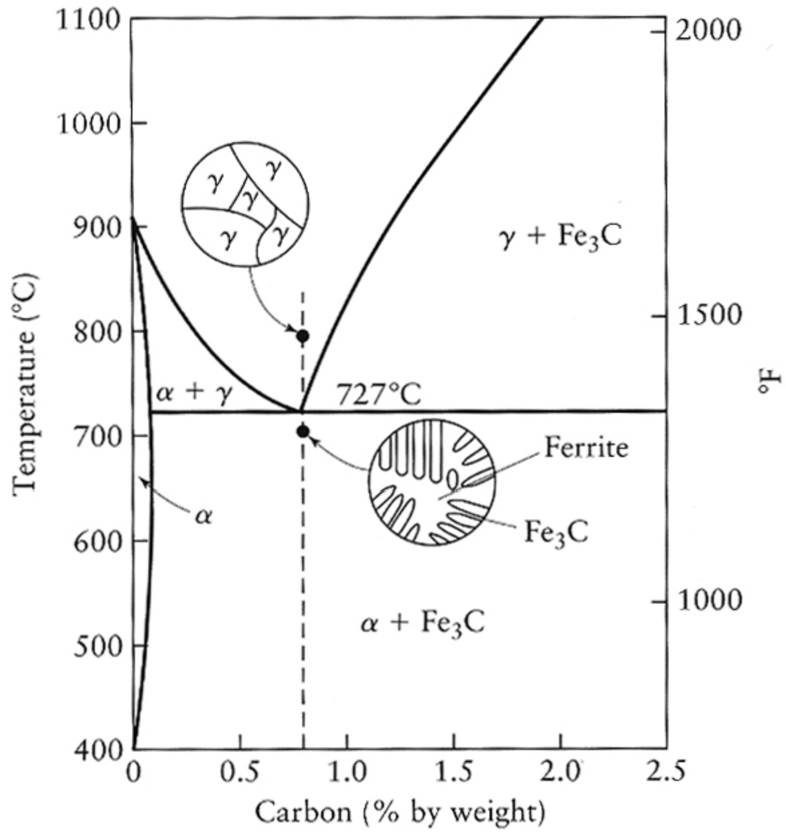


FIGURE 5.6 Schematic illustration of the microstructures for an iron–carbon alloy of eutectoid composition (0.77% carbon) above and below the eutectoid temperature of 727°C (1341°F).

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Amount of phases in carbon steel

Casting 1040 steel 10kg, calculate α phase and γ phase at (a) 900°C, (b) 728°C and (c) 726°C

(a) Austenite:100% g

(b) $$\alpha(\%) = \left(\frac{C_\gamma - C_o}{C_\gamma - C_\alpha}\right)100 = \left(\frac{0.77-0.40}{0.77-0.022}\right)100 = 50\%, \text{ that is } 5kg,$$

$$\gamma(\%) = \left(\frac{C_o - C_\alpha}{C_\gamma - C_\alpha}\right)100 = \left(\frac{0.40-0.022}{0.77-0.022}\right)100 = 50\%, \text{ that is } 5kg,$$

(c) $$\alpha = \left(\frac{6.67-0.40}{6.67-0.022}\right)100 = 94\%, \text{ that is } 9.4kg$$

Cast irons

- **Fe, C 2.11~4.5%, Si ~3.5%**
- **According to solidification morphology :**

Gray cast iron(회주철)
- Flake graphite(편상흑연)
- Gray fracture surface(회색파단면)
- Damping(진동감쇠)

Ductile(nodular) iron(구상흑연주철)
- Ductile

White cast iron(백주철)
- Large amount of Fe_3C
- Brittle
- White fracture surface(흰색 파단면)

Malleable cast iron(가단주철)
- Obtained by annealing white cast iro

Compact graphite iron(컴팩트 흑연주철)

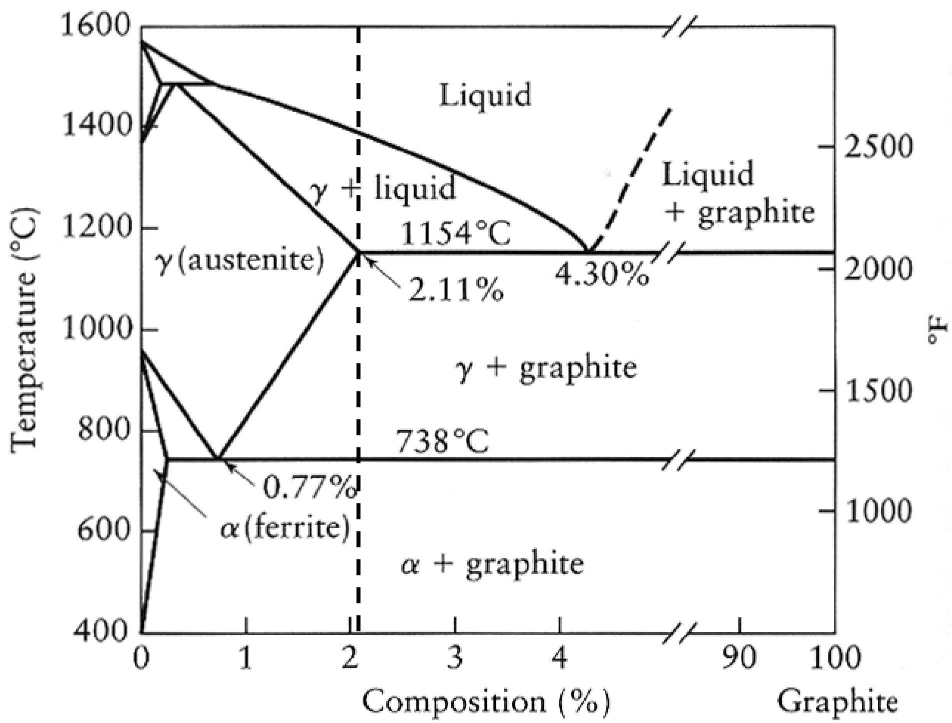
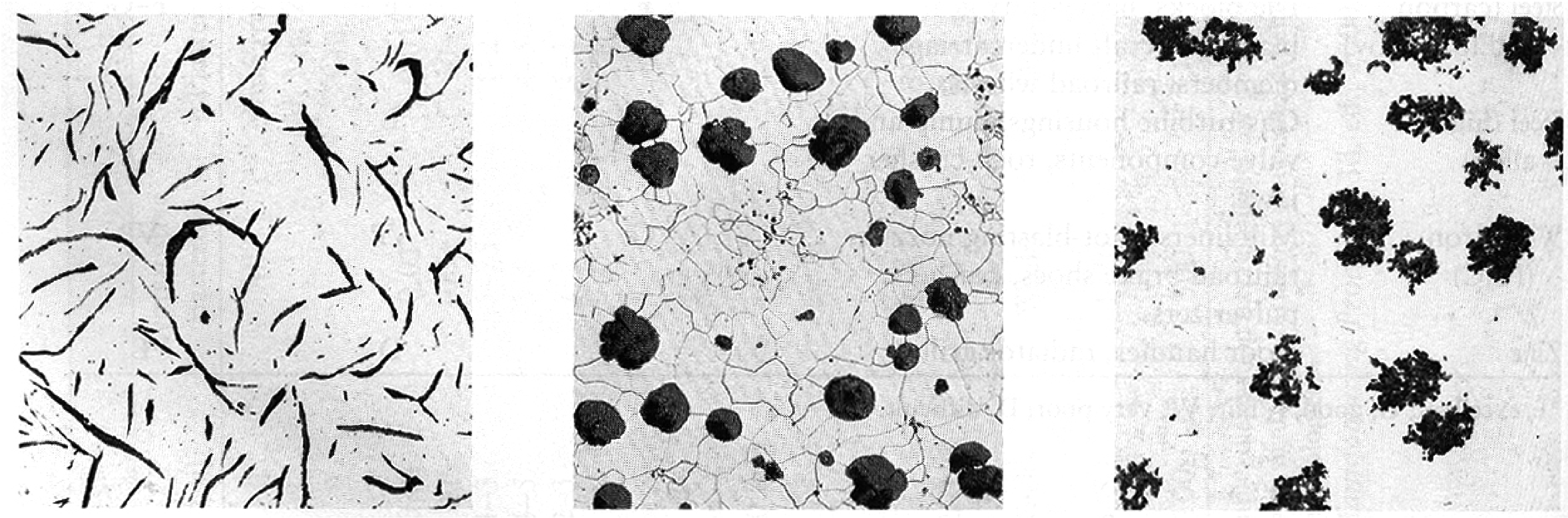


FIGURE 5.7 Phase diagram for the iron–carbon system with graphite, instead of cementite, as the stable phase. Note that this figure is an extended version of Fig. 5.4.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Cast irons



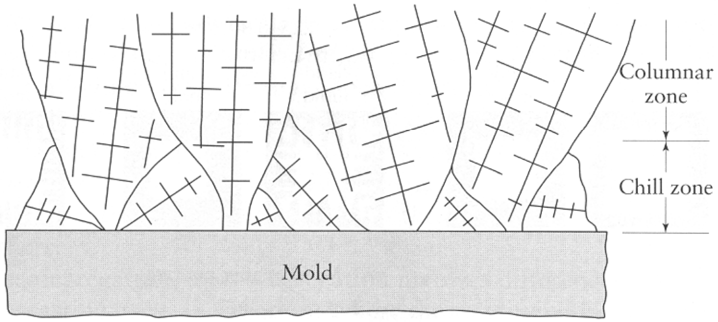
(a) (b) (c)

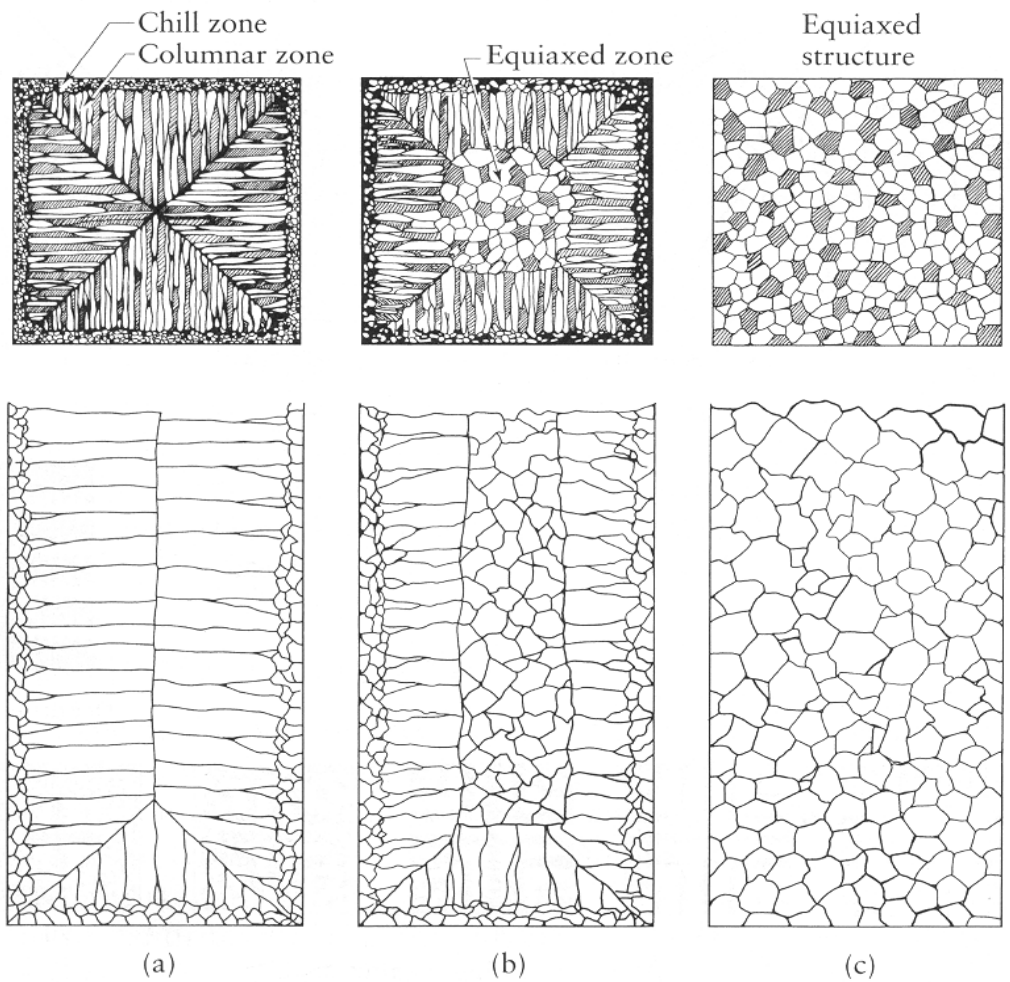
FIGURE 5.20 Microstructure for cast irons. Magnification: 100×. (a) Ferritic gray iron with graphite flakes. (b) Ferritic nodular iron (ductile iron), with graphite in nodular form. (c) Ferritic malleable iron. This cast iron solidified as white cast iron, with the carbon present as cementite (Fe_3C), and was heat treated to graphitize the carbon. *Source*: ASM International, Materials Park, OH.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Cast structures

- **Pure metal vs. alloys**





Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Dendrites (수지상정)

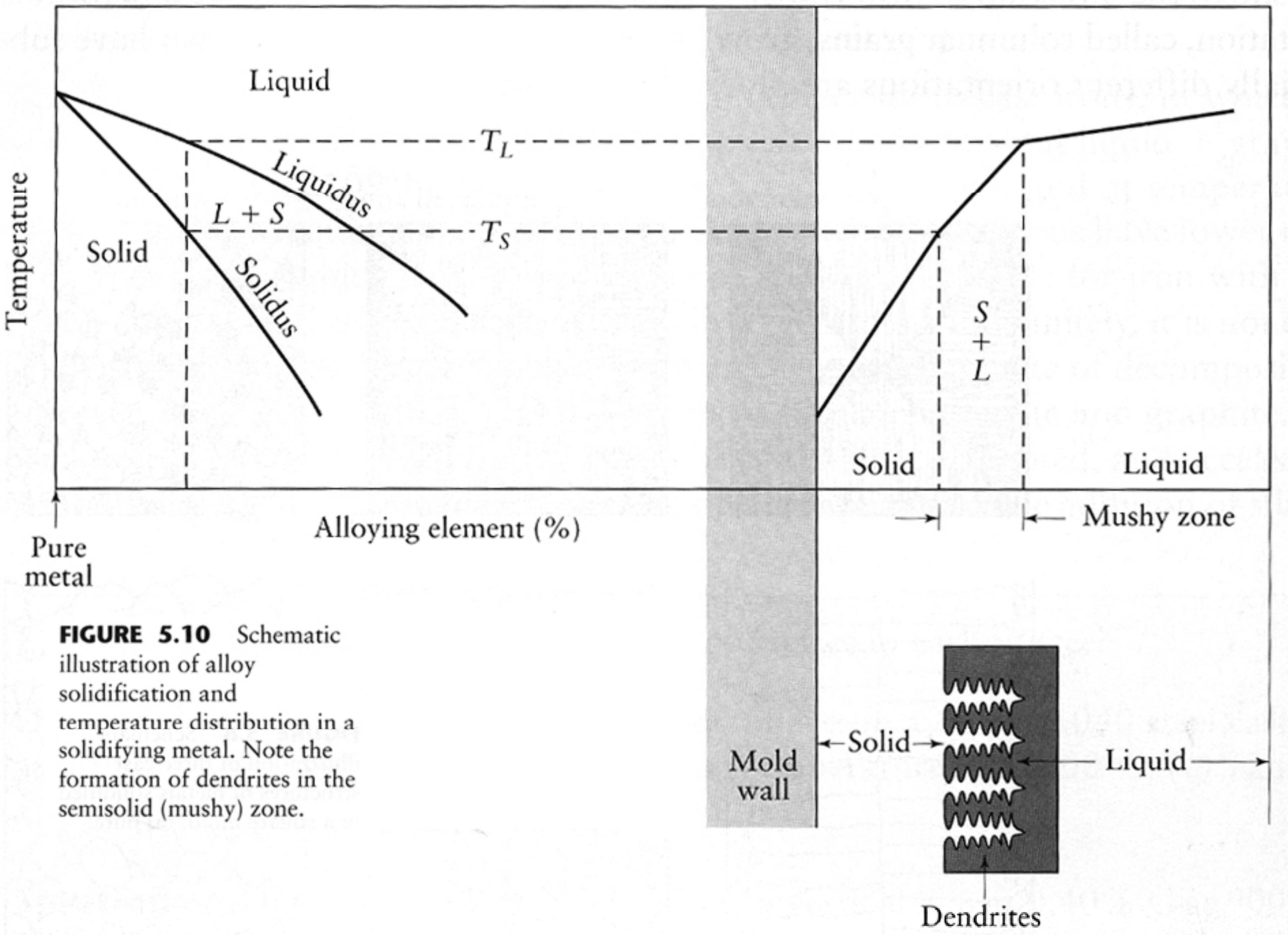
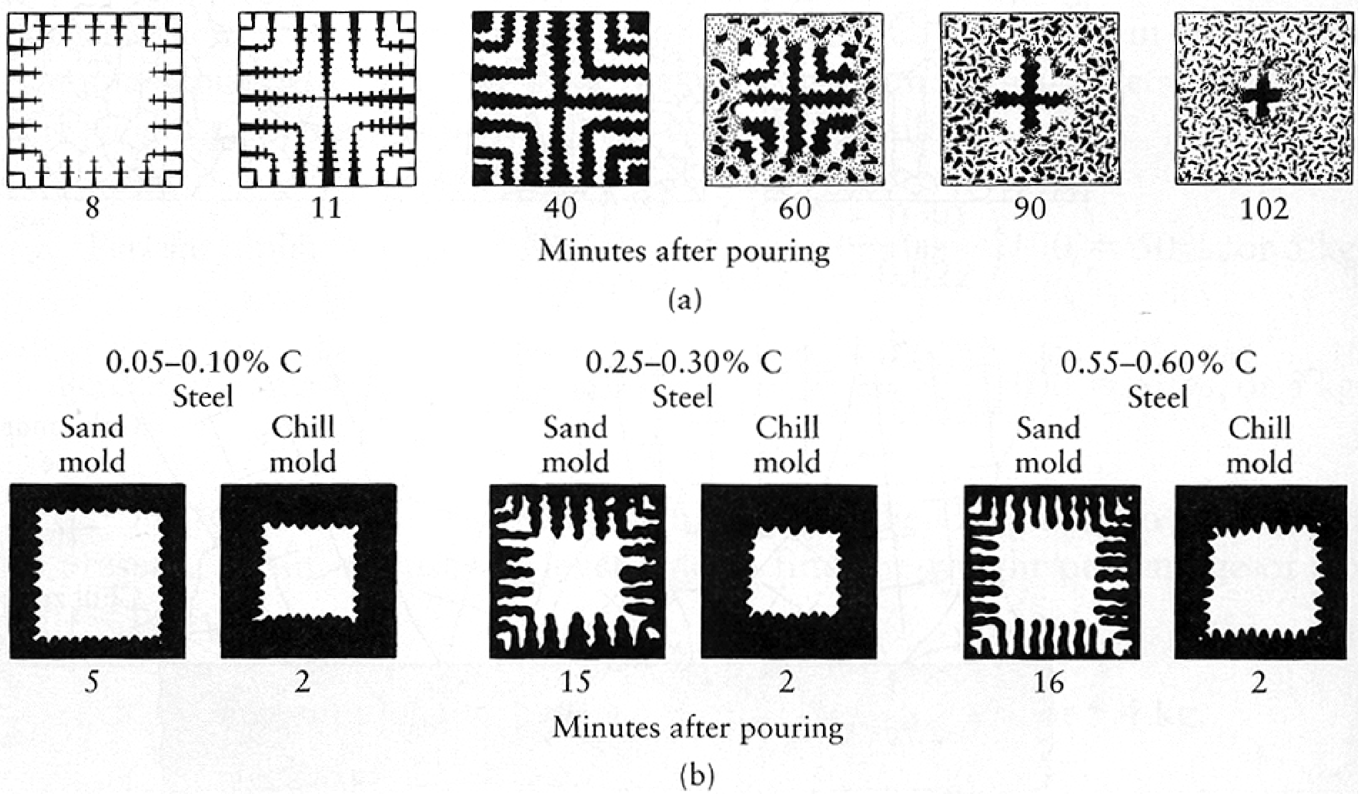


FIGURE 5.10 Schematic illustration of alloy solidification and temperature distribution in a solidifying metal. Note the formation of dendrites in the semisolid (mushy) zone.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Dendrites

FIGURE 5.11
(a) Solidification patterns for gray cast iron in a 180-mm (7-in.) square casting. Note that after 11 minutes of cooling, dendrites reach each other, but the casting is still mushy throughout. It takes about two hours 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 increases. *Source*: H. F. Bishop and W. S. Pellini.



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S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Fluid flow

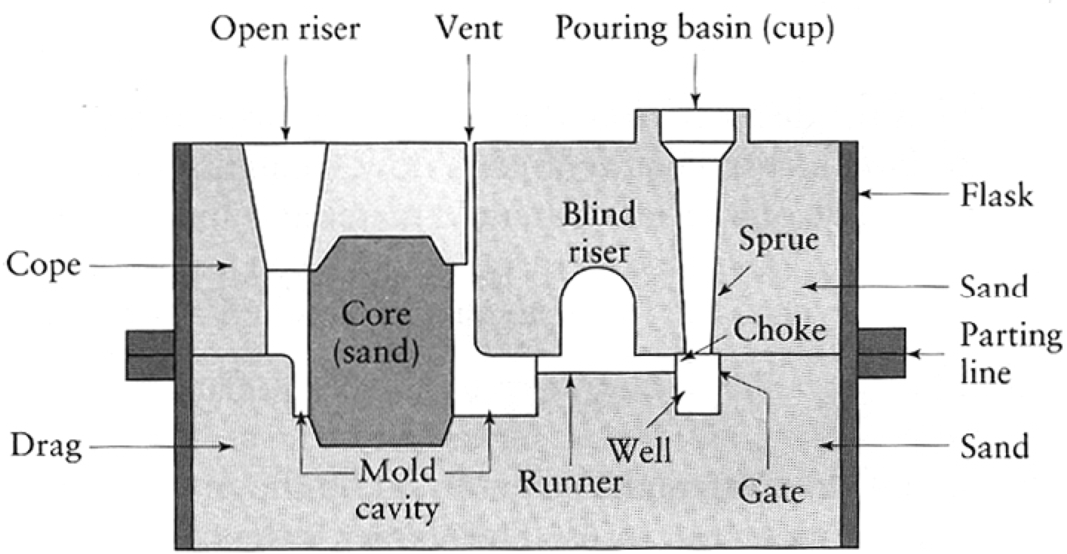


FIGURE 5.14 Schematic illustration of a sand mold, showing various features.

$$v = c\sqrt{2gh}$$

$$h + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{constant}$$

$$h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} = h_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + f$$

$$Q = A_1 v_1 = A_2 v_2$$

$$\frac{A_1}{A_2} = \sqrt{\frac{h_2}{h_1}}$$

$$\text{Re} = \frac{vD\rho}{\eta}$$

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Solidification time & shrinkage

- **Chvonrinov's rule**

  Solidification time

  = C(volume/surface area)^2

- **Shrinkage occurs at**
  - Molten metal
  - Phase change
  - Solid metal

- **Cast iron expands**
  - Graphite has high volume/mass
  - Net expansion during precipitation

- **Similarly Bi-Sn alloys expand**

TABLE 5.1

Volumetric Solidification Contraction or Expansion Percentages 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		

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Defects/DFM

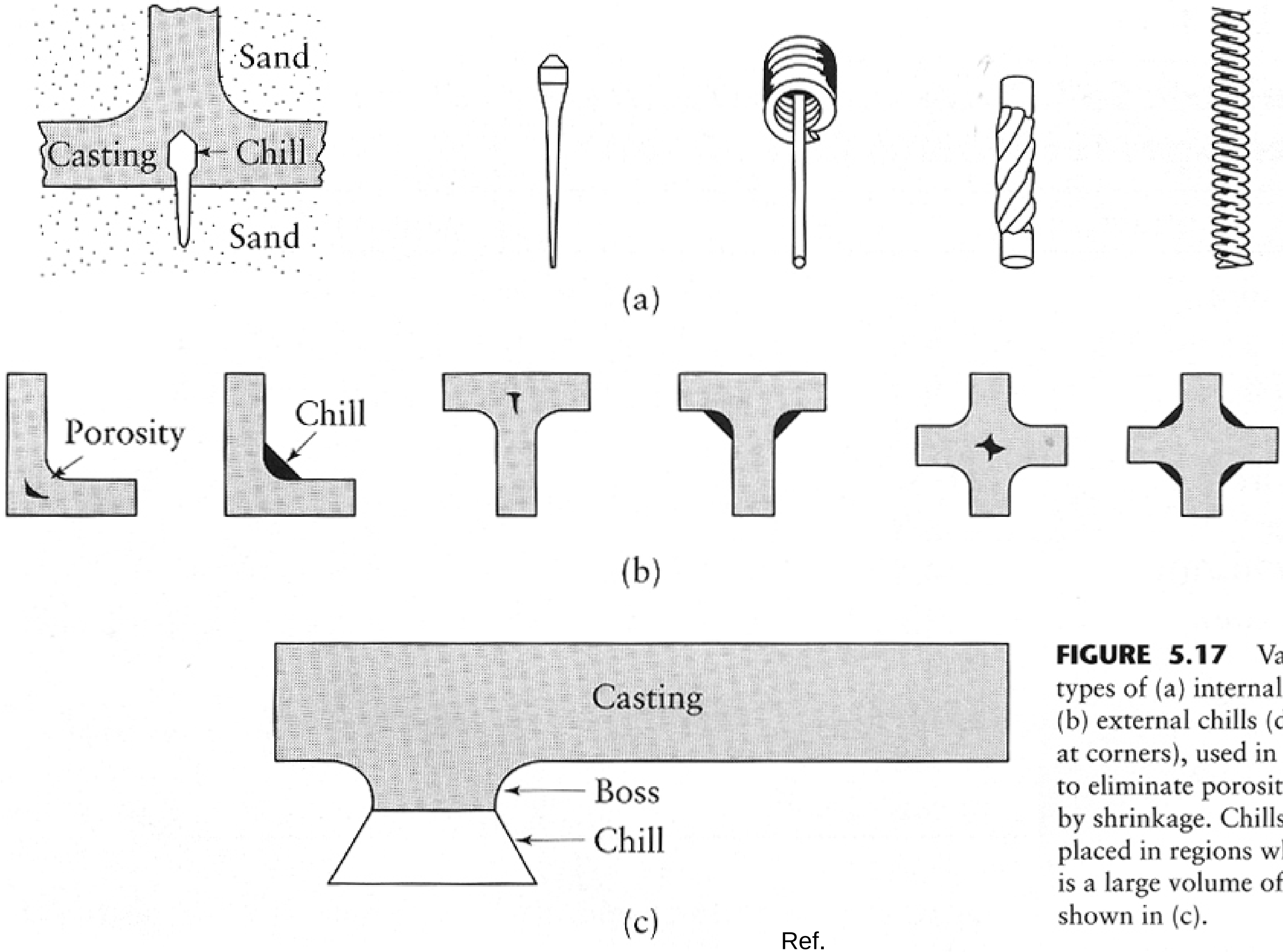


FIGURE 5.17 Various types of (a) internal and (b) external chills (dark areas at corners), used in castings to eliminate porosity caused by shrinkage. Chills are placed in regions where there is a large volume of metal, as shown in (c).

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Casting alloys

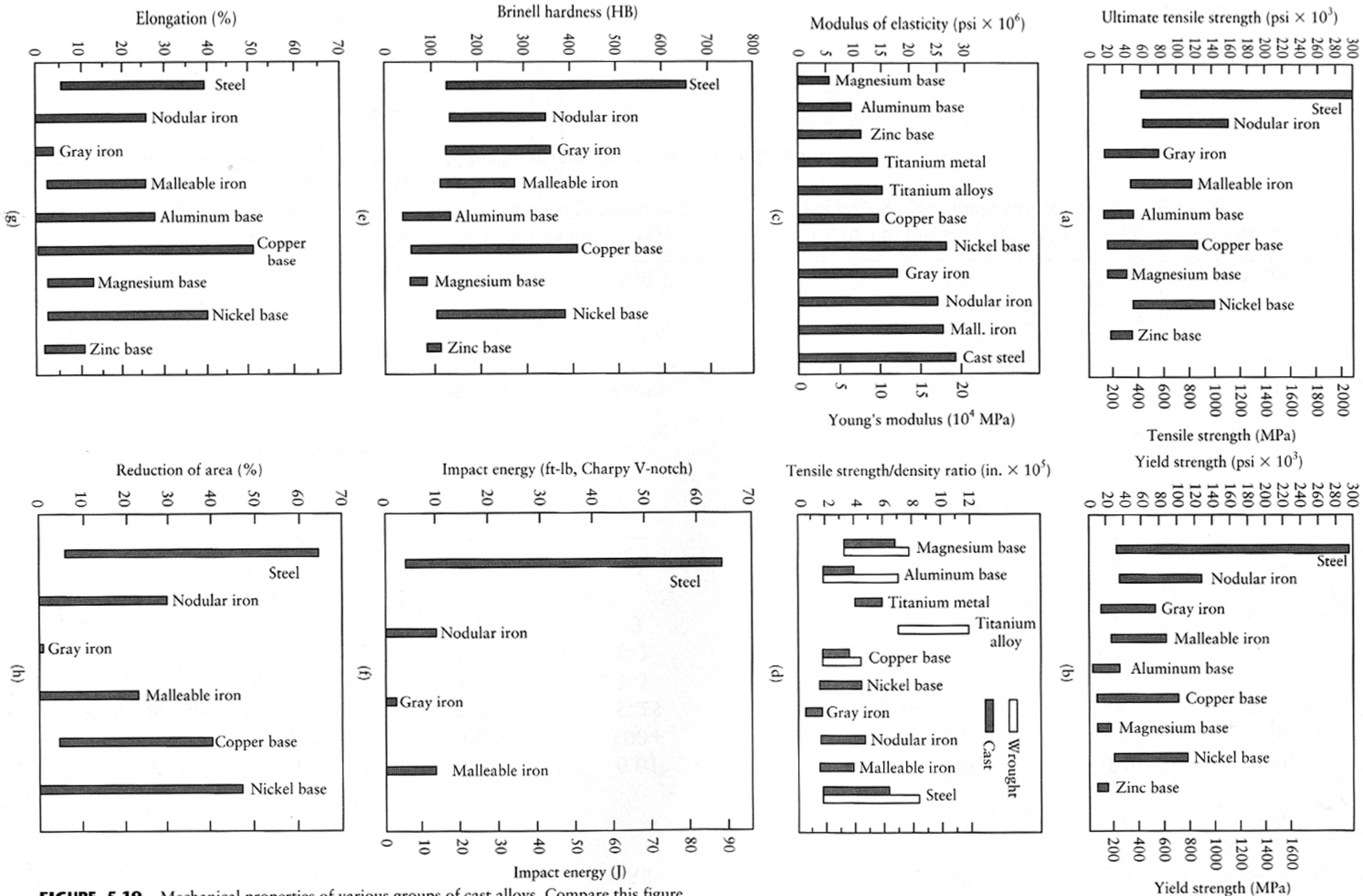


FIGURE 5.19 Mechanical properties of various groups of cast alloys. Compare this figure with the various tables of properties in Chapter 3. *Source*: Courtesy of Steel Founders' Society of America.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Applications

TABLE 5.3

Typical Applications and Characteristics for Castings

Type of Alloy	Application	Castability*	Weldability*	Machin-ability*
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	Crankcases, 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, pulverizers.	G	VP	VP
Zinc	Door handles, radiator grills.	E	D	E

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

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Properties

Properties and Typical Applications of Cast Irons

Cast Iron	Type	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation in 50 mm (%)	Typical Applications
Gray	Ferritic	170	140	0.4	Pipe, sanitary ware.
	Pearlitic	275	240	0.4	Engine blocks, machine tools.
	Martensitic	550	550	0	Wearing 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.
	Pearlitic	450	310	10	Couplings.
	Tempered	700	550	2	Gears, connecting rods.
White	Pearlitic	275	275	0	Wear resistance, mill rolls.

Typical Properties of Nonferrous Casting Alloys

Alloy	Condition	Casting Method*	UTS (MPa)	Yield Stress (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.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Casting processes

- **Expendable mold, permanent pattern**
  - Sand casting
  - Shell-mold casting
  - Plaster mold casting
  - Ceramic mold casting
  - Vacuum casting

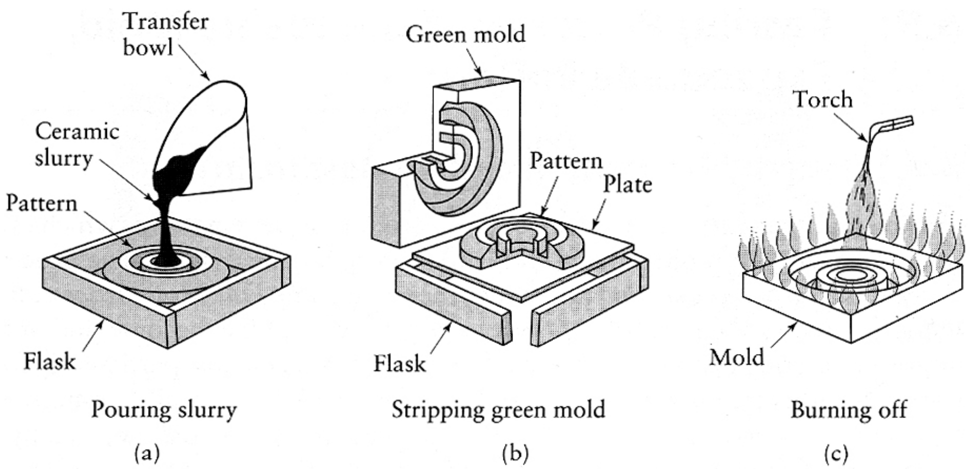


FIGURE 5.23 Sequence of operations in making a ceramic mold. *Source: Metals Handbook*, 8th ed., Vol. 5: *Forging and Casting*, ASM International, 1970.

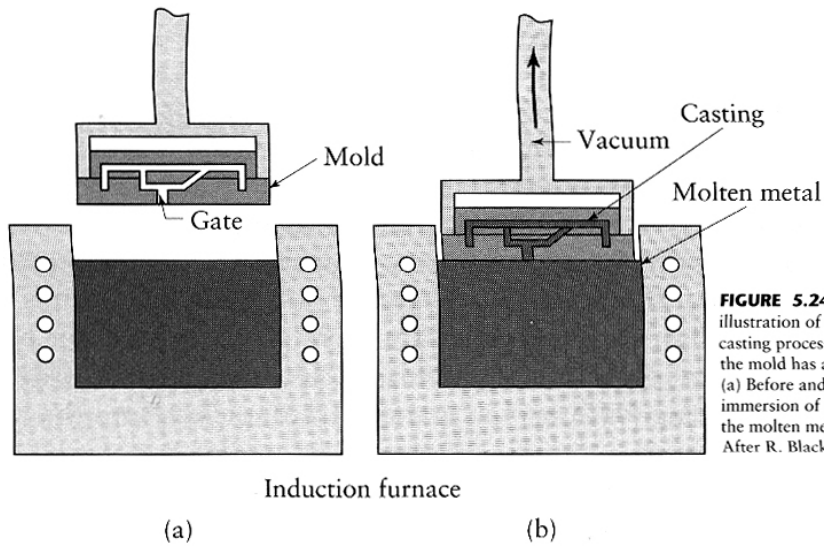


FIGURE 5.24 Schematic illustration of the vacuum-casting process. Note that the mold has a bottom gate. (a) Before and (b) after immersion of the mold into the molten metal. *Source:* After R. Blackburn.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Casting processes (2)

- **Expendable mold, expendable pattern**
  - Evaporative-pattern casting (lost foam)
  - Investment casting (lost wax)

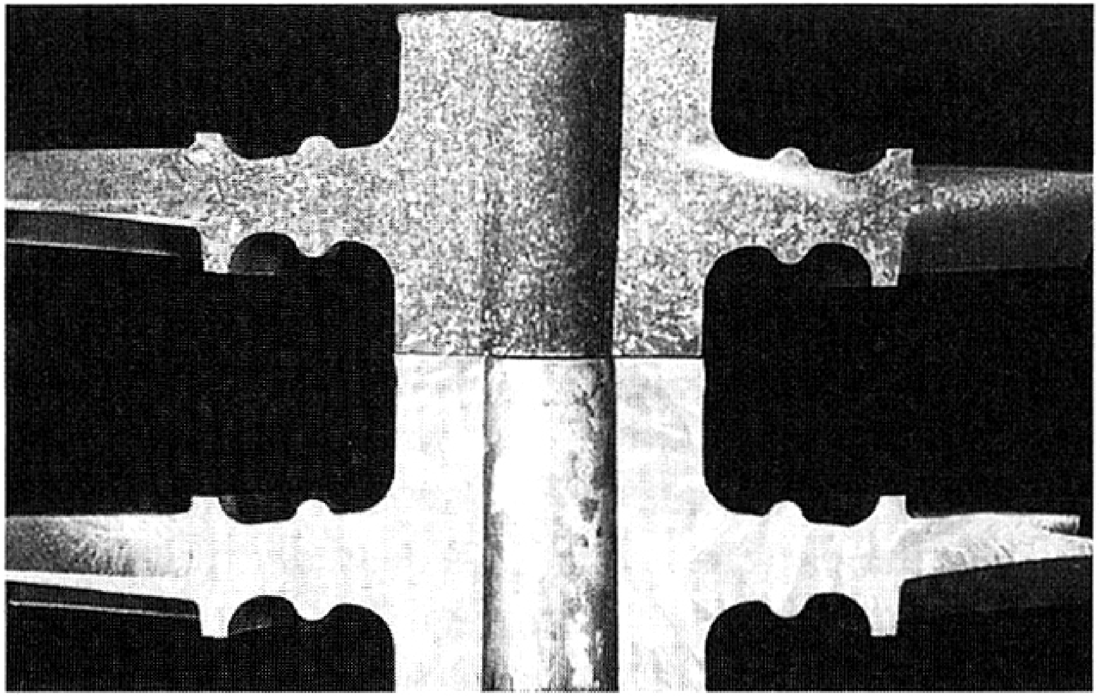


FIGURE 5.26 The top rotor was investment cast; the lower rotor was cast conventionally. *Source: Advanced Materials and Processes*, ASM International, October 1990, p. 25.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Investment casting

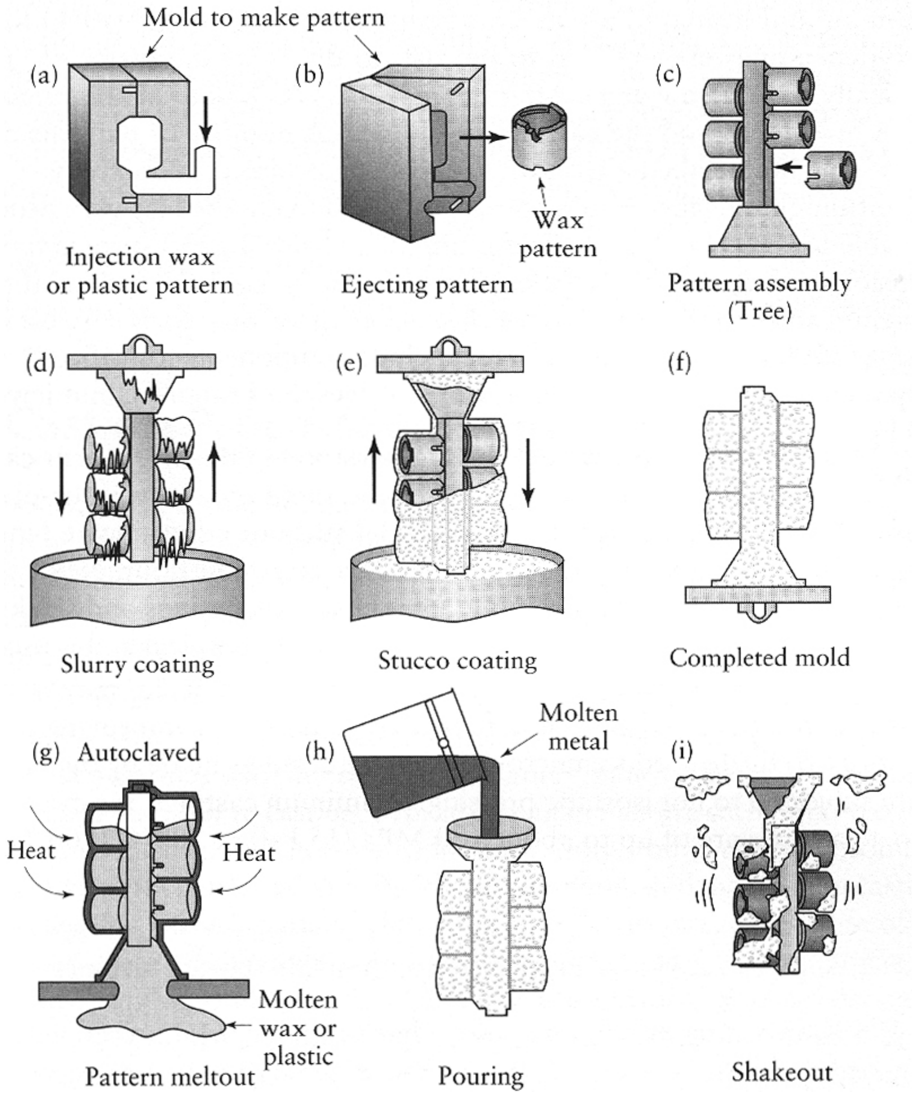


FIGURE 5.25 Schematic illustration of investment casting (lost-wax process). Castings by this method can be made with very fine detail and from a variety of metals. *Source*: Steel Founders' Society of America.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Casting processes (3)

- **Permanent mold**
  - Slush casting
  - Pressure casting
  - Die casting
  - Centrifugal casting
  - Squeeze casting
  - Semisolid metal forming
  - Casting for single crystal
  - Rapid solidification

- In permanent-mold casting, a mold are made from materials such as steel, bronze, refractory metal alloys, or graphite. Because metal molds are better heat conductors than expendable molds, the solidifying casting is subjected to a higher rate of cooling, which turn affects the microstructure and grain size within the casting.

- Cooling methods : water, air-cooled fin
- Used for aluminum, magnesium, and copper alloys due to their lower melting points
- Pros : good surface finishing, close dimensional tolerances, and uniform and good mechanical properties
- Cons : not economical for small production runs, not good for intricate shapes

Pressure casting/centrifugal casting

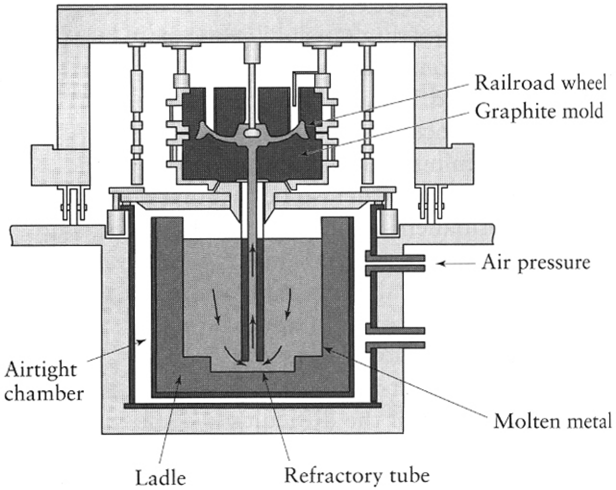


FIGURE 5.27 The pressure-casting process uses graphite molds for the production of steel railroad wheels. *Source*: Griffin Wheel Division of Amsted Industries Incorporated.

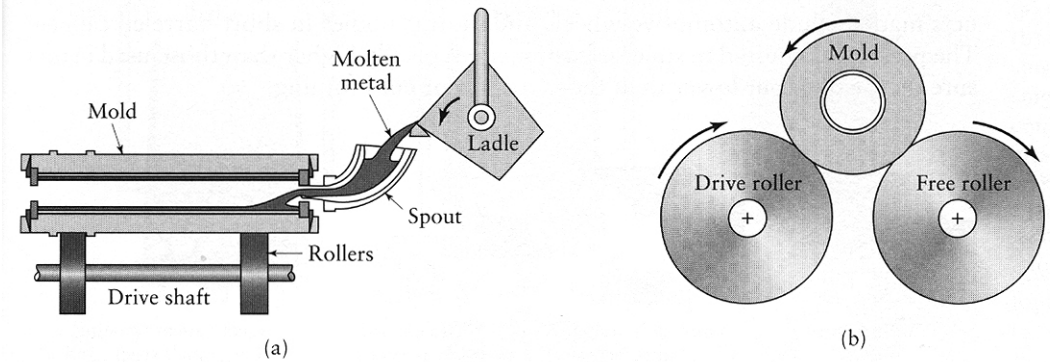


FIGURE 5.30 Schematic illustration of the centrifugal casting process. Pipes, cylinder liners, and similarly shaped parts can be cast by this process.

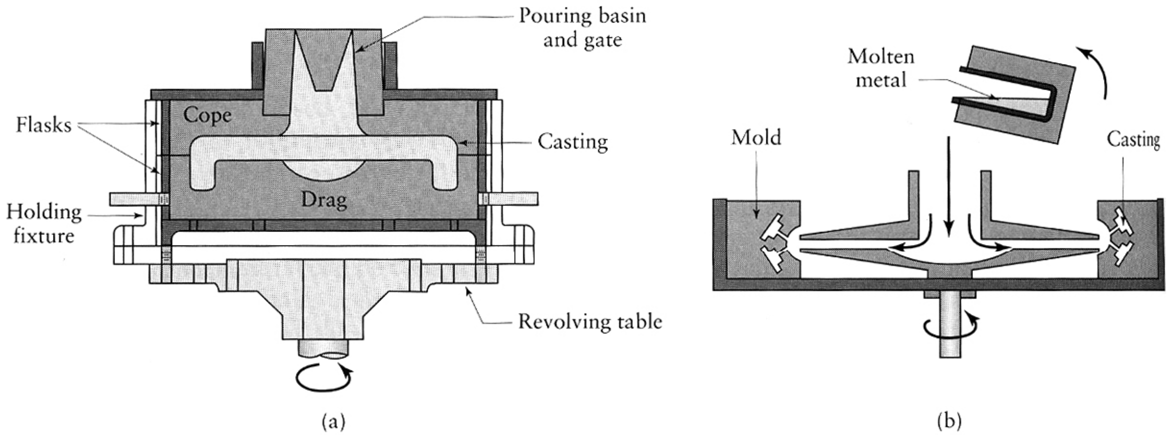


FIGURE 5.31 (a) Schematic illustration of the semicentrifugal casting process. Wheels with spokes can be cast by this process. (b) Schematic illustration of casting by centrifuging. The molds are placed at the periphery of the machine, and the molten metal is forced into the molds by centrifugal forces.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Die casting

- **Hot-chamber process**
- **Cold-chamber process**

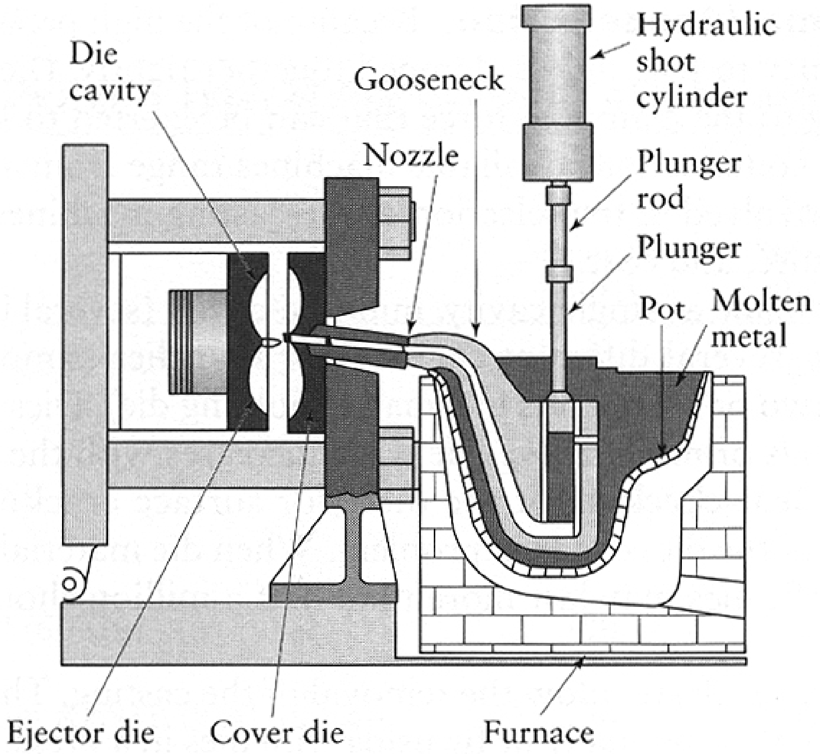


FIGURE 5.28 Sequence of steps in die casting of a part in the hot-chamber process. *Source*: Courtesy of Foundry Management and Technology.

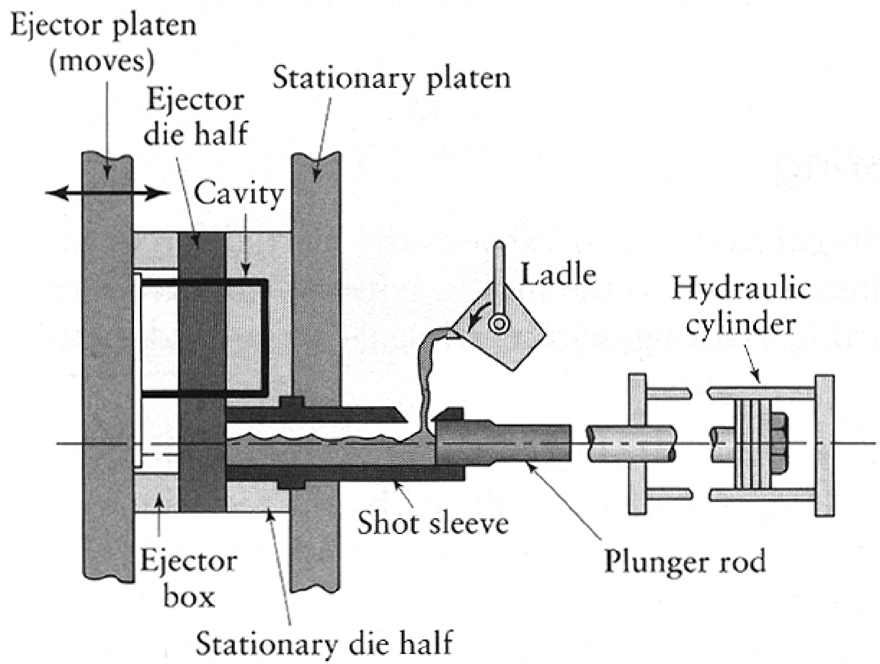
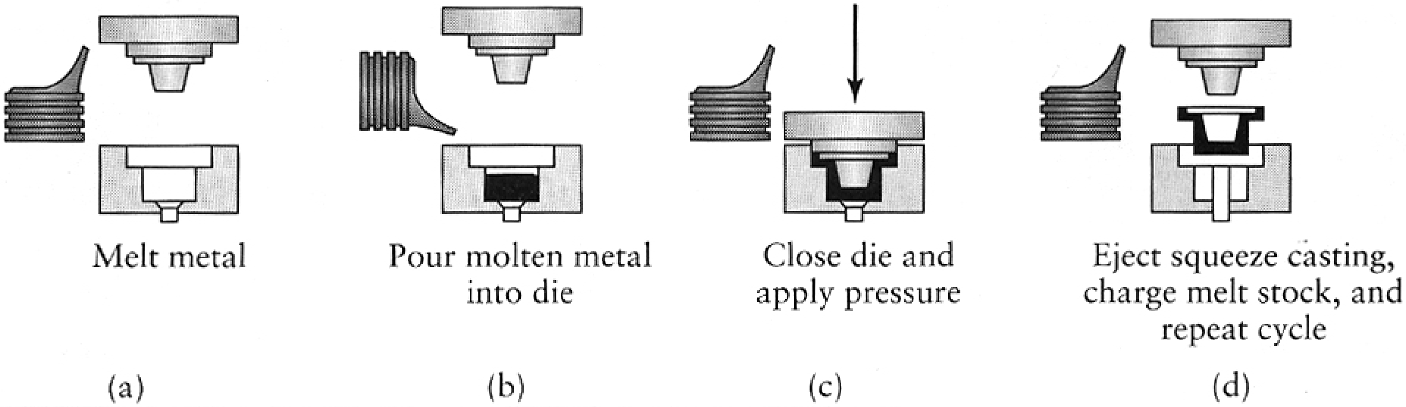


FIGURE 5.29 Sequence of operations in die casting of a part in the cold-chamber process. *Source*: Courtesy of Foundry Management and Technology.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Squeeze casting/single crystal

FIGURE 5.32 Sequence of operations in the squeeze-casting process. This process combines the advantages of casting and forging.



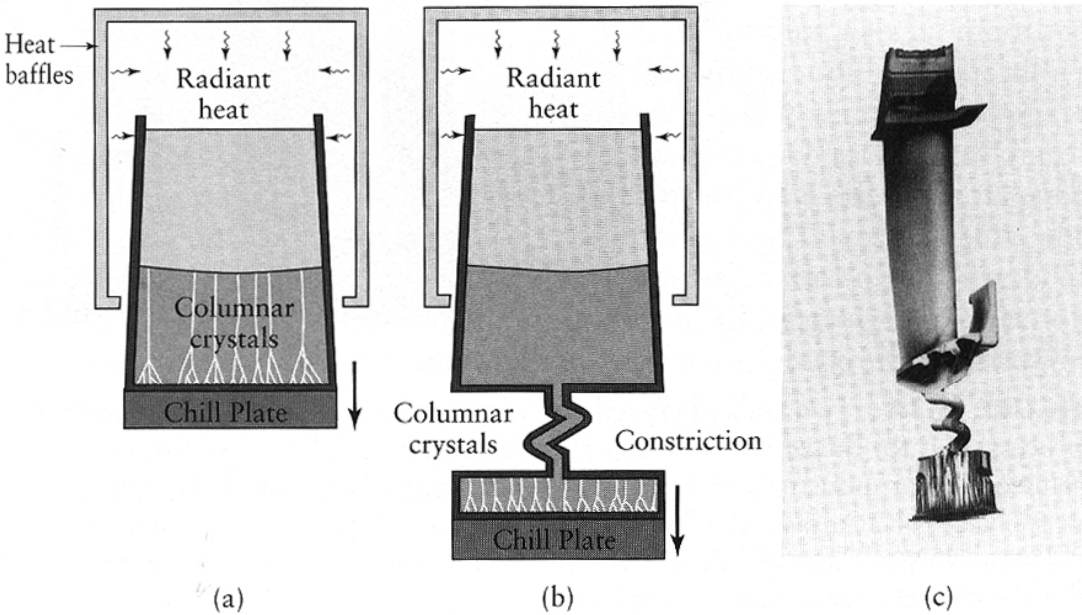
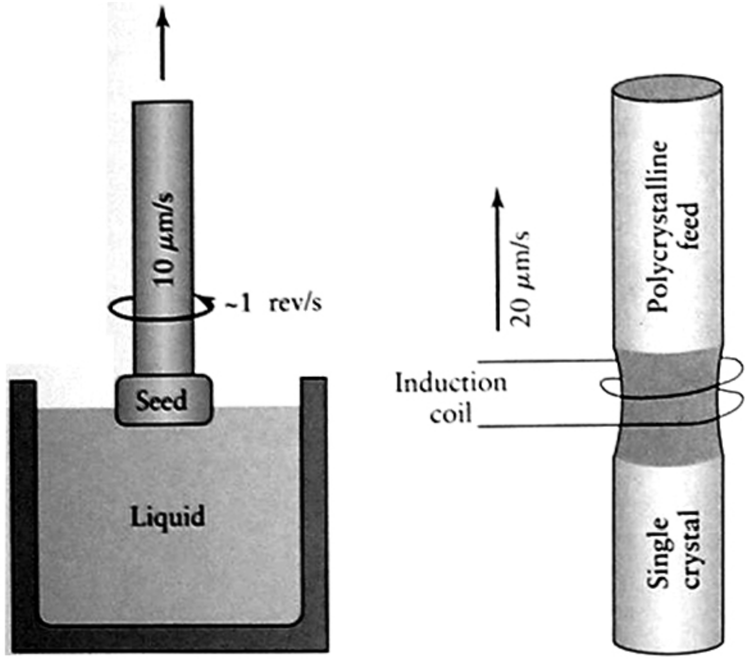


FIGURE 5.33 Methods of casting turbine blades: (a) directional solidification; (b) method to produce a single-crystal blade; and (c) a single-crystal blade with a constriction portion still attached. *Source*: (a) and (b) adapted from "Advanced Metal" by B. H. Kear, copyright © 1986 by Scientific American, Inc. All Rights Reserved. (c) *Advanced Materials and Processes*, ASM International, October 1990, p. 29.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

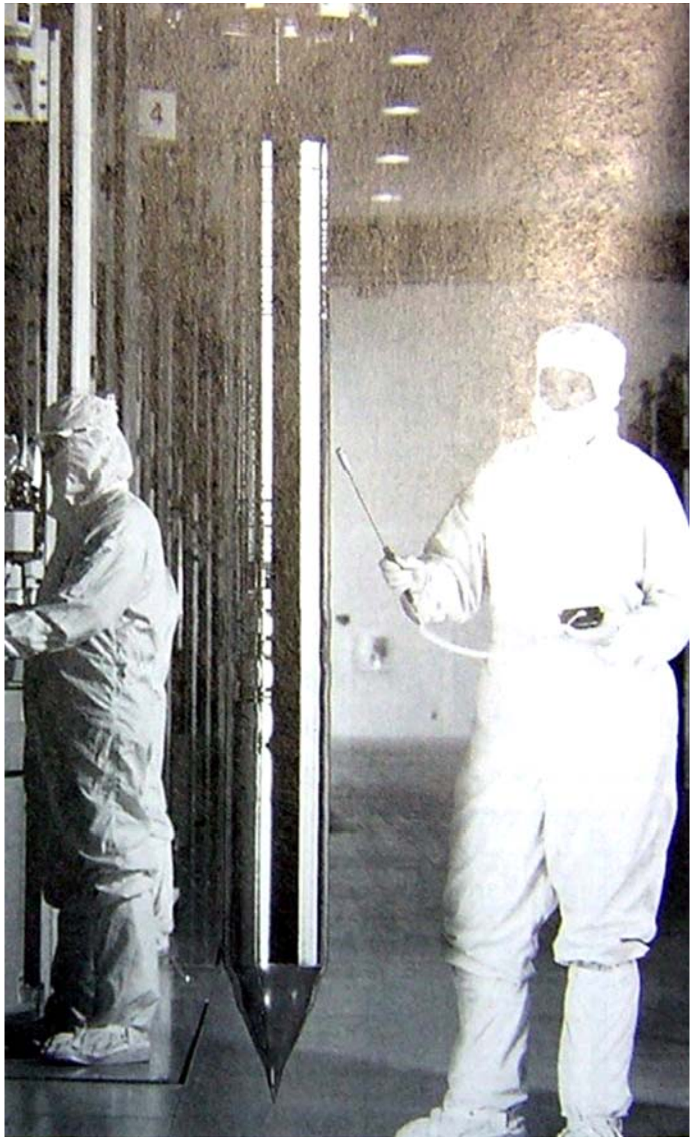
Casting for single crystal



(a) (b)

Crystal-pulling method (Czochralski process)

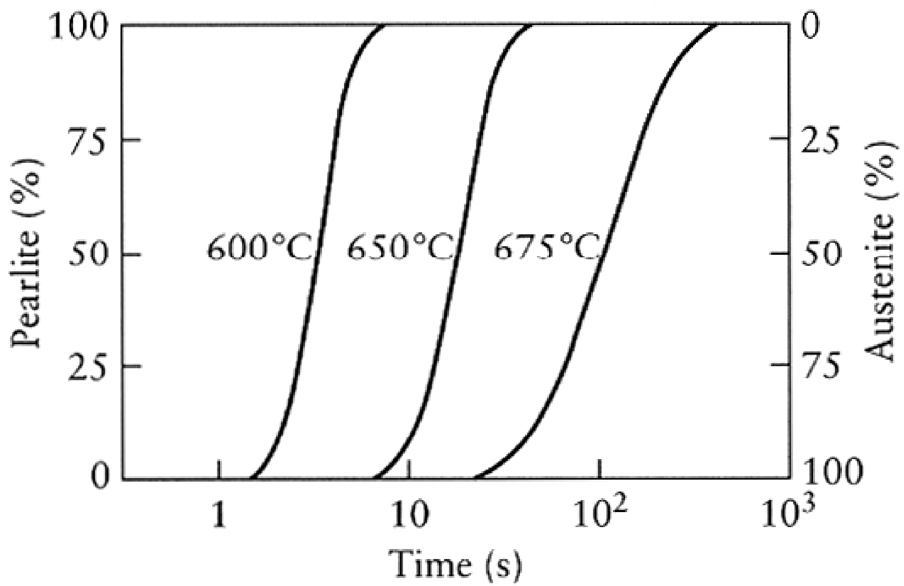
floating-zone method



Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Heat treatment-ferrous alloys

- **Pearlite**
- **Spheroidite**
- **Bainite**
- **Martensite**
  - Quenching(담금질)
  - Body Centered Tetragonal(BCT)
- **Retained austenite**
- **Tempered martensite**



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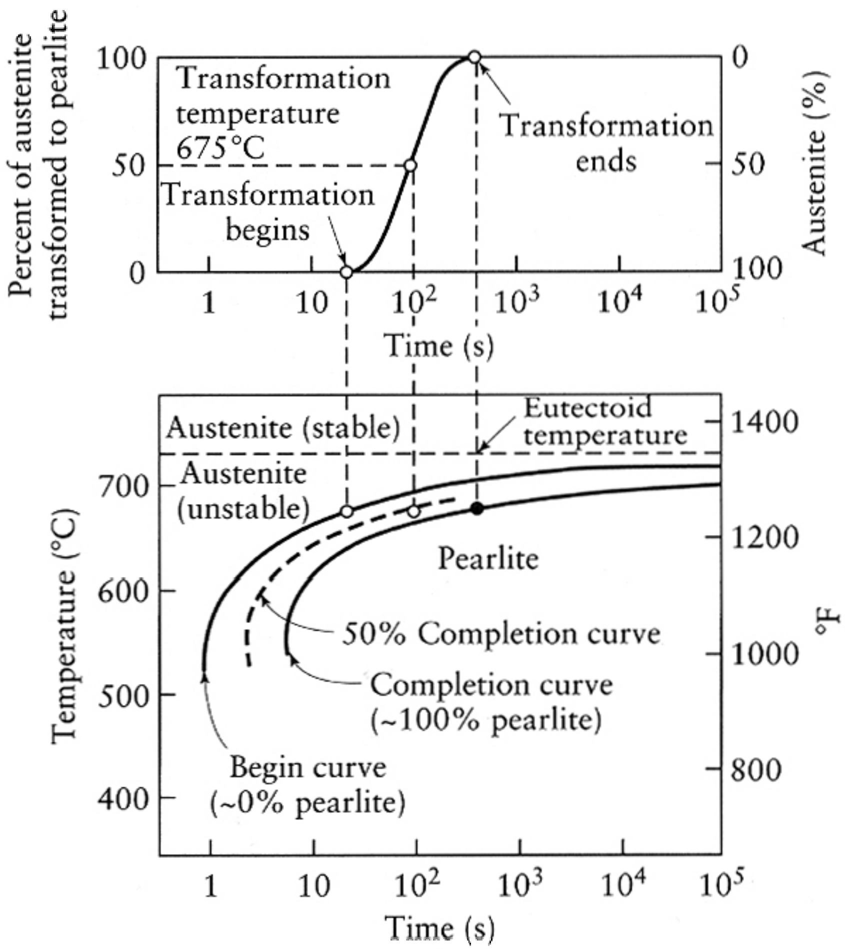
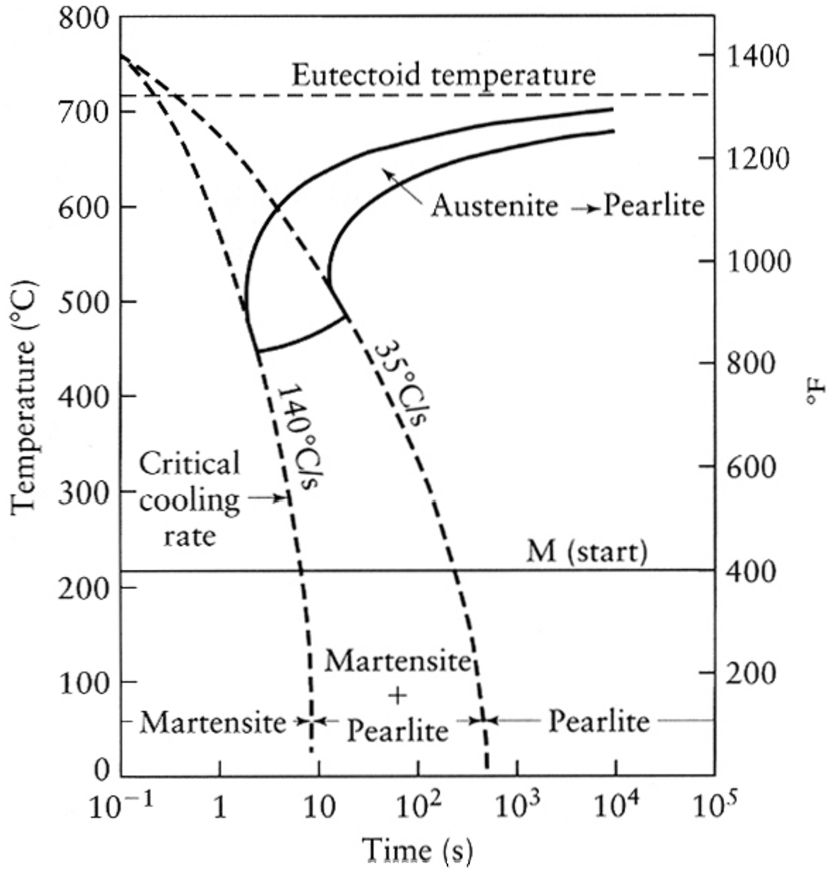
Ferrous alloys





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Nonferrous alloys/stainless steel (1)

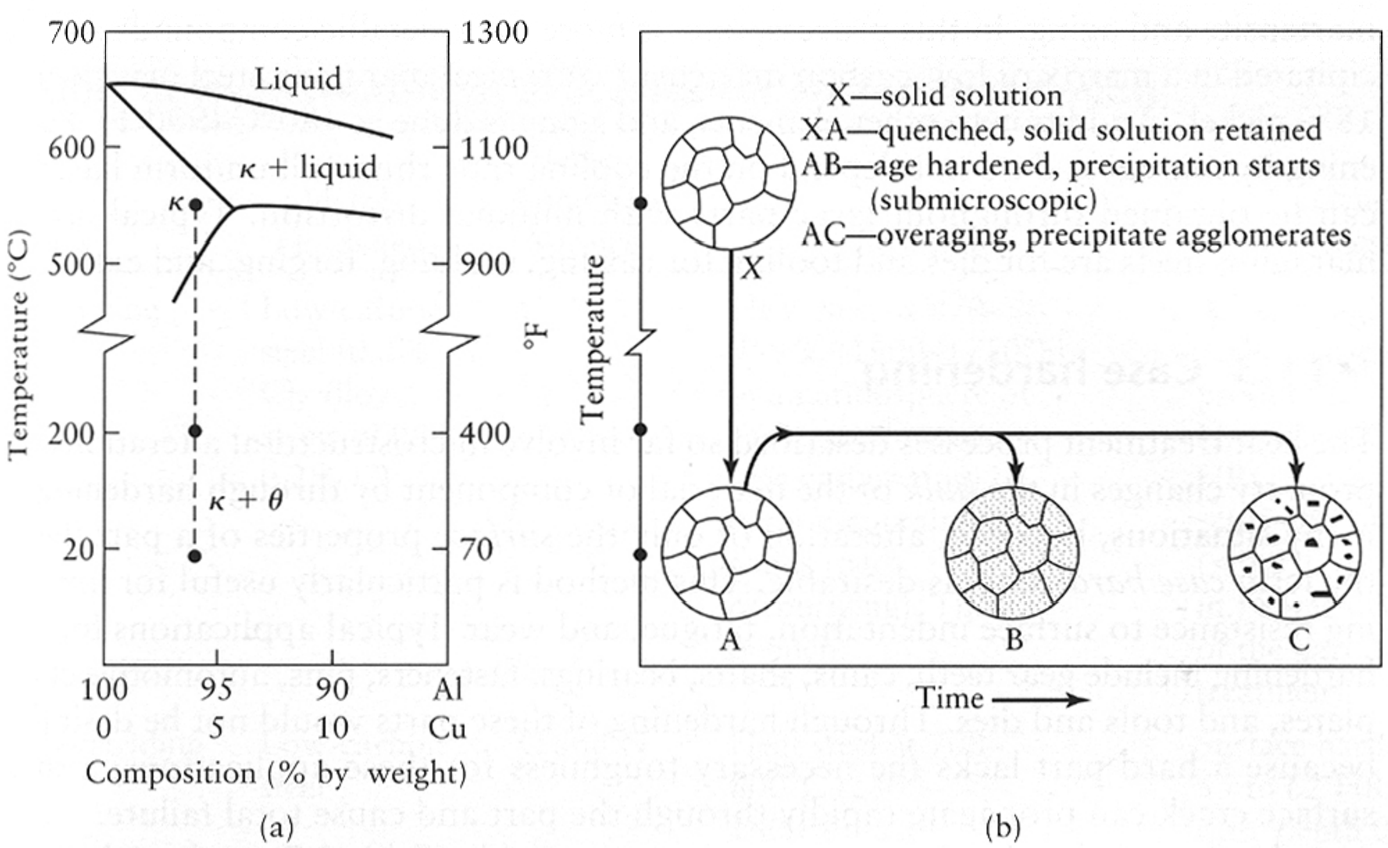

FIGURE 5.37 (a) Phase diagram for the aluminum–copper alloy system. (b) Various microstructures obtained during the age-hardening process. *Source*: L. H. Van Vlack, *Materials for Engineering* (Fig. 5.6.1, p. 123), © 1982 Addison-Wesley Publishing Company, Inc. Reprinted by permission of Addison-Wesley Longman Publishing Co., Inc.

Precipitation hardening (석출경화), Al-Cu alloy

Age hardening(시효경화)

Ref.
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Nonferrous alloys/stainless steel (2)

- **Solution treatment**
- **Precipitation hardening**
- **Aging**
- **Maraging(martensite + aging)**

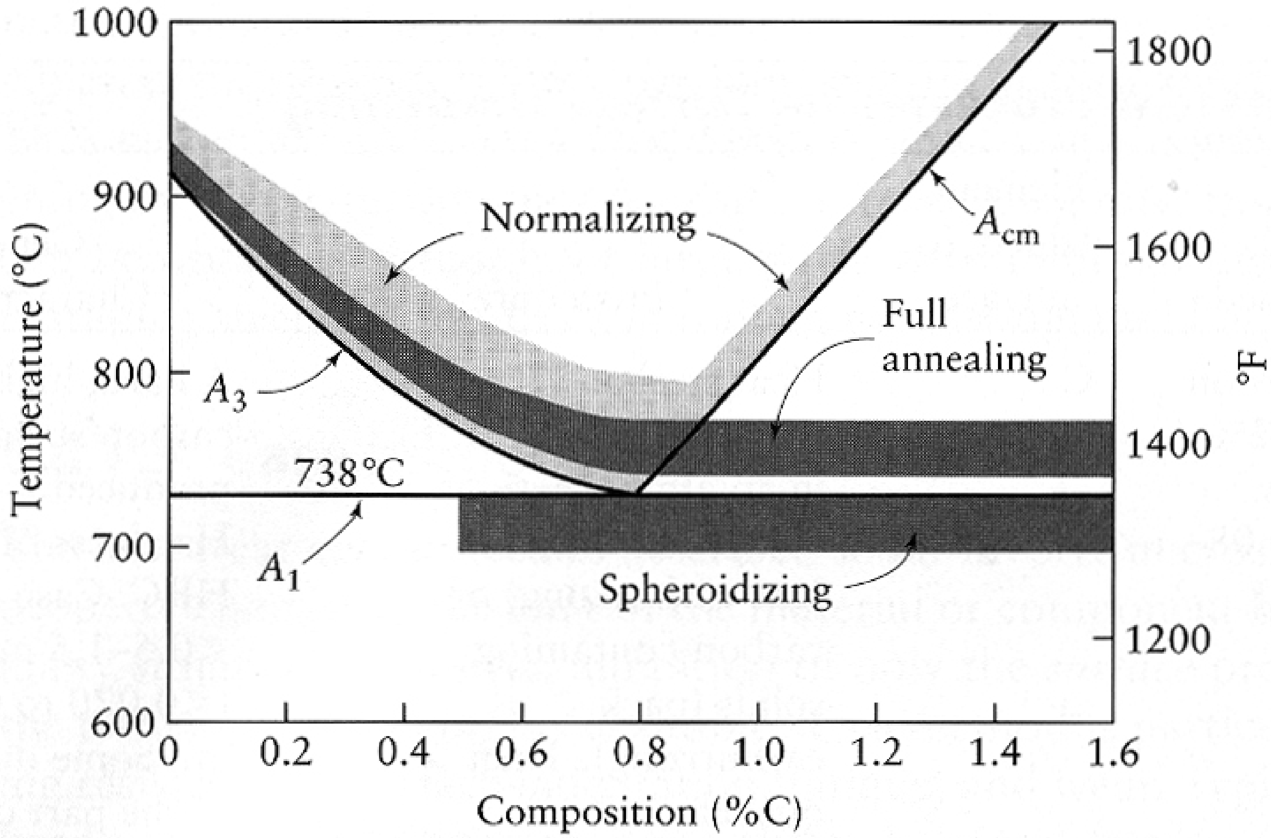
Case hardening

- **Surface hardening**
  - Carburizing (침탄법)
  - Carbonitriding (침탄질화법)
  - Cyaniding (청화법)
  - Nitriding (질화법)
  - Boronizing (붕화법)
  - Flame hardening (화염경화법)
  - Induction hardening (유도경화법)

Annealing (풀림)/ tempering (뜨임)

- **Normalizing(불림)**

FIGURE 5.38 Heat-treating temperature ranges for plain-carbon steels, as indicated on the iron–iron-carbide phase diagram. *Source*: ASM International, Materials Park, OH.



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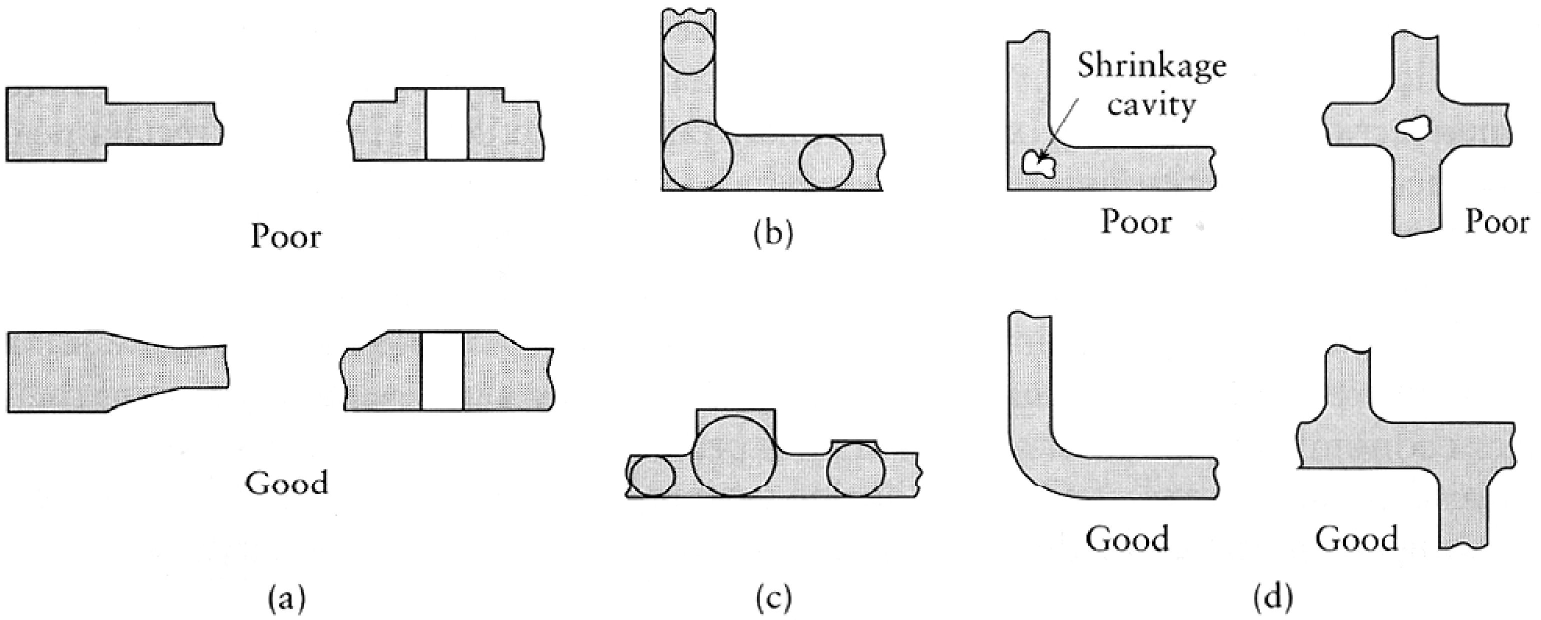
Design consideration (1)

FIGURE 5.39
(a) Suggested design modifications to avoid defects in castings. Note that sharp corners are avoided to reduce stress concentrations. (b)–(d) Examples of designs that show the importance of maintaining uniform cross-sections in castings to avoid hot spots and shrinkage cavities.



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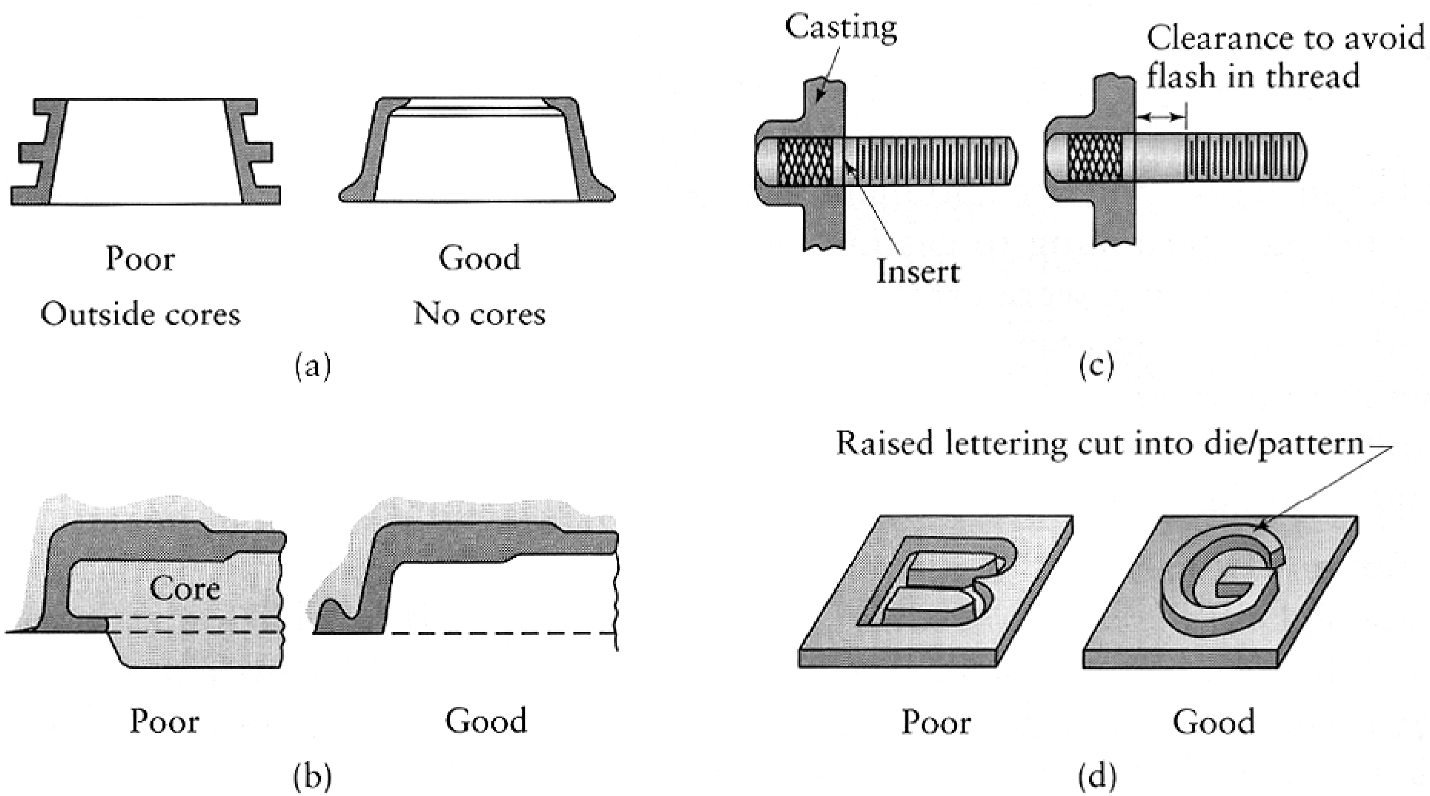
Design consideration (2)

FIGURE 5.40 Examples of casting design modifications. *Source:* Steel Castings Handbook, 5th ed., Steel Founders' Society of America, 1980. Used with permission.



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Economics of casting

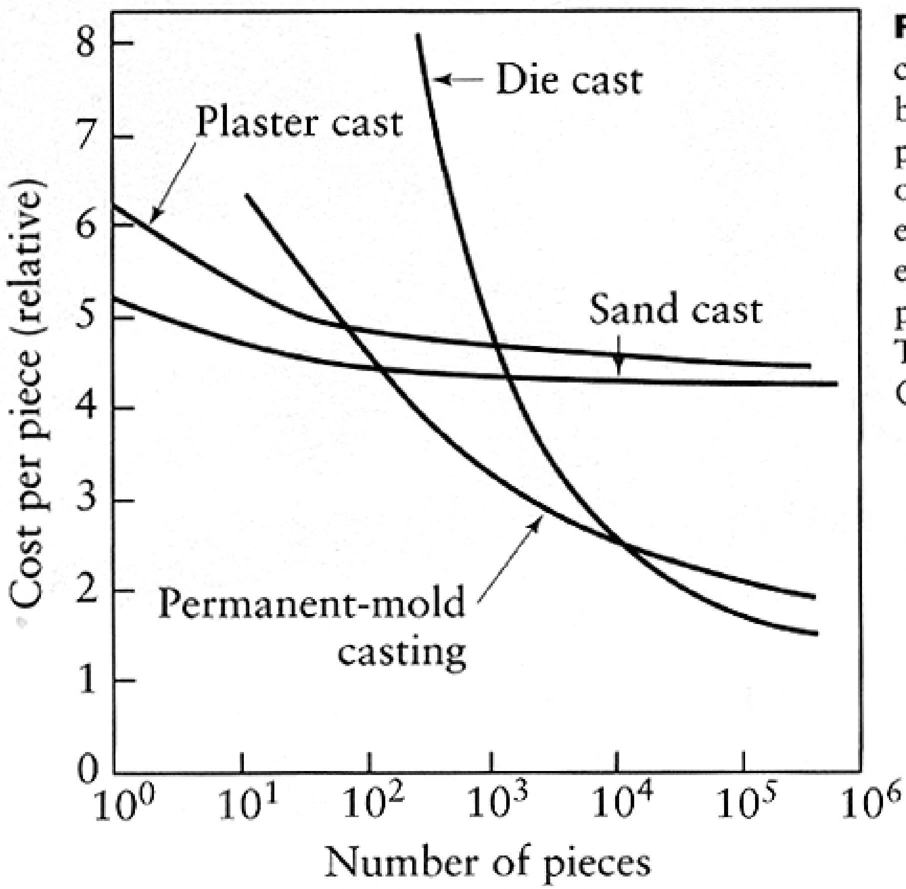

FIGURE 5.42 Economic comparison of making a part by different casting processes. Note that because of the high cost of equipment, die casting is economical for large production runs. *Source*: The North American Die Casting Association.

Ref.
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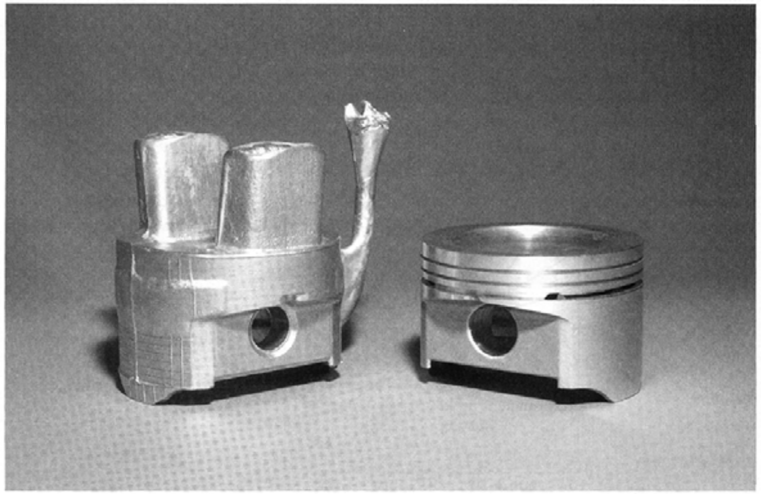
Case study

FIGURE 5.43 Aluminum piston for an internal combustion engine. (a) As cast; (b) after machining.



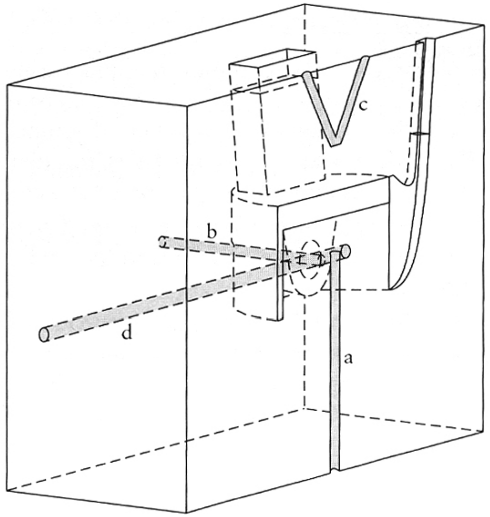


FIGURE 5.44 Schematic illustration of the permanent mold used to produce aluminum pistons, showing the position of four cooling channels.

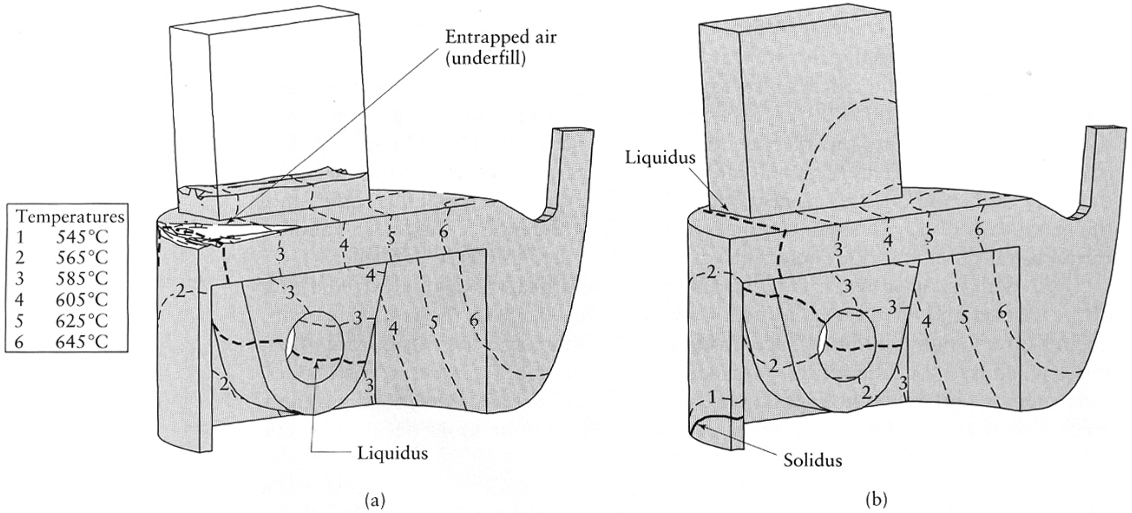


FIGURE 5.45 Simulation of mold filling and solidification. (a) 3.7 seconds after start of pour. Note that the mushy zone has been established before the mold is completely filled. (b) Using a vent in the mold for removal of entrapped air five seconds after pour.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley