P/M Parts


(a) (b)

FIGURE 11.1 (a) Examples of typical parts made by powder-metallurgy processes. (b) Upper trip lever for a commercial irrigation sprinkler, made by P/M. Made of unleaded brass alloy, it replaces a die-cast part, at a 60% cost savings. *Source:* Courtesy of Metal Powder Industries Federation.

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Particle Shapes

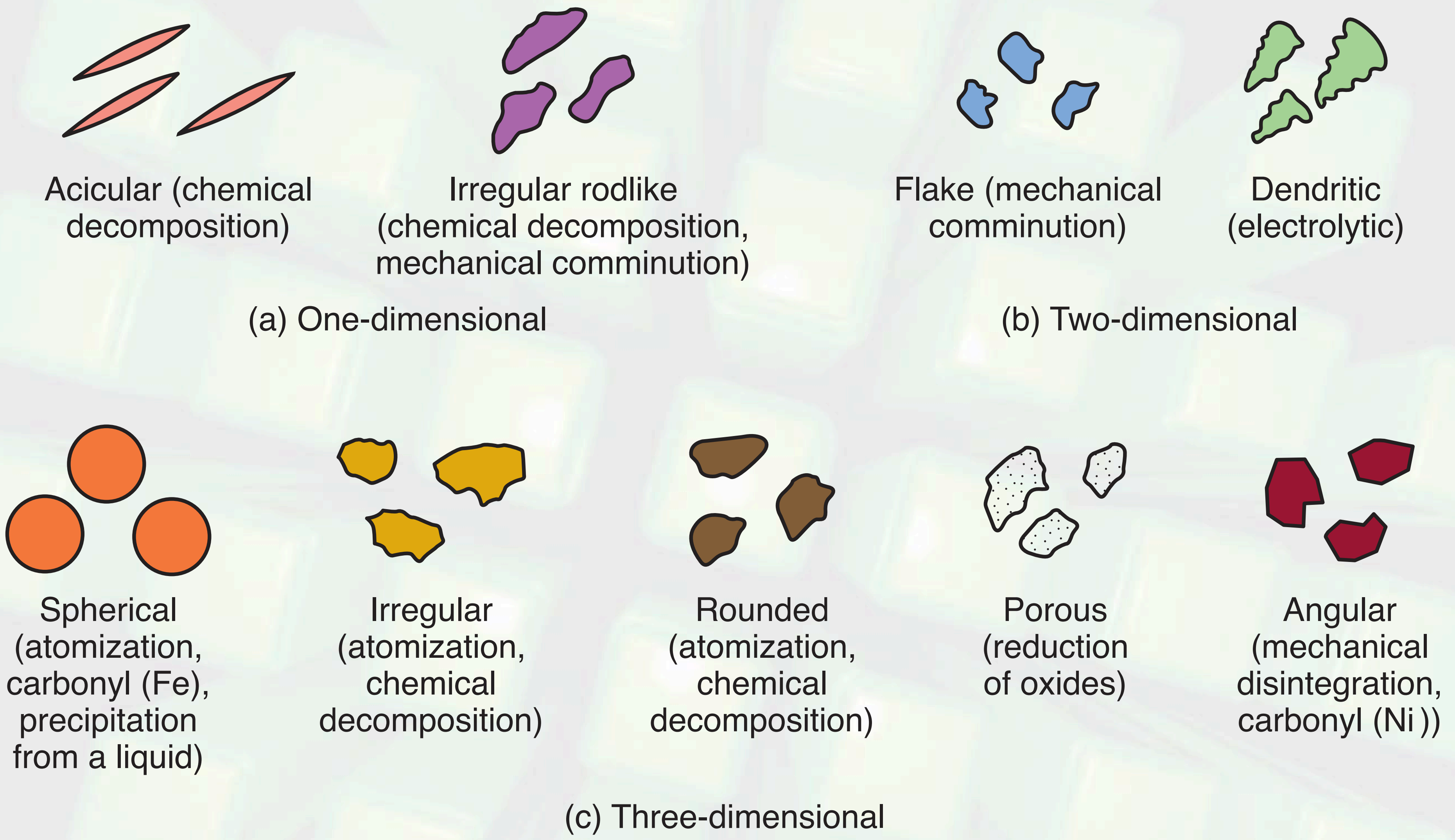

FIGURE 11.2 Particle shapes and characteristics of metal powders and the processes by which they are produced.

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Powder Production

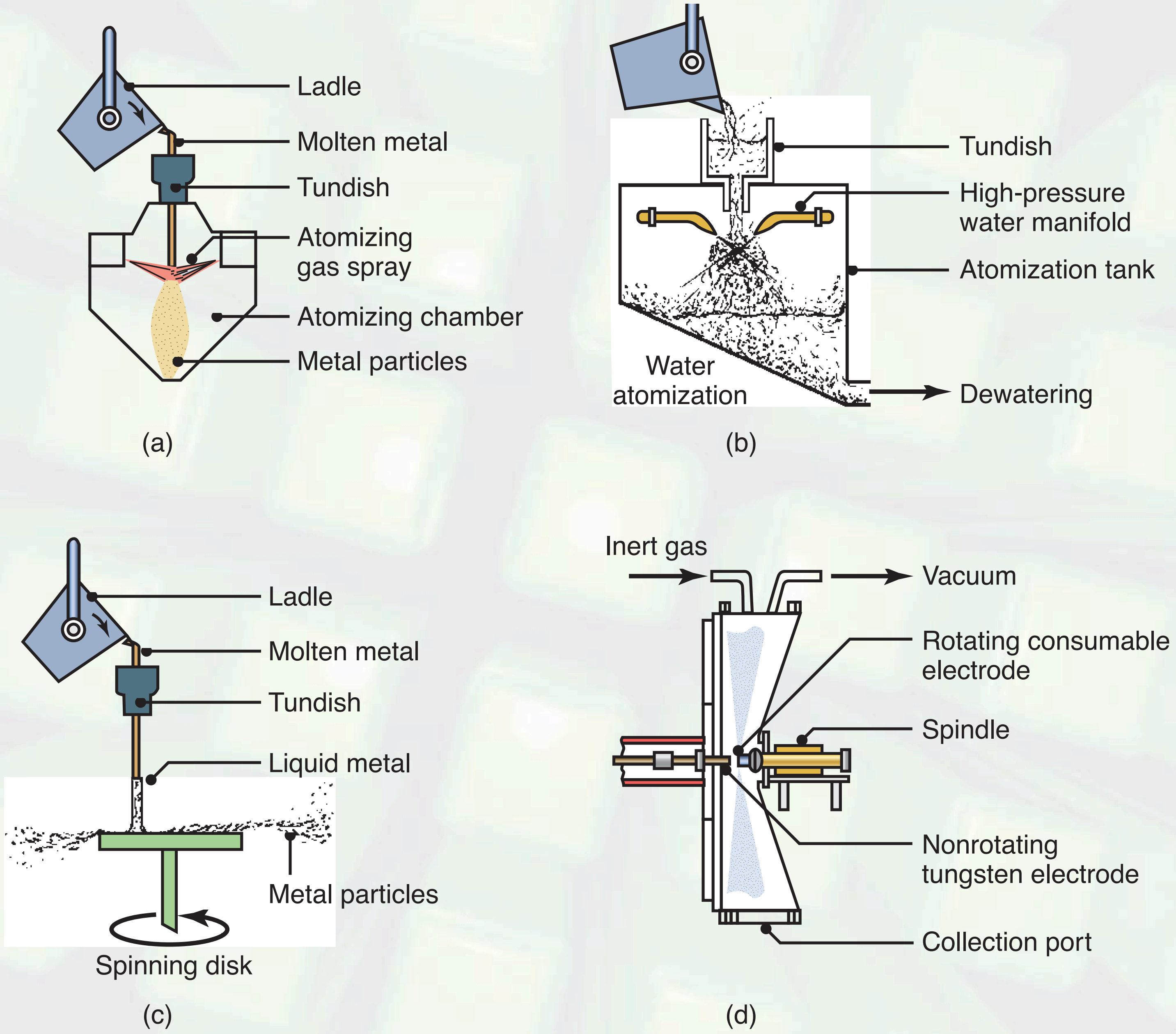

FIGURE 11.3 Methods of metal-powder production by atomization: (a) gas atomization; (b) water atomization; (c) atomization with a rotating consumable electrode; and (d) centrifugal atomization with a spinning disk or cup.

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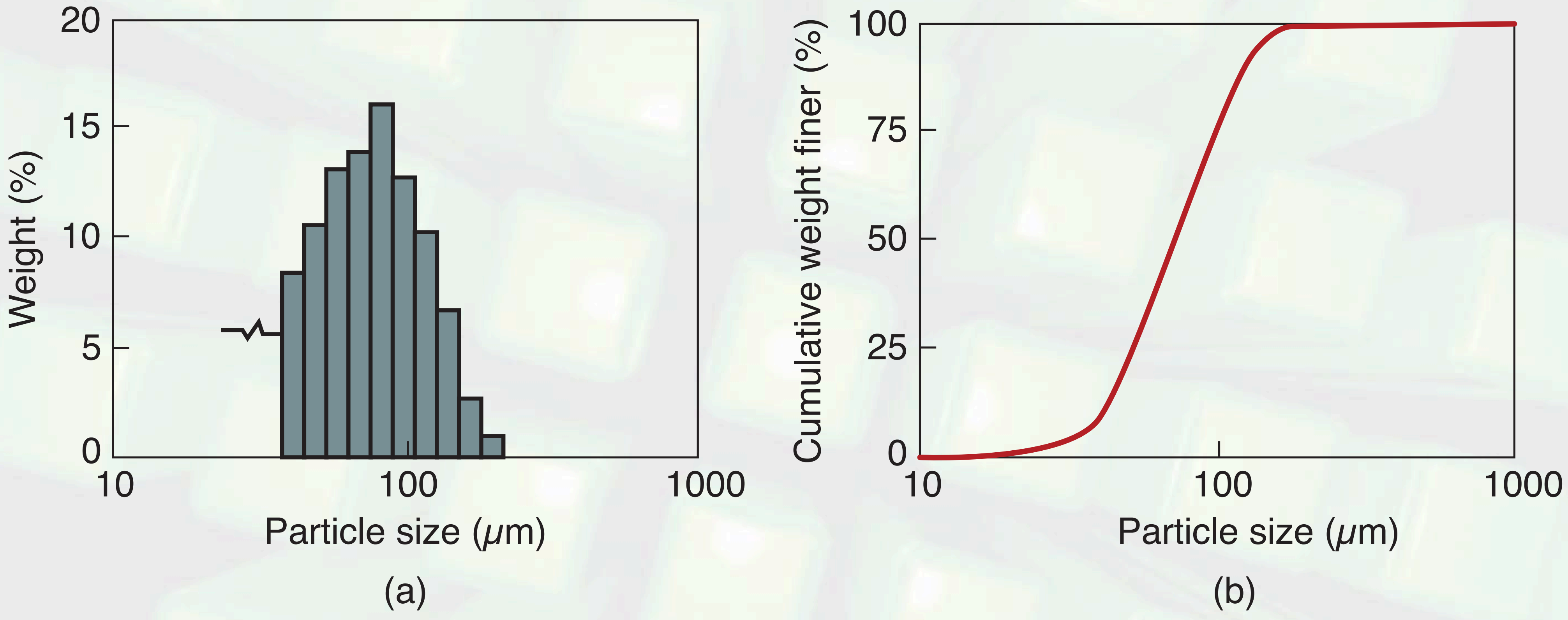
Particle Size Distribution



(a)

(b)

FIGURE 11.4 (a) Distribution of particle size, given as weight percentage; note that the highest percentage of particles have a size between 75 and 90 μm. (b) Cumulative particle-size distribution as a function of weight. *Source:* After R.M. German.

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Compaction

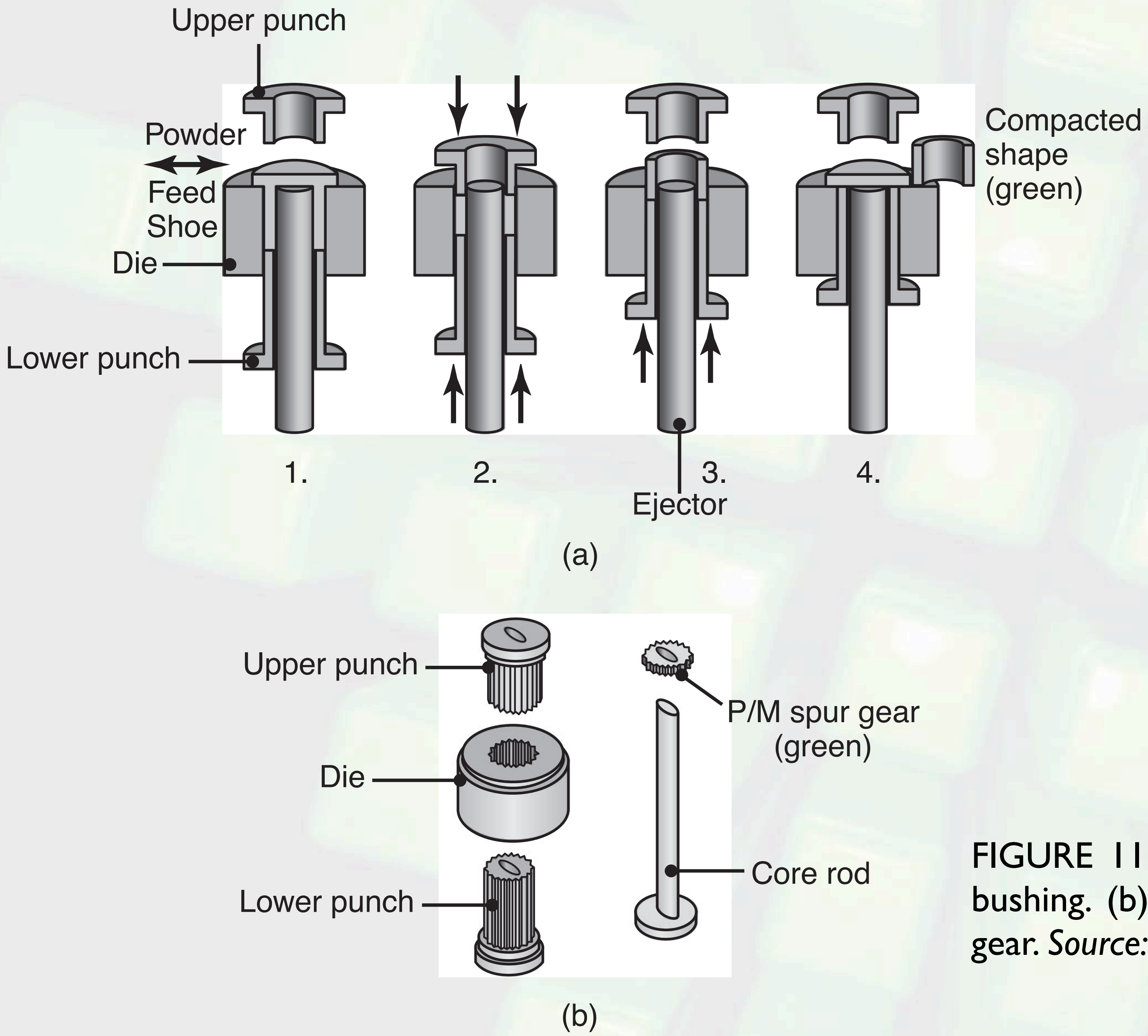

FIGURE 11.5 (a) Compaction of metal powder to produce a bushing. (b) A typical tool and die set for compacting a spur gear. *Source:* Courtesy of Metal Powder Industries Federation.

Density vs. Compacting Pressure

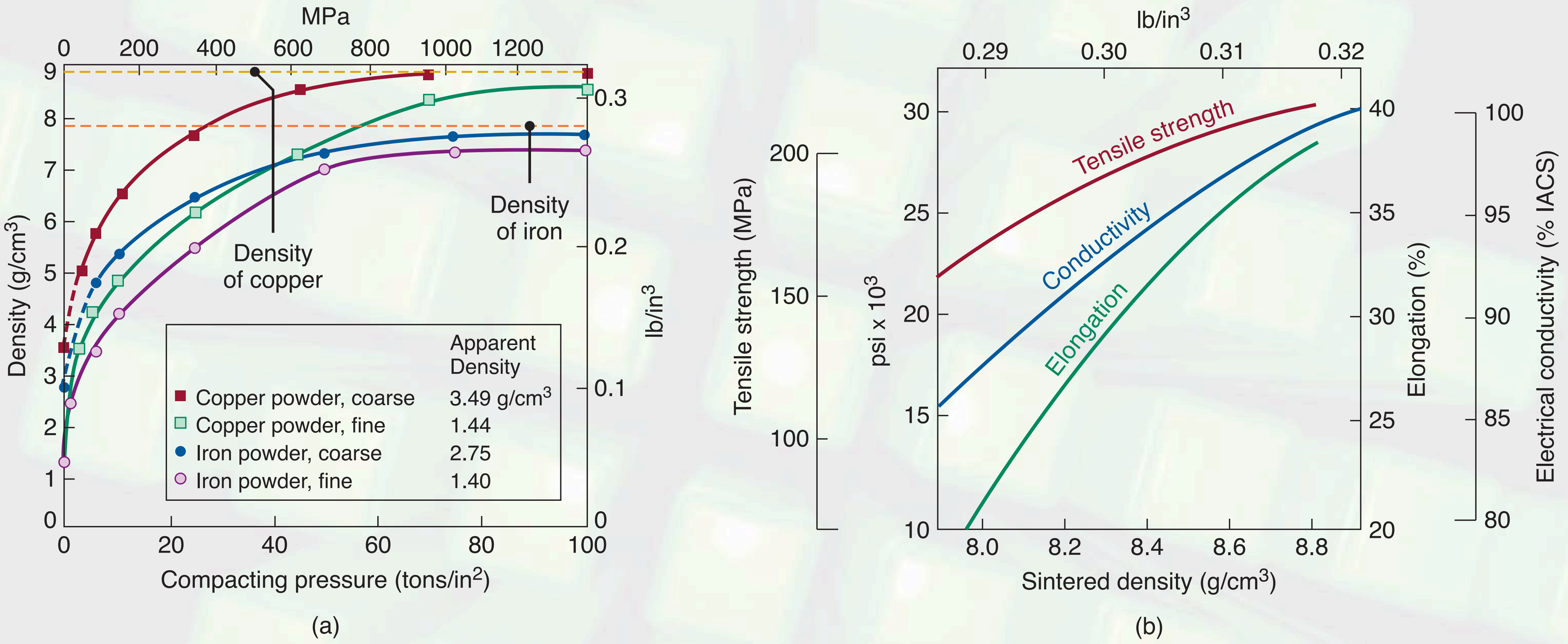

FIGURE 11.6 (a) Density of copper- and iron-powder compacts as a function of compacting pressure. Density greatly influences the mechanical and physical properties of P/M parts. *Source:* After F.V. Lenel. (b) Effect of density on tensile strength, elongation, and electrical conductivity of copper powder. (IACS is International Annealed Copper Standard for electrical conductivity.)

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Mechanics of Compaction

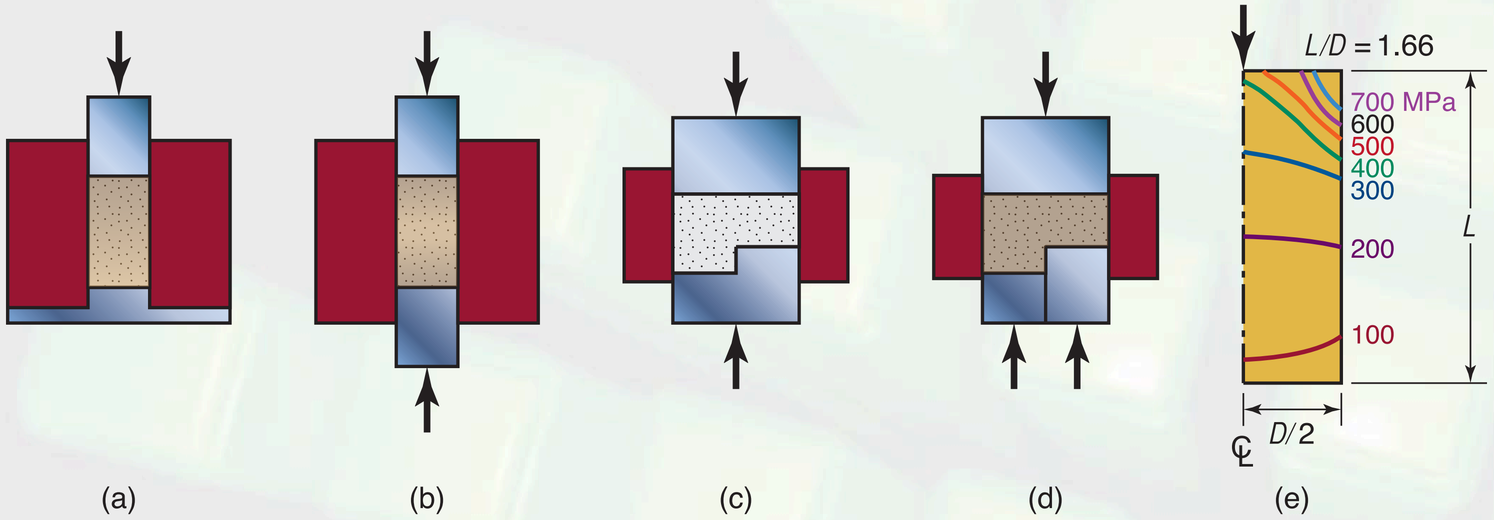

FIGURE 11.7 Density variation in compacting metal powders in different dies: (a) and (c) single-action press; (b) and (d) double-action press, where the punches have separate movements. Note the greater uniformity of density in (d) as compared with (c). Generally, uniformity of density is preferred, although there are situations in which density variation, and hence variation of properties, within a part may be desirable. (e) Pressure contours in compacted copper powder in a single-action press. *Source:* After P. Duwez and L. Zwell.

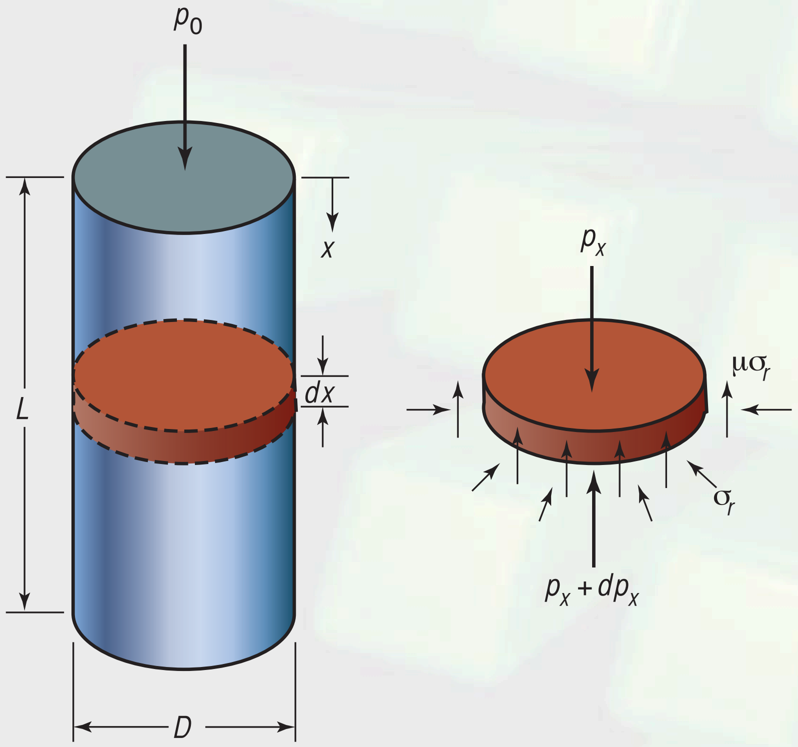

FIGURE 11.8 Coordinate system and stresses acting on an element in compaction of powders. The pressure is assumed to be uniform across the cross-section. (See also Fig. 6.4.)

Resultant pressure distribution:

$$p_x = p_o e^{-4\mu k x/D}$$

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Cold Isostatic Pressing

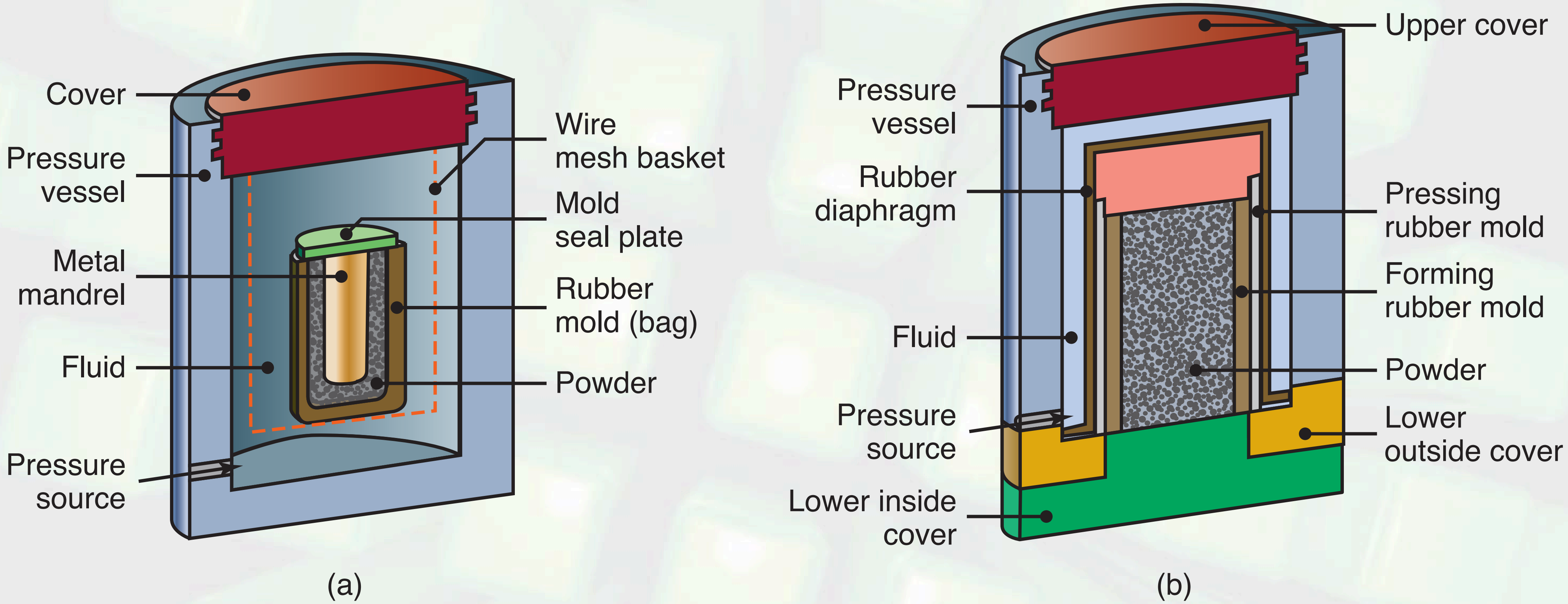

FIGURE 11.9 Schematic illustration of cold isostatic pressing in compaction of a tube. (a) The *wet-bag process*, where the rubber mold is inserted into a fluid that is subsequently pressurized. In the arrangement shown, the powder is enclosed in a flexible container around a solid core rod. (b) The *dry bag process*, where the rubber mold does not contact the fluid, but instead is pressurized through a diaphragm. *Source:* After R.M. German.

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Pressures and Capabilities

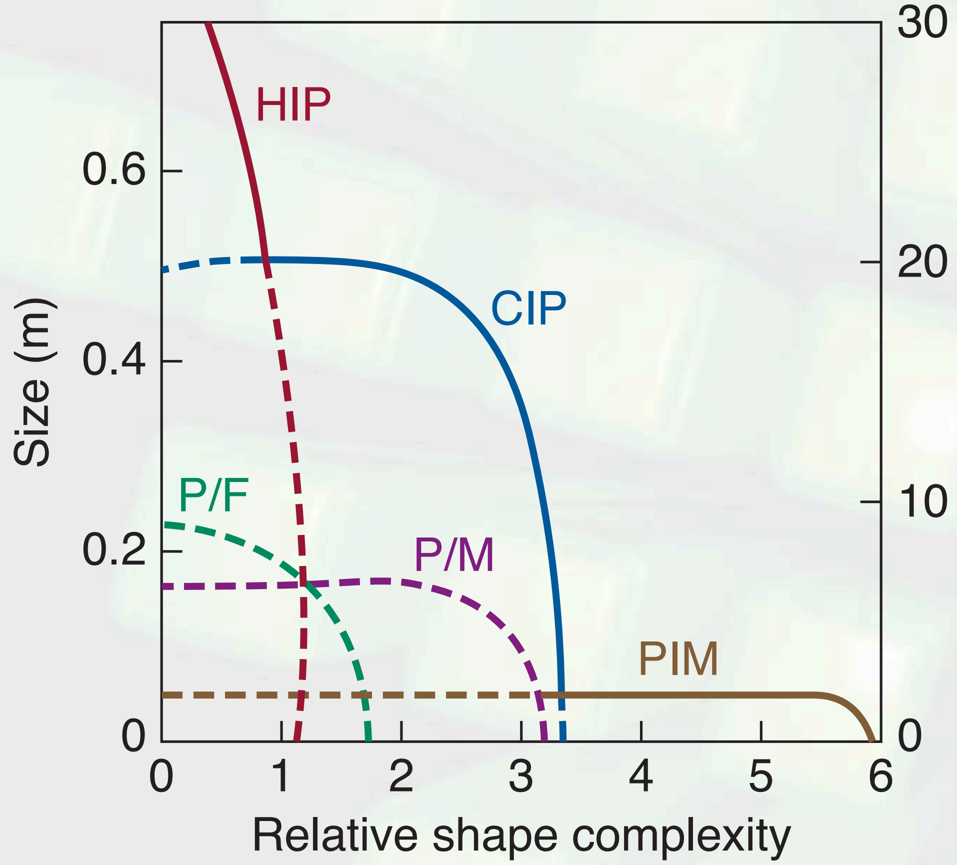

FIGURE 11.10 Process capabilities of part size and shape complexity for various P/M operations; P/F is powder forging. *Source:* Metal Powder Industries Federation.

	Pressure	
	MPa	psi $\times 10^3$
Metal		
Aluminum	70–275	10–40
Brass	400–700	60–100
Bronze	200–275	30–40
Iron	350–800	50–120
Tantalum	70–140	10–20
Tungsten	70–140	10–20
Other Materials		
Auminum oxide	110–140	16–20
Carbon	140–165	20–24
Cemented carbides	140–400	20–60
Ferrites	110–165	16–24

TABLE 11.1 Compacting Pressures for Various Metal Powders

Hot Isostatic Pressing

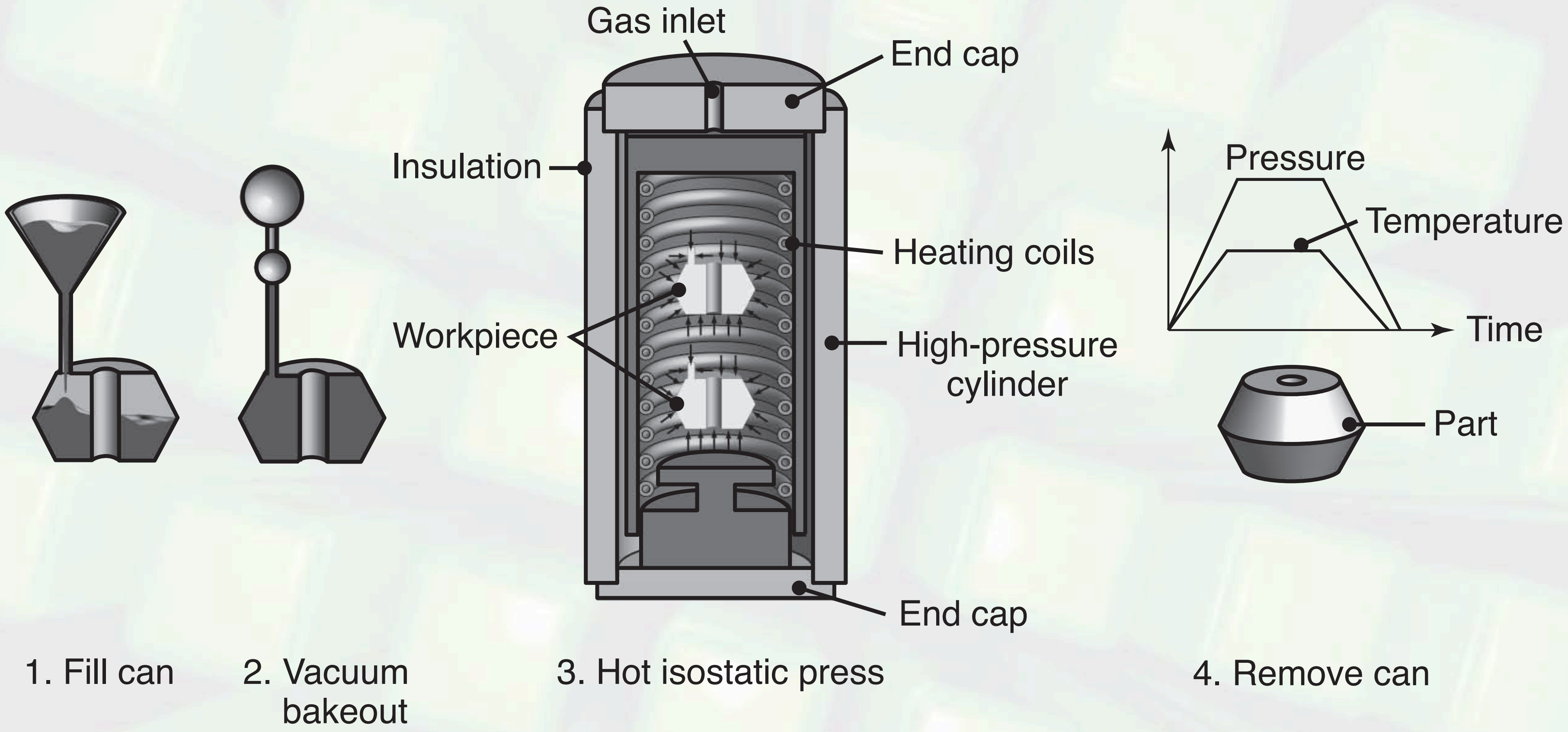

FIGURE 11.11 Schematic illustration of the sequence of steps in hot isostatic pressing. Diagram (4) shows the pressure and temperature variation versus time.

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Powder Rolling

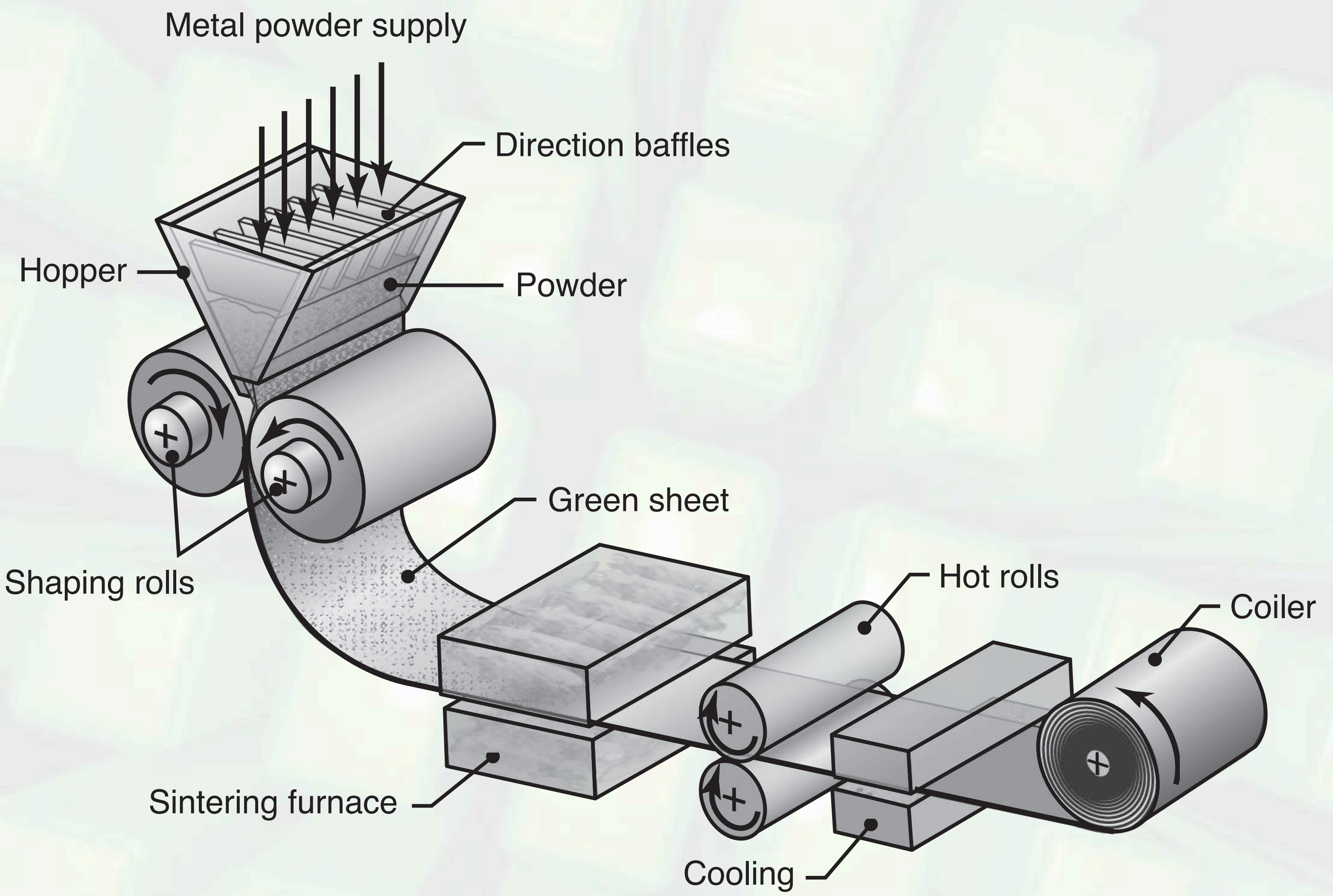

FIGURE 11.12 An example of powder rolling. The purpose of direction baffles in the hopper is to ensure uniform distribution of powder across the width of the strip.

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Spray Casting

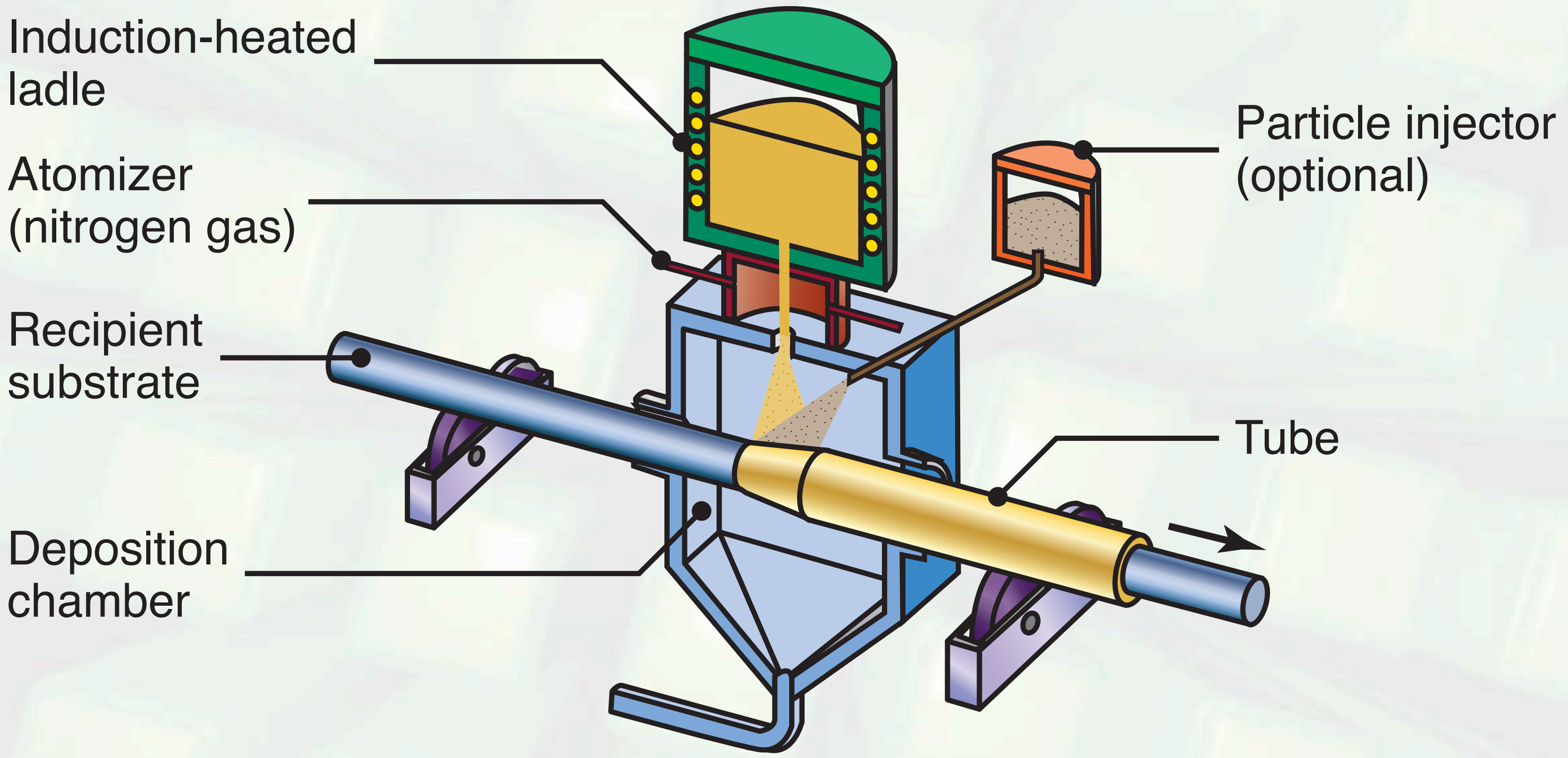

FIGURE 11.13 Spray casting (Osprey process) in which molten metal is sprayed over a rotating mandrel to produce seamless tubing and pipe.

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Sintering

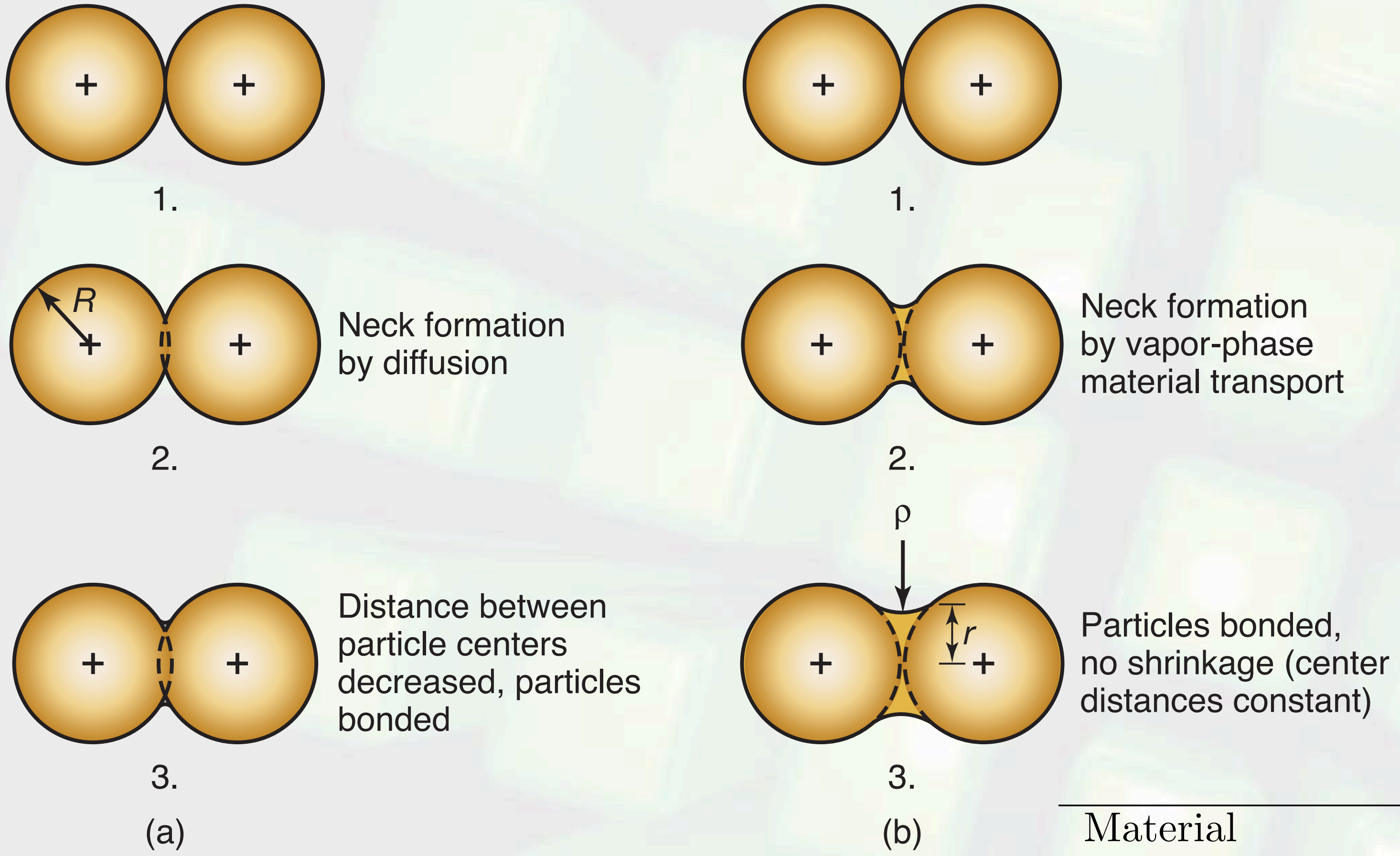
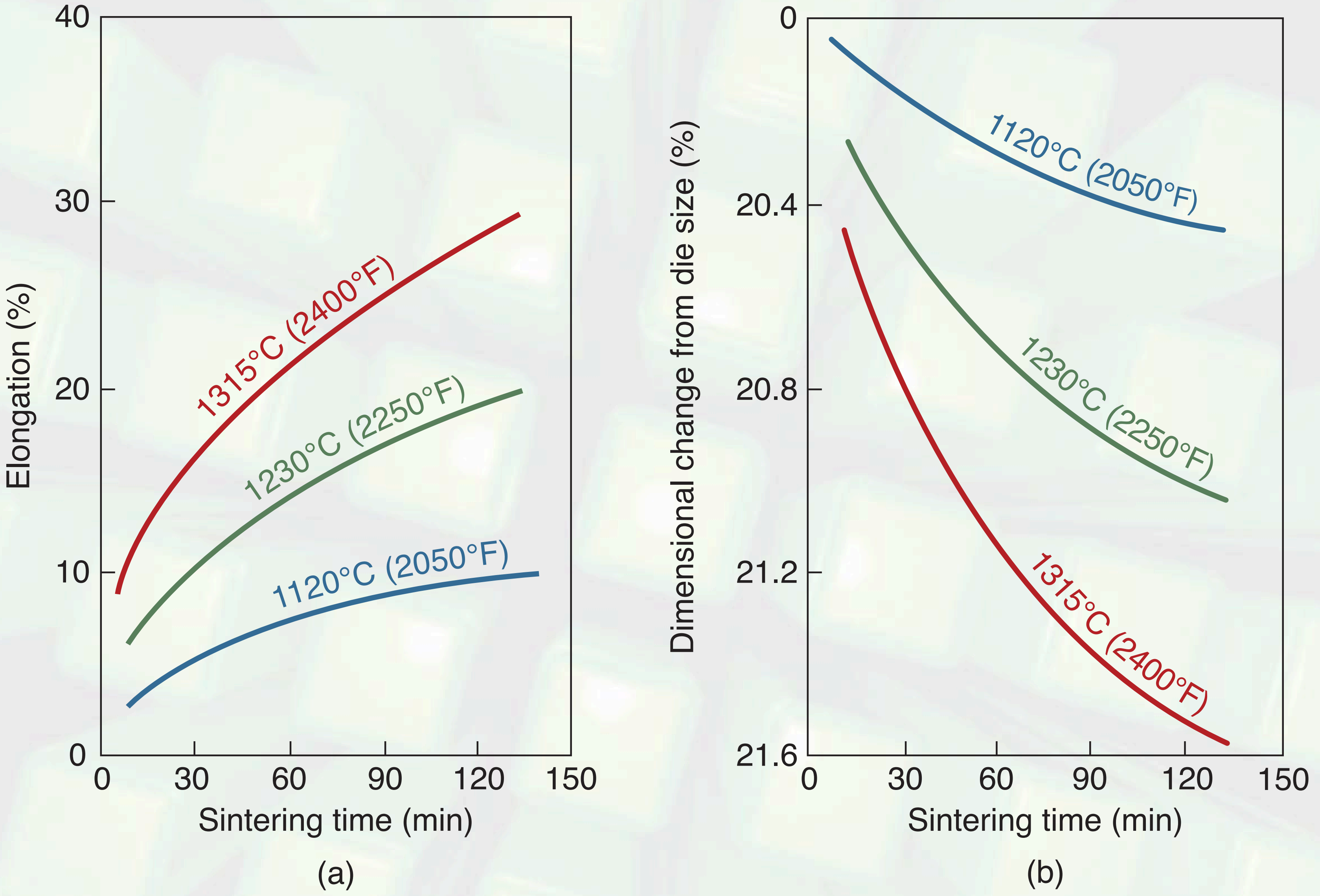


FIGURE 11.14 Schematic illustration of two basic mechanisms in sintering metal powders: (a) solid-state material transport and (b) liquid-phase material transport. *R*=particle radius, *r*=neck radius, and ρ =neck profile radius.

TABLE 11.2 Sintering temperature and time for various metal powders.

Material	Temperature (°C)	Time (min)
Copper, brass, and bronze	760–900	10–45
Iron and iron graphite	1000–1150	8–45
Nickel	1000–1150	30–45
Stainless steels	1100–1290	30–60
Alnico alloys (for permanent magnets)	1200–1300	120–150
Ferrites	1200–1500	10–600
Tungsten carbide	1430–1500	20–30
Molybdenum	2050	120
Tungsten	2350	480
Tantalum	2400	480

Effect of Temperature and Time



(a) (b)

FIGURE 11.5 Effect of sintering temperature and time on (a) elongation and (b) dimensional change during sintering of type 316L stainless steel. *Source:* ASM International.

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Mechanical Properties of P/M Materials

Designation	MPIF type	Condition	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Hardness	Elongation in 25 mm (%)	Elastic Modulus (GPa)
Ferrous							
FC-0208	N	AS	225	205	45 HRB	< 0.5	70
		HT	295	–	95 HRB	< 0.5	70
	R	AS	415	330	70 HRB	1	110
		HT	550	–	35 HRC	< 0.5	110
	S	AS	550	395	80 HRB	1.5	130
		HT	690	655	40 HRC	< 0.5	130
FN-0405	S	AS	425	240	72 HRB	4.5	145
		HT	1060	880	39 HRC	1	145
	T	AS	510	295	80 HRB	6	160
		HT	1240	1060	44 HRC	1.5	160
Aluminum							
601 AB		AS	110	48	60 HRH	6	–
pressed bar		HT	252	241	75 HRH	2	–
Brass							
CZP-0220	T	–	165	76	55 HRH	13	–
	U	–	193	89	68 HRH	19	–
	W	–	221	103	75 HRH	23	–
Titanium							
Ti-6Al-4V		HIP	917	827	–	13	–
Superalloys							
Stellite 19		–	1035	–	49 HRC	< 1	–

Note: MPIF=Metal Powder Industries Federation; AS=as sintered; HT=heat treated; HIP=hot isostatically pressed.

TABLE 11.3 Typical mechanical properties of selected P/M materials.

Titanium Property Comparison

Process	Density (%)	Yield Stress (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Reduction of Area (%)
Cast	100	840	930	7	15
Cast and forged	100	875	965	14	40
Powder metallurgy					
Blended elemental (P+S)*	98	786	875	8	14
Blended elemental (HIP)*	> 99		875	9	17
Realloyed (HIP)	100	880	975	14	26

* P+S=pressed and sintered; HIP=hot isostatically pressed.

Source: After R.M. German

TABLE 11.4 Mechanical property comparison for Ti-6Al-4V titanium alloy.

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P/M Example: Bearing Caps

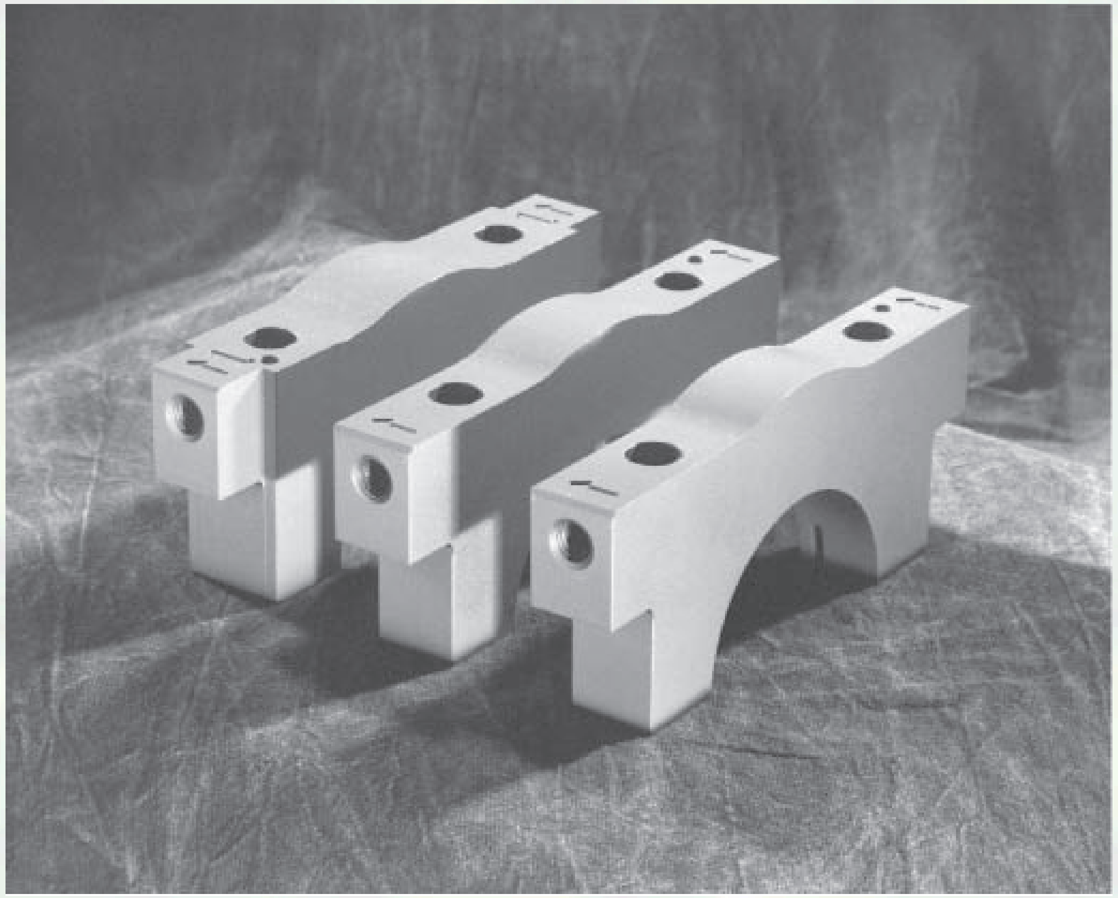

FIGURE 11.16 Powder-metal main bearing caps for 3.8- and 3.1-liter General Motors engines. *Source:* Courtesy of Zenith Sintered Products, Inc., Milwaukee, WI.

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Geometry for P/M Dies

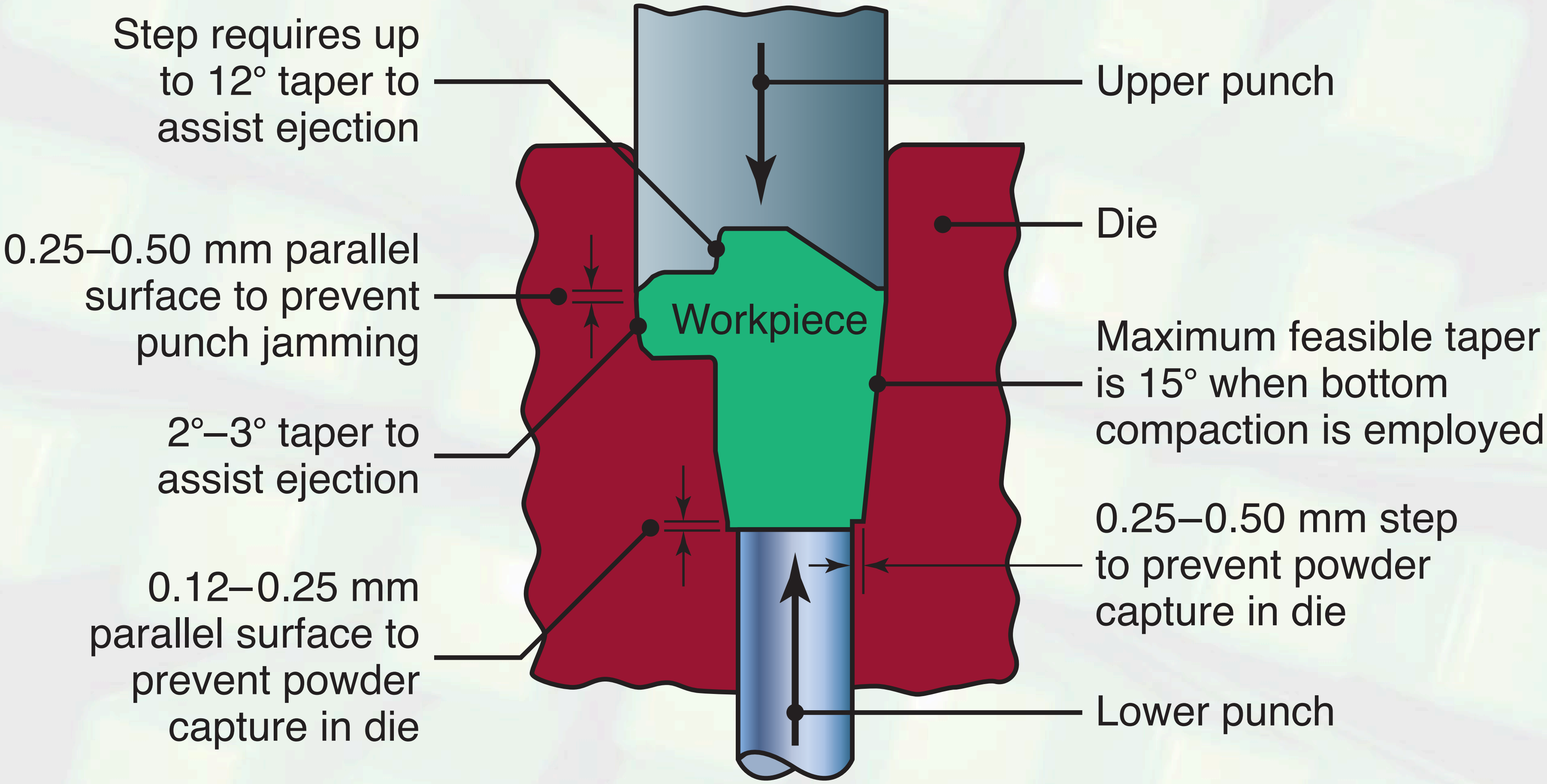

FIGURE 11.17 Die geometry and design features for powder-metal compaction. *Source:* Metal Powder Industries Federation.

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Design Considerations

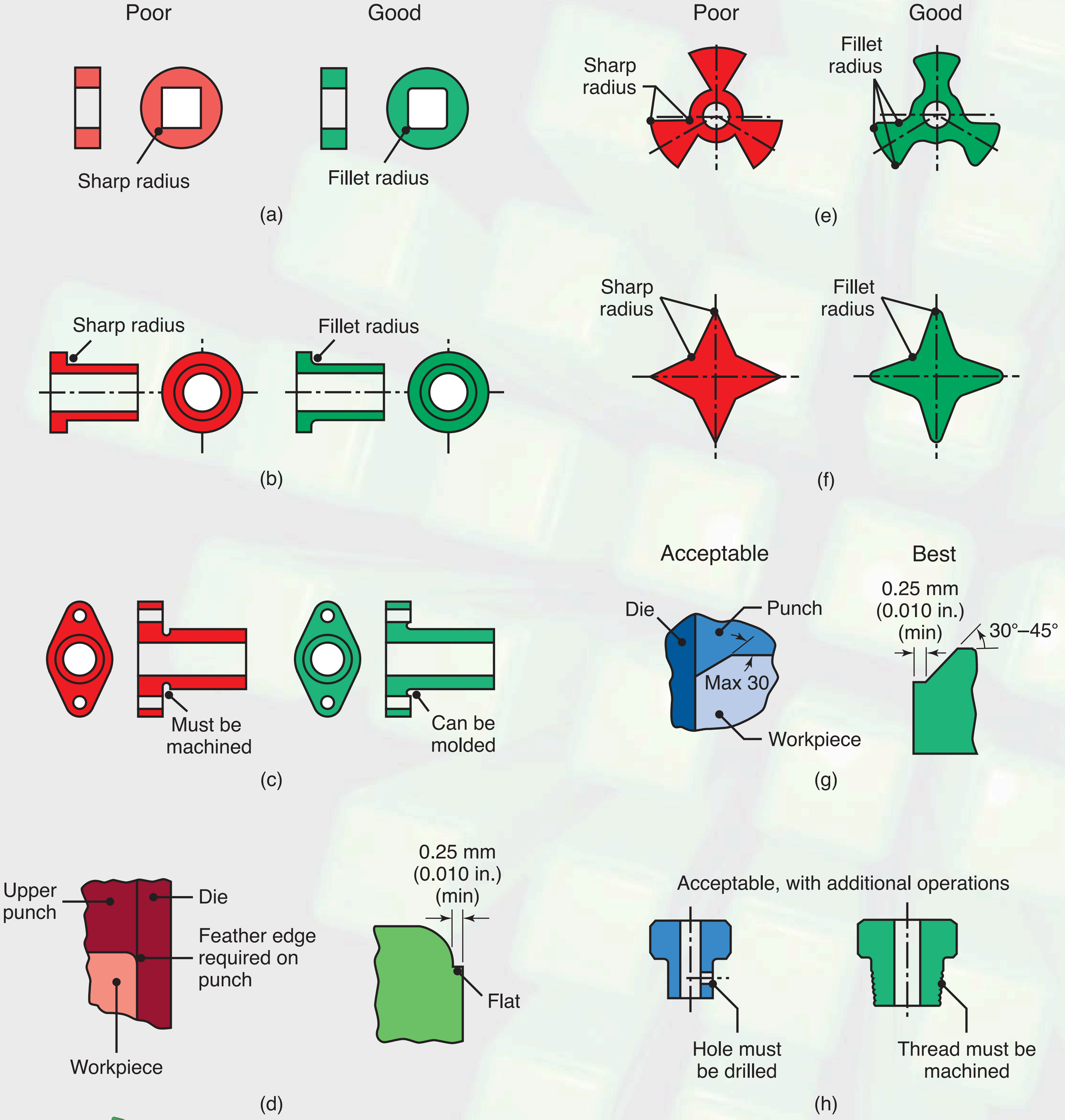

FIGURE 11.18 Examples of P/M parts, showing various poor and good designs. Note that sharp radii and reentry corners should be avoided, and that threads and transverse holes have to be produced separately, by additional operations such as machining or grinding. *Source:* Metal Powder Industries Federation.

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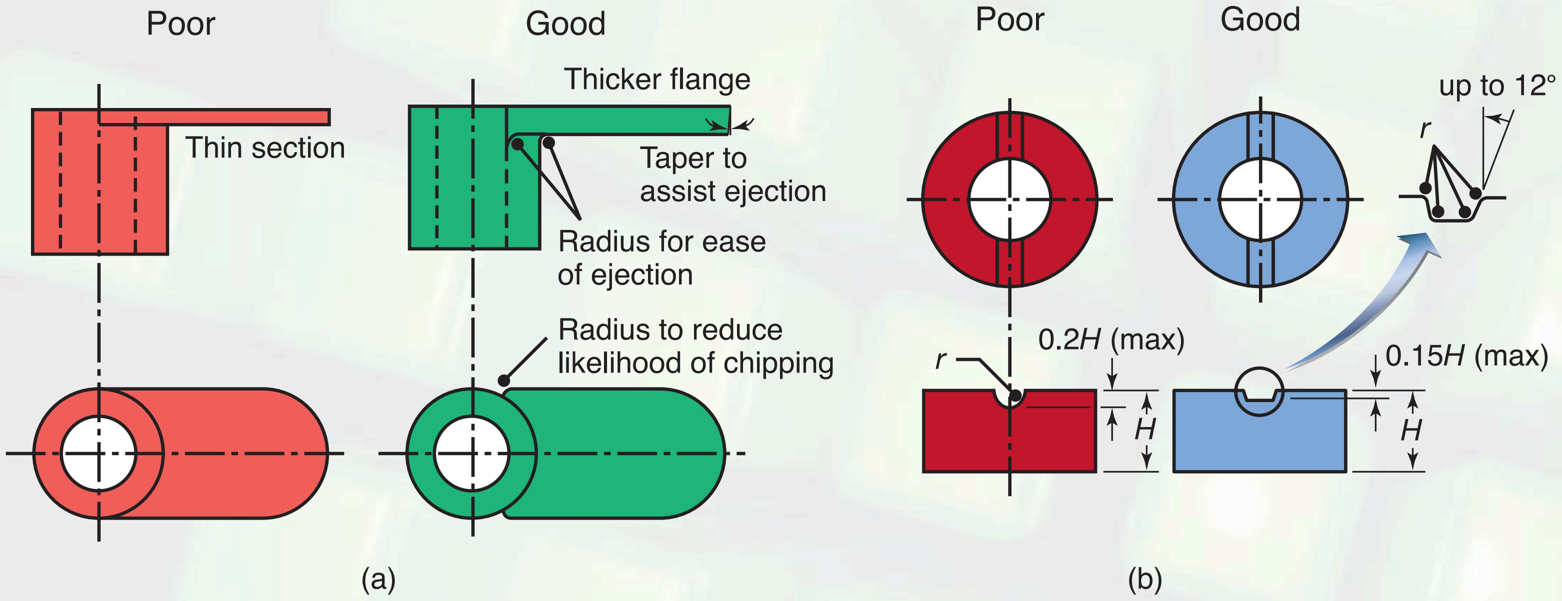
Design Considerations



(a)

(b)

FIGURE 11.19 (a) Design features for use with unsupported flanges. (b) Design features for use with grooves. *Source:* Metal Powder Industries Federation.

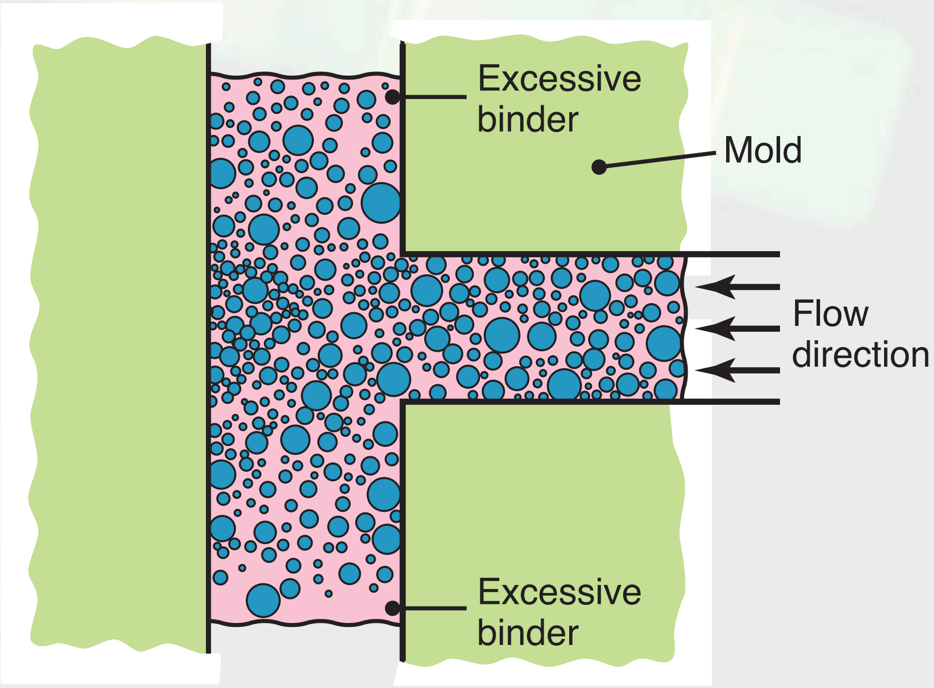


FIGURE 11.20 The use of abrupt transitions in molds for powder injection molding causing non-uniform metal-powder distribution within a part.

Process Comparison

Process	Advantages Over P/M	Limitations as Compared With P/M
Casting	Wide range of part shapes and sizes produced; generally low mold and setup cost.	Some waste of material in processing; some finishing required; may not be feasible for some high-temperature alloys.
Forging (hot)	High production rate of a wide range of part sizes and shapes; high mechanical properties through control of grain flow.	Some finishing required; some waste of material in processing; die wear; relatively poor surface finish and dimensional control.
Extrusion (hot)	High production rate of long parts; complex cross-sections may be produced.	Only a constant cross-sectional shape can be produced; die wear; poor dimensional control.
Machining	Wide range of part shapes and sizes; short lead time; flexibility; good dimensional control and surface finish; simple tooling.	Waste of material in the form of chips; relatively low productivity.

TABLE 11.5 Competitive features of P/M and some other manufacturing processes.

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Types of Ceramics and Glasses

Type	General Characteristics
Oxide Ceramics	
Alumina	High hot hardness and abrasion resistance, moderate strength and toughness; most widely used ceramic; used for cutting tools, abrasives, and electrical and thermal insulation.
Zirconia	High strength and toughness; resistance to thermal shock, wear, and corrosion; partially-stabilized zirconia and transformation-toughened zirconia have better properties; suitable for heat-engine components.
Carbides	
Tungsten carbide	High hardness, strength, toughness, and wear resistance, depending on cobalt binder content; commonly used for dies and cutting tools.
Titanium carbide	Not as tough as tungsten carbide, but has a higher wear resistance; has nickel and molybdenum as the binder; used as cutting tools.
Silicon carbide	High-temperature strength and wear resistance, used for engines components and as abrasives.
Nitrides	
Cubic boron nitride	Second hardest substance known, after diamond; high resistance to oxidation; used as abrasives and cutting tools.
Titanium nitride	Used as coatings on tools, because of its low friction characteristics.
Silicon nitride	High resistance to creep and thermal shock; high toughness and hot hardness; used in heat engines.
Sialon	Consists of silicon nitrides and other oxides and carbides; used as cutting tools.
Cermets	Consist of oxides, carbides, and nitrides; high chemical resistance but is somewhat brittle and costly; used in high-temperature applications.
Nanophase ceramics	Stronger and easier to fabricate and machine than conventional ceramics; used in automotive and jet-engine applications.
Silica	High temperature resistance; quartz exhibits piezoelectric effects; silicates containing various oxides are used in high-temperature, nonstructural applications.
Glasses	Contain at least 50% silica; amorphous structure; several types available, with a wide range of mechanical, physical, and optical properties.
Glass ceramics	High crystalline component to their structure; stronger than glass; good thermal-shock resistance; used for cookware, heat exchangers, and electronics.
Graphite	Crystalline form of carbon; high electrical and thermal conductivity; good thermal-shock resistance; also available as fibers, foam, and buckyballs for solid lubrication; used for molds and high-temperature components.
Diamond	Hardest substance known; available as single-crystal or polycrystalline form; used as cutting tools and abrasives and as die insert for fine wire drawing; also used as coatings.

TABLE 11.6 Types and general characteristics of ceramics and glasses.

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Ceramic Structure

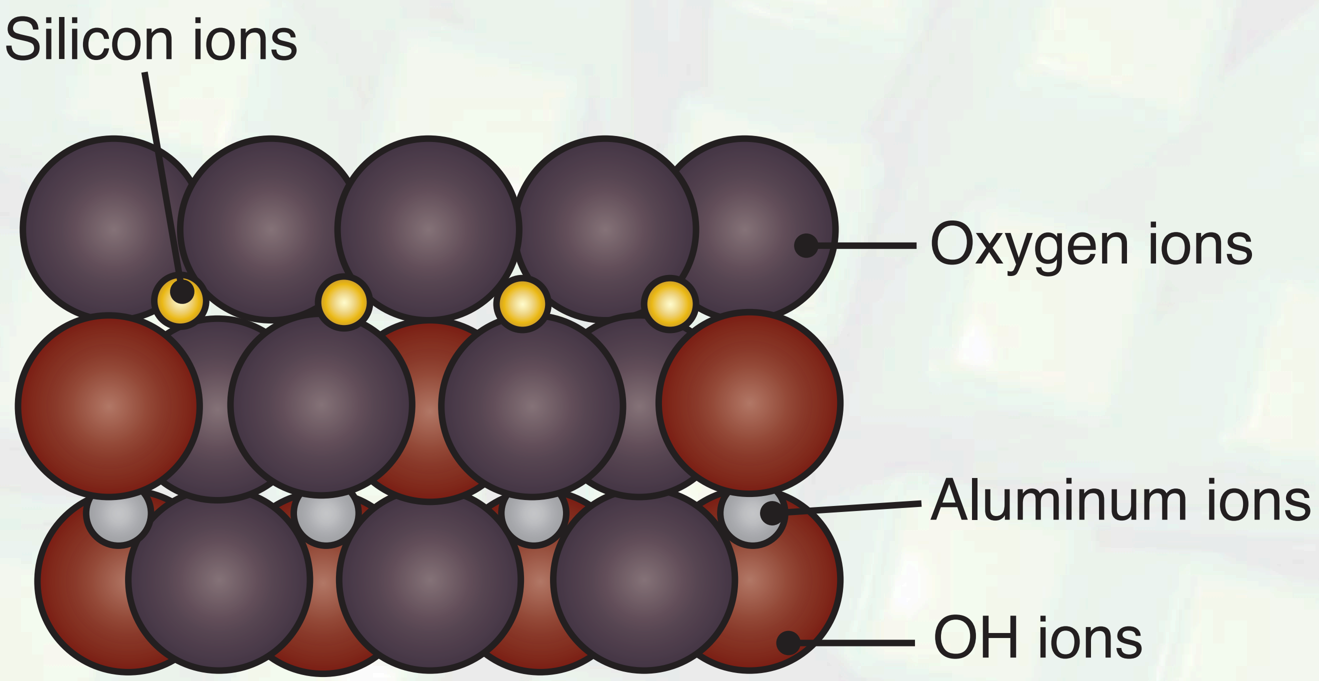

FIGURE 11.21 The crystal structure of kaolinite, commonly known as clay; compare with Figs. 3.2-3.4 for metals.

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Properties of Ceramics

Material	Symbol	Transverse Rupture Strength (MPa)	Compressive Strength (MPa)	Elastic Modulus (GPa)	Hardness (HK)	Poisson's Ratio (ν)	Density (kg/m^3)
Aluminum oxide	Al_2O_3	140–240	1000–2900	310–410	2000–3000	0.26	4000–4500
Cubic boron nitride	cBN	725	7000	850	4000–5000	–	3480
Diamond	–	1400	7000	830–1000	7000–8000	–	3500
Silica, fused	SiO_2	–	1300	70	550	0.25	–
Silicon carbide	SiC	100–750	700–3500	240–480	2100–3000	0.14	3100
Silicon nitride	Si_3N_4	480–600	–	300–310	2000–2500	0.24	3300
Titanium carbide	TiC	1400–1900	3100–3850	310–410	1800–3200	–	5500–5800
Tungsten carbide	WC	1030–2600	4100–5900	520–700	1800–2400	–	10,000–15,000
Partially stabilized zirconia	PSZ	620	–	200	1100	0.3	5800

Note: These properties vary widely, depending on the condition of the material.

TABLE 11.7 Approximate range of properties of various ceramics at room temperature.

Strength:

$$\mathrm{UTS} \approx \mathrm{UTS}_o e^{-nP}$$

Elastic modulus:

$$E \approx E_o(1 - 1.9P + 0.9P^2)$$

Thermal conductivity:

$$k = k_o(1 - P)$$

Temperature Effects

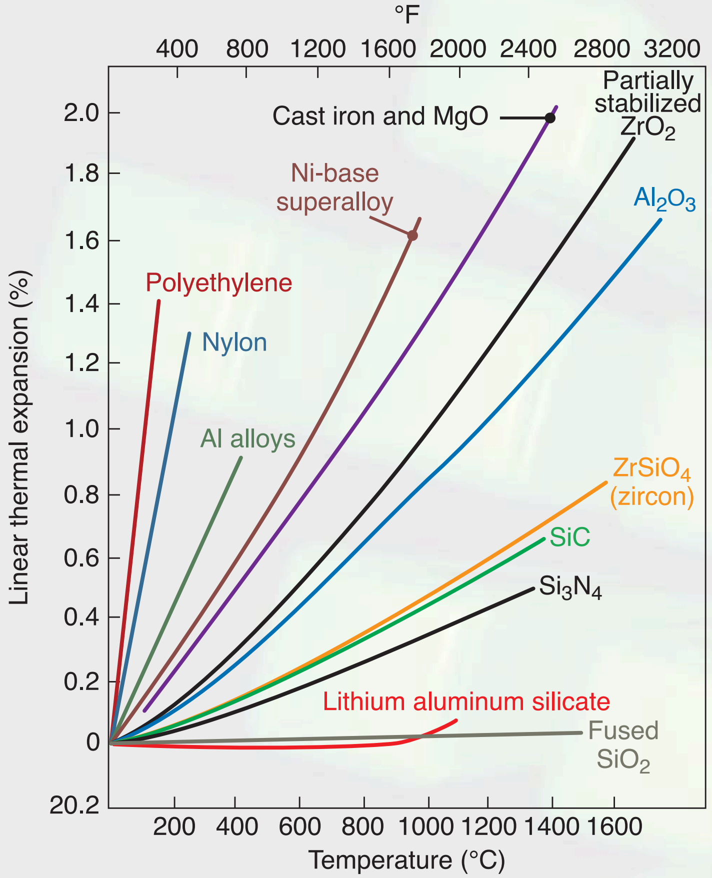

FIGURE 11.22 Effect of temperature on thermal expansion for several ceramics, metals, and plastics. Note that the expansions for cast iron and for partially stabilized zirconia (PSZ) are within about 20%.

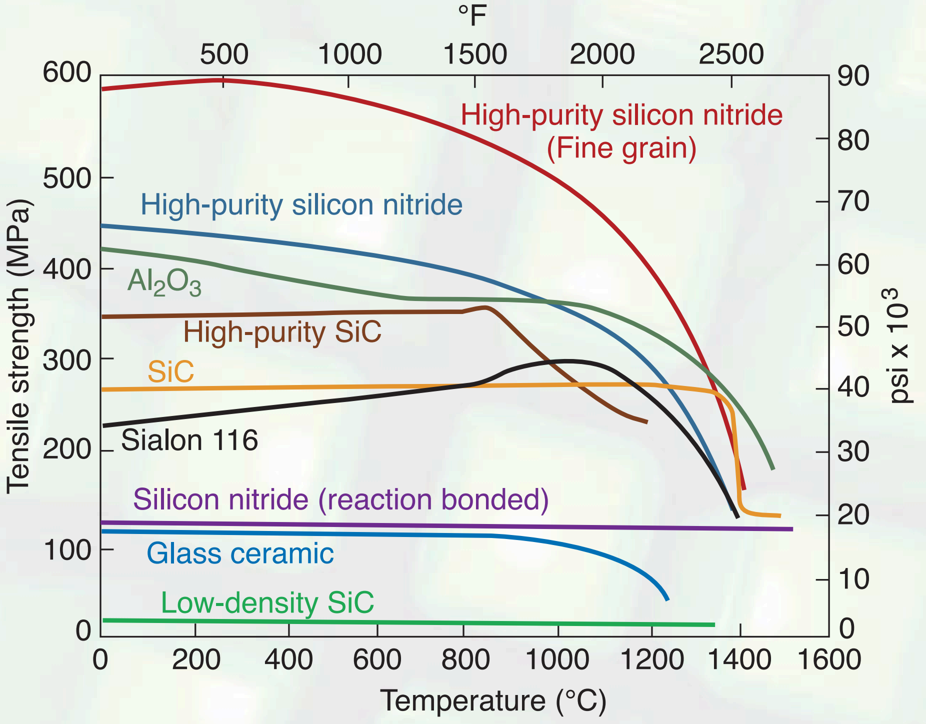

FIGURE 11.23 Effect of temperature on the strength of various engineering ceramics. Note that much of the strength is maintained at high temperatures; compare with Figs. 2.9 and 8.30.

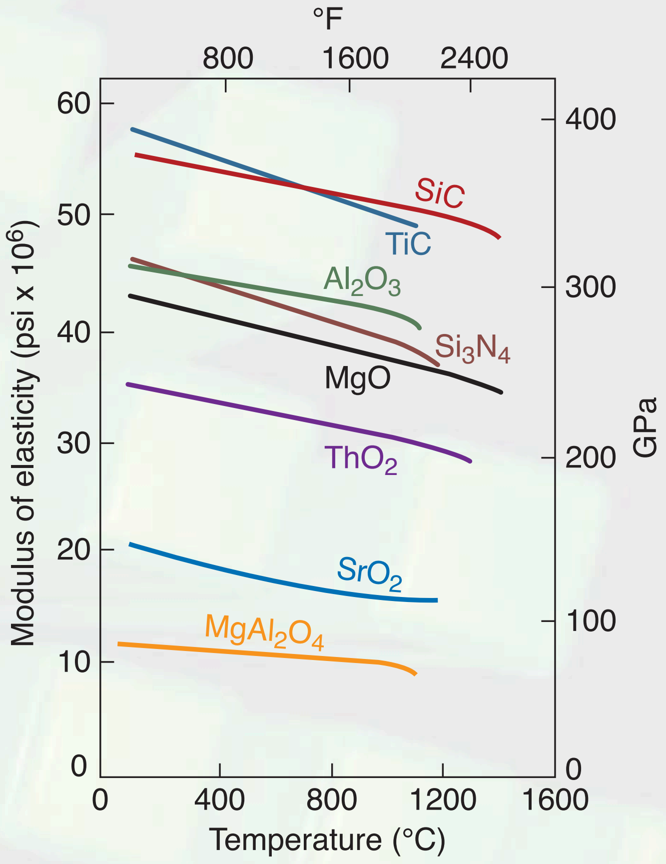

FIGURE 11.24 Effect of temperature on the modulus of elasticity for various ceramics; compare with Fig. 2.9. *Source:* After D.W. Richerson.

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Example: Ceramic Bearings


(a)
(b)

FIGURE 11.25 A selection of ceramic bearings and races. *Source:* Courtesy of Timken, Inc.

Processes & Particle Production

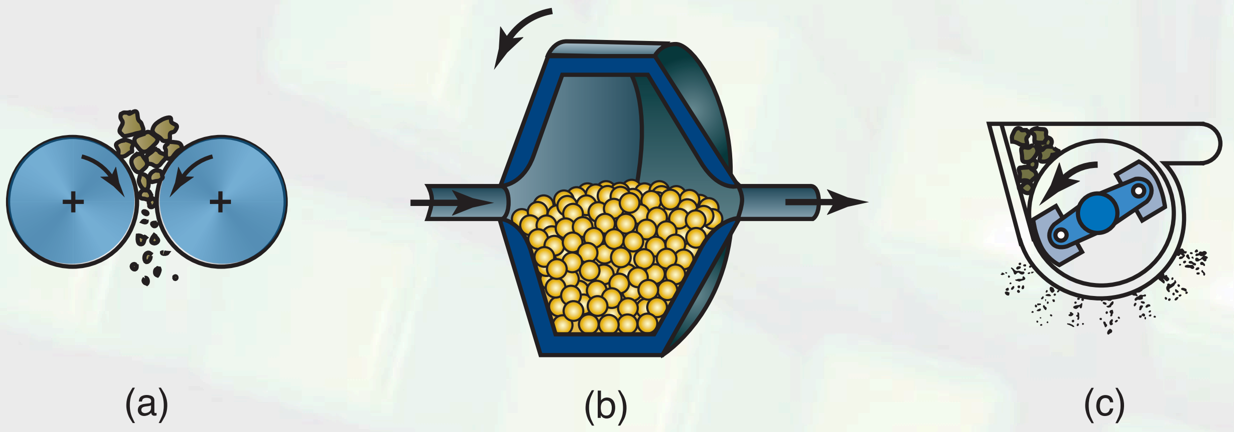

FIGURE 11.26 Methods of crushing ceramics to obtain very fine particles: (a) roll crushing, (b) ball milling, and (c) hammer milling.

TABLE 11.8 General characteristics of ceramics processing methods.

Process	Advantages	Limitations
Slip casting	Large parts; complex shapes; low equipment cost.	Low production rate; limited dimensional accuracy.
Extrusion	Hollow shapes and small diameters; high production rate.	Parts have constant cross-section; limited thickness.
Dry pressing	Close tolerances; high production rate with automation.	Density variation in parts with high length-to-diameter ratios; dies require high abrasive-wear resistance; equipment can be costly.
Wet pressing	Complex shapes; high production rate.	Limited part size and dimensional accuracy; tooling costs can be high.
Hot pressing	Strong, high-density parts.	Protective atmospheres required; die life can be short.
Isostatic pressing	Uniform density distribution.	Equipment can be costly.
Jiggering	High production rate with automation; low tooling cost.	Limited to axisymmetric parts; limited dimensional accuracy.
Injection molding	Complex shapes; high production rate.	Tooling costs can be high.

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Slip Casting

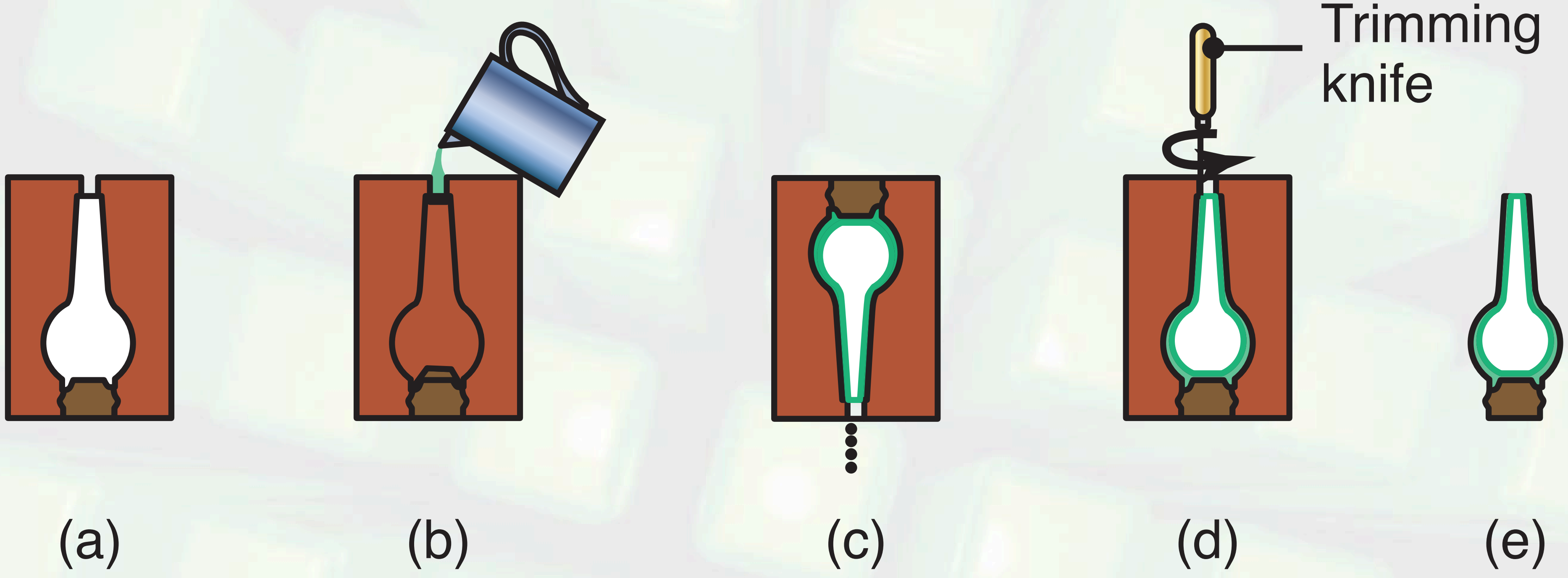

FIGURE 11.27 Sequence of operations in slip casting a ceramic part. After the slip has been poured, the part is dried and fired in an oven to give it strength and hardness. The step in (d) is a trimming operation. *Source:* After F.H. Norton.

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Doctor-Blade Process

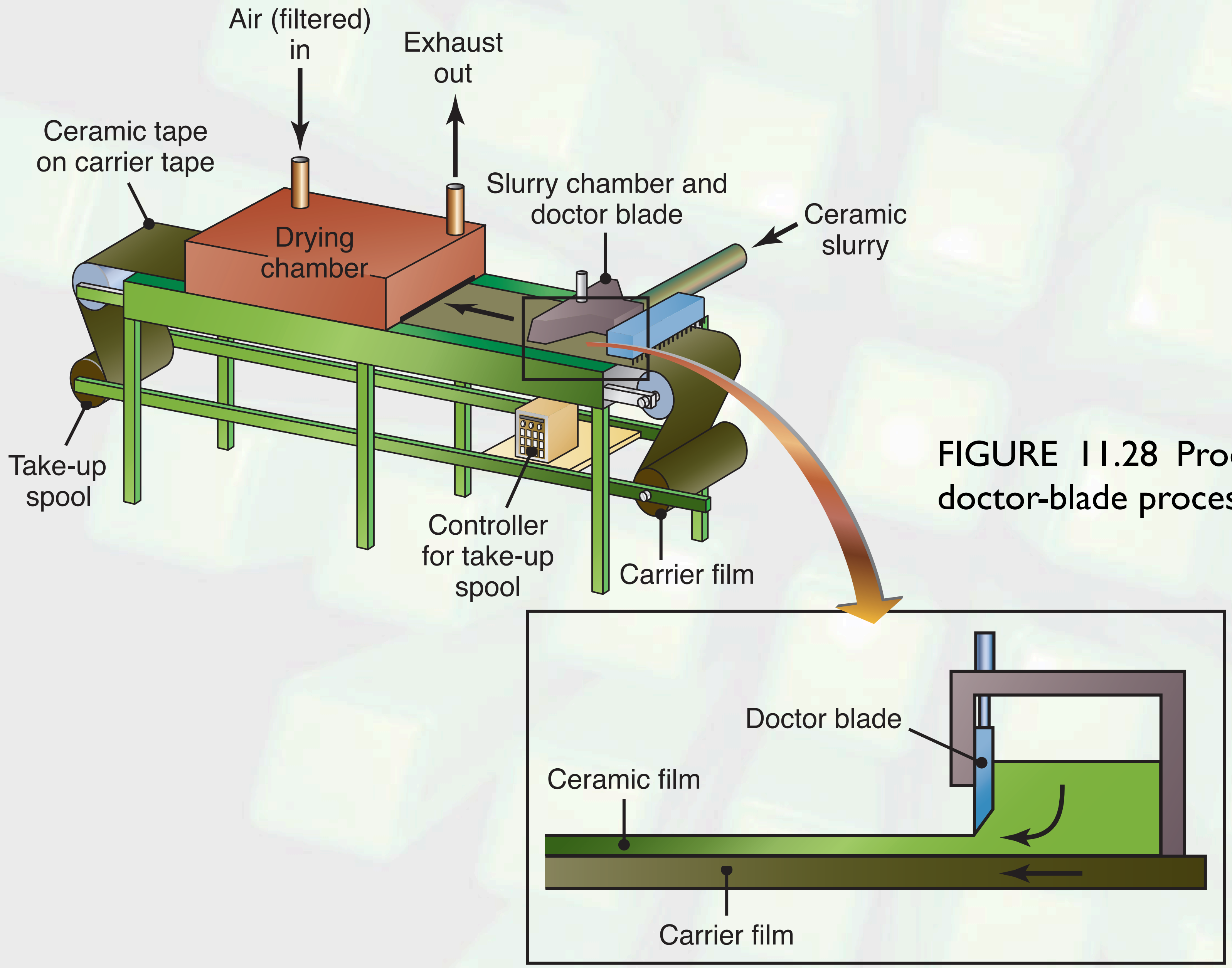

FIGURE 11.28 Production of ceramic sheets through the doctor-blade process.

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Density Variation in Compacts

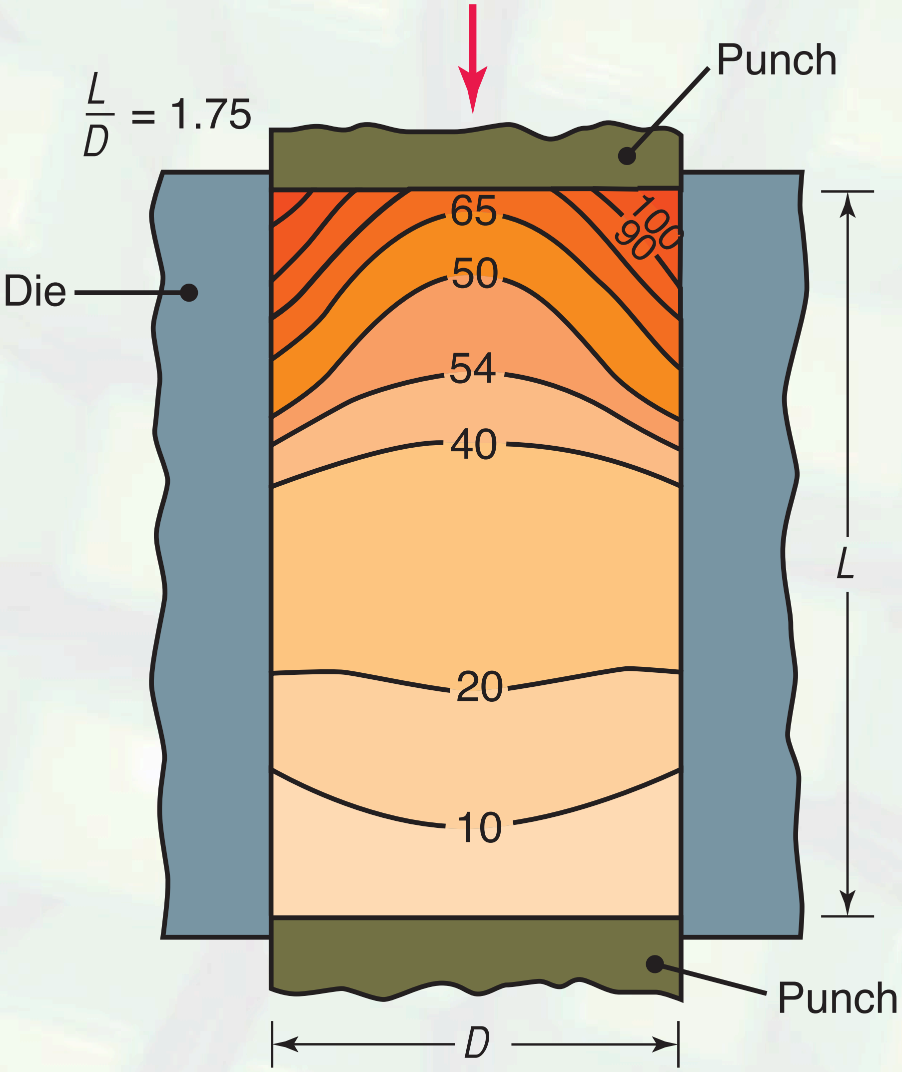

FIGURE 11.29 Density variation in pressed compacts in a single-action press. Note that the variation increases with increasing *L*/*D* ratio; see also Fig. 11.7e. *Source:* After W.D. Kingery.

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Extruding and Joggering

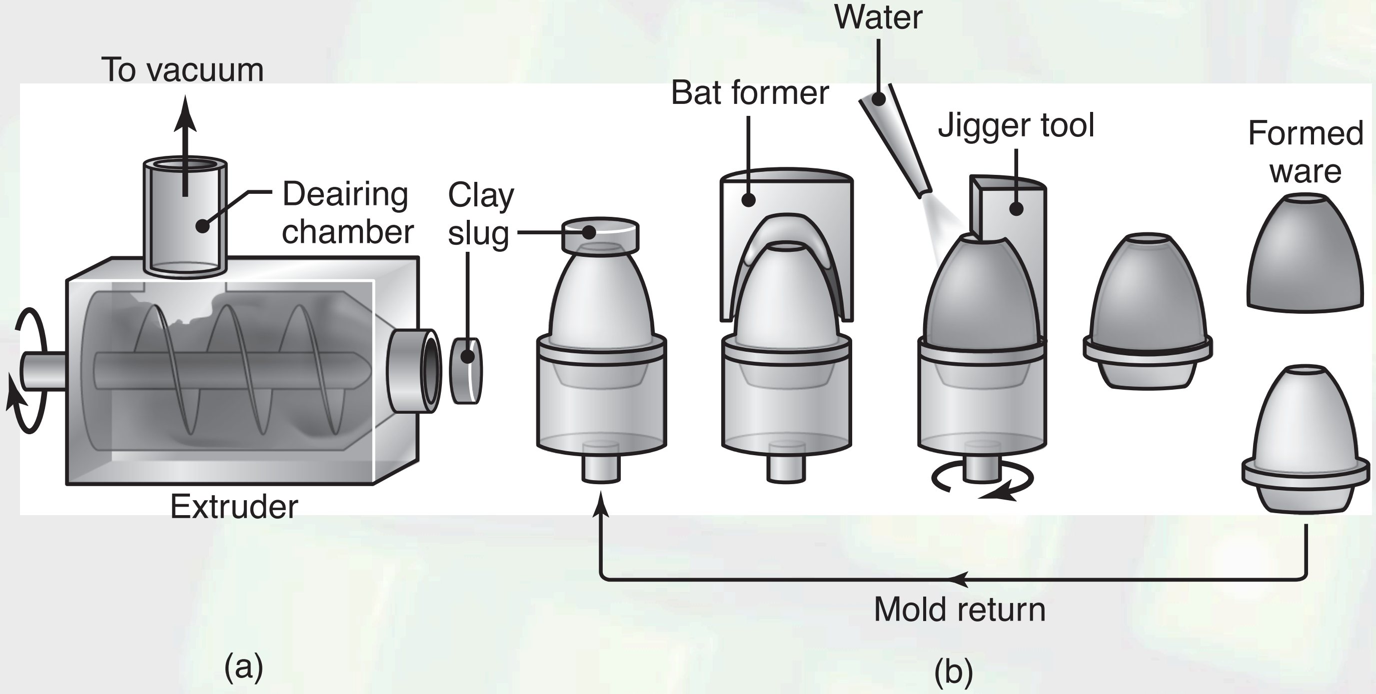

FIGURE 11.30 (a) Extruding and (b) jiggering operations in shaping ceramics. *Source:* After R.F. Stoops.

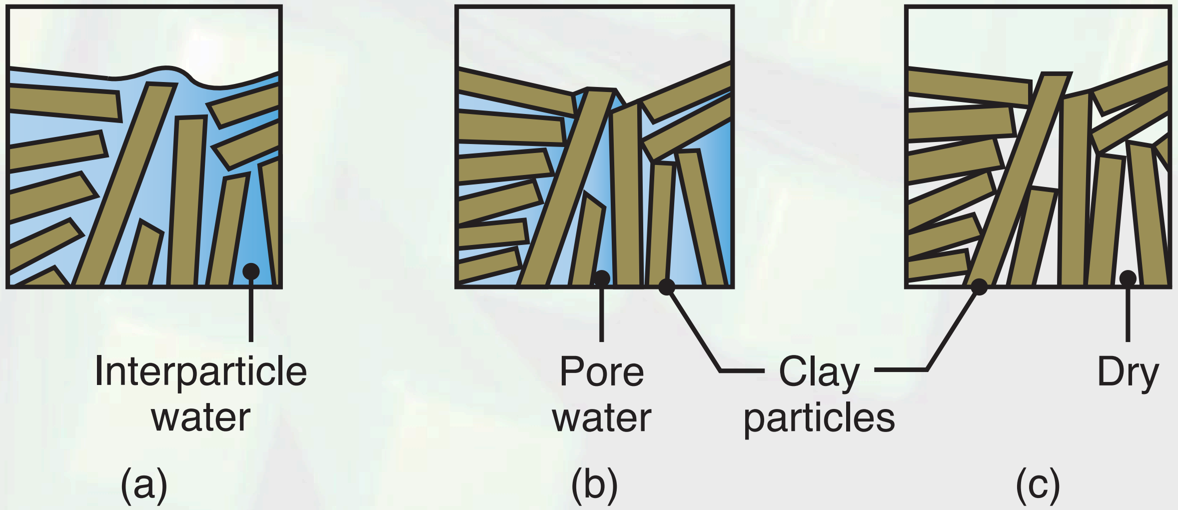

FIGURE 11.31 Shrinkage of wet clay, caused by removal of water during drying; shrinkage may be as much as 20% by volume. *Source:* After F.H. Norton.

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Glasses

	Soda-lime Glass	Lead Glass	Borosilicate Glass	Fused	96% Silica Glass
Density	High	Highest	Medium	Low	Lowest
Strength	Low	Low	Moderate	High	Highest
Resistance to thermal shock	Low	Low	Good	Better	Best
Electrical resistivity	Moderate	Best	Good	Good	Good
Hot workability	Good	Best	Fair	Poor	Poorest
Heat treatability	Good	Good	Poor	None	None
Chemicals resistance	Poor	Fair	Good	Better	Best
Impact abrasion resistance	Fair	Poor	Good	Good	Best
Ultraviolet-light transmission	Poor	Poor	Fair	Good	Good
Relative cost	Lowest	Low	Medium	High	Highest

TABLE 11.9 General characteristics of various types of glasses.

Glass Sheet & Tubing

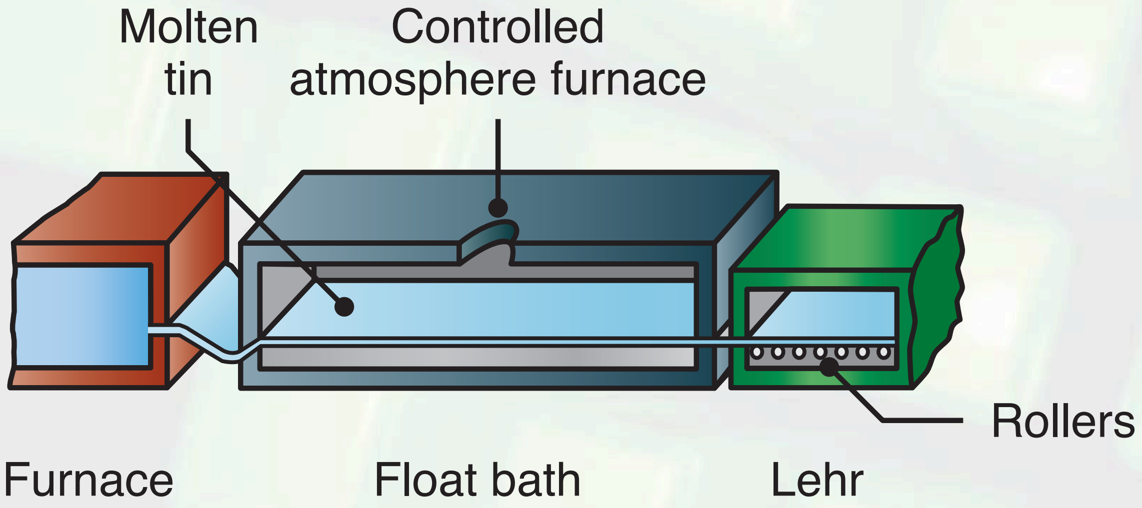

FIGURE 11.32 The float method of forming sheet glass. *Source:* Corning Glass Works.

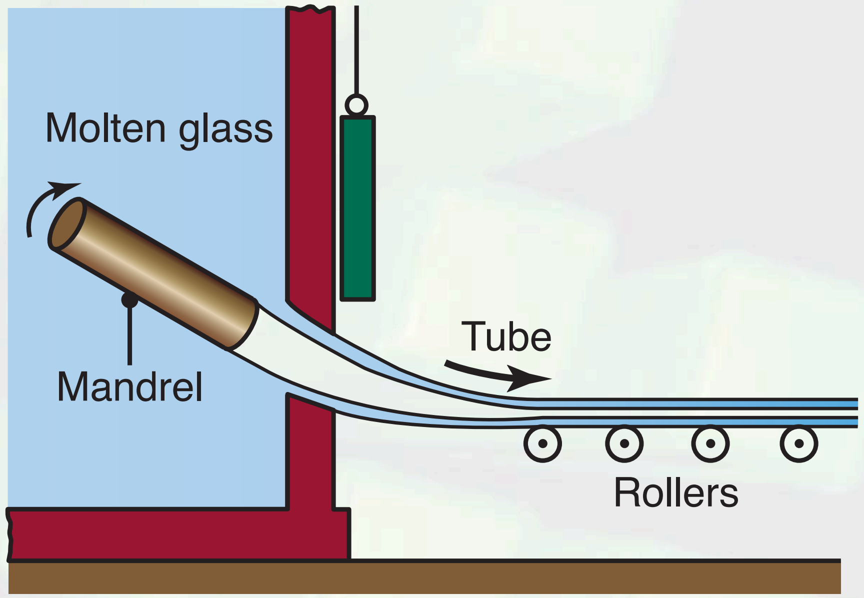

FIGURE 11.33 Continuous manufacturing process for glass tubing. Air is blown through the mandrel to keep the tube from collapsing. *Source:* Corning Glass Works.

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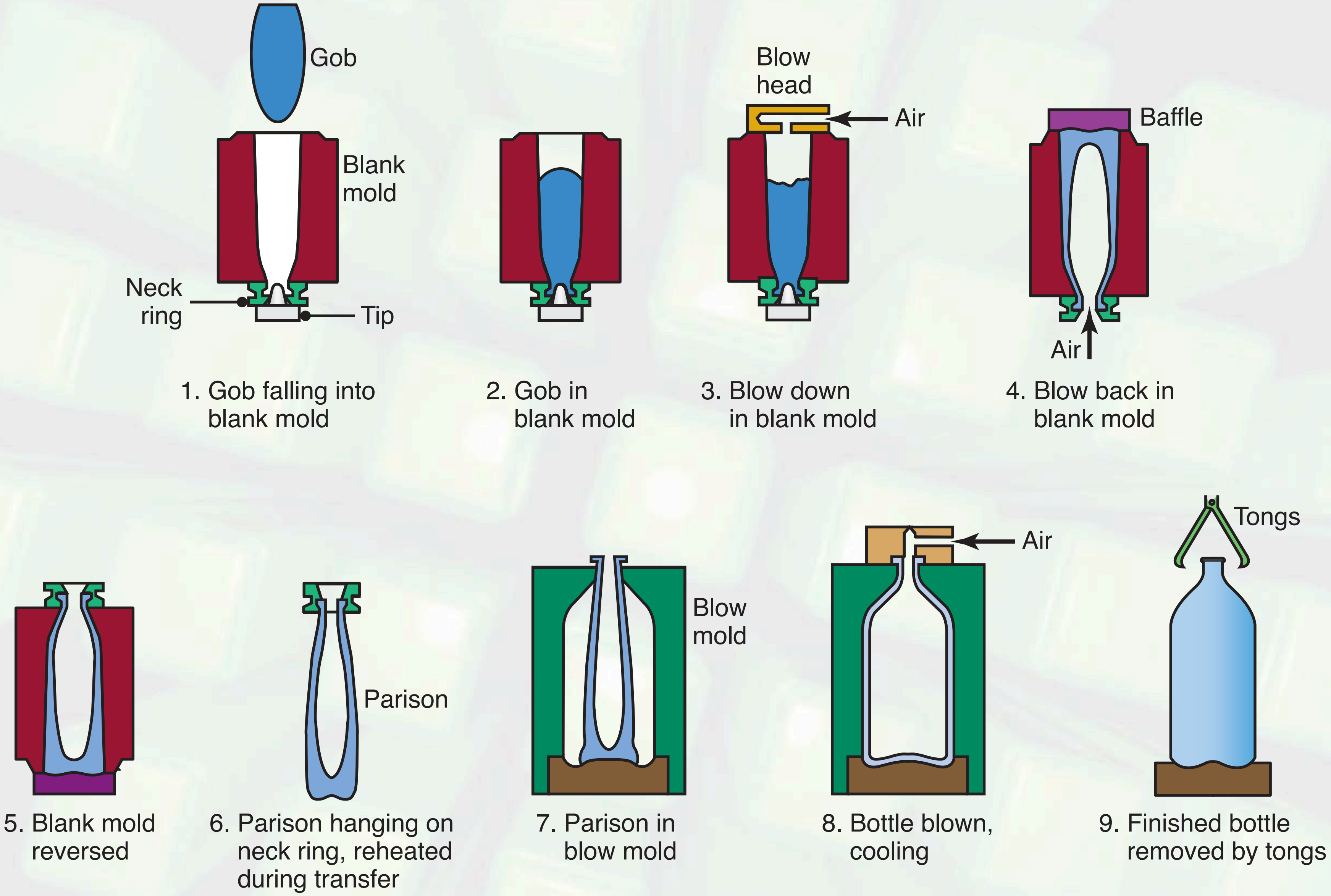
Glass Bottles



1. Gob falling into blank mold
2. Gob in blank mold
3. Blow down in blank mold
4. Blow back in blank mold
5. Blank mold reversed
6. Parison hanging on neck ring, reheated during transfer
7. Parison in blow mold
8. Bottle blown, cooling
9. Finished bottle removed by tongs

FIGURE 11.34 Stages in manufacturing a common glass bottle. *Source:* After F.H. Norton.

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Glass Pressing

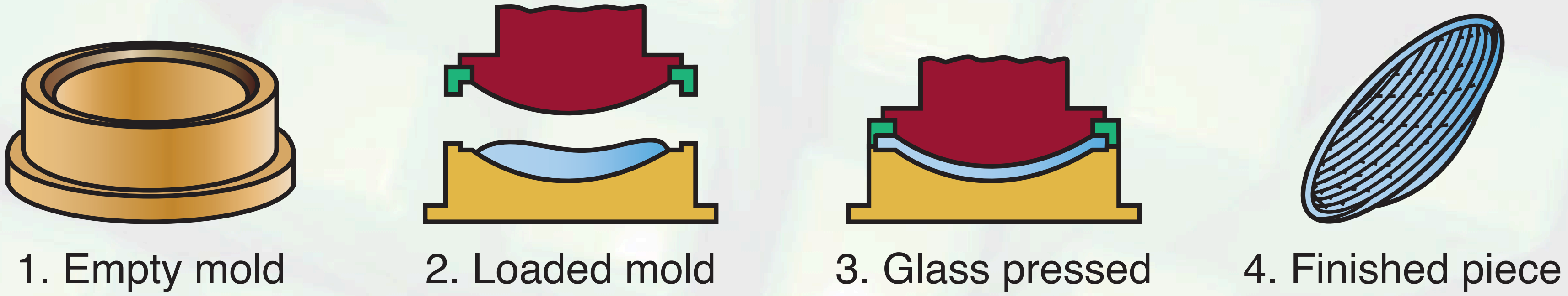

FIGURE 11.35 Manufacturing steps for a glass item by pressing in a mold. *Source:* Corning Glass Works.

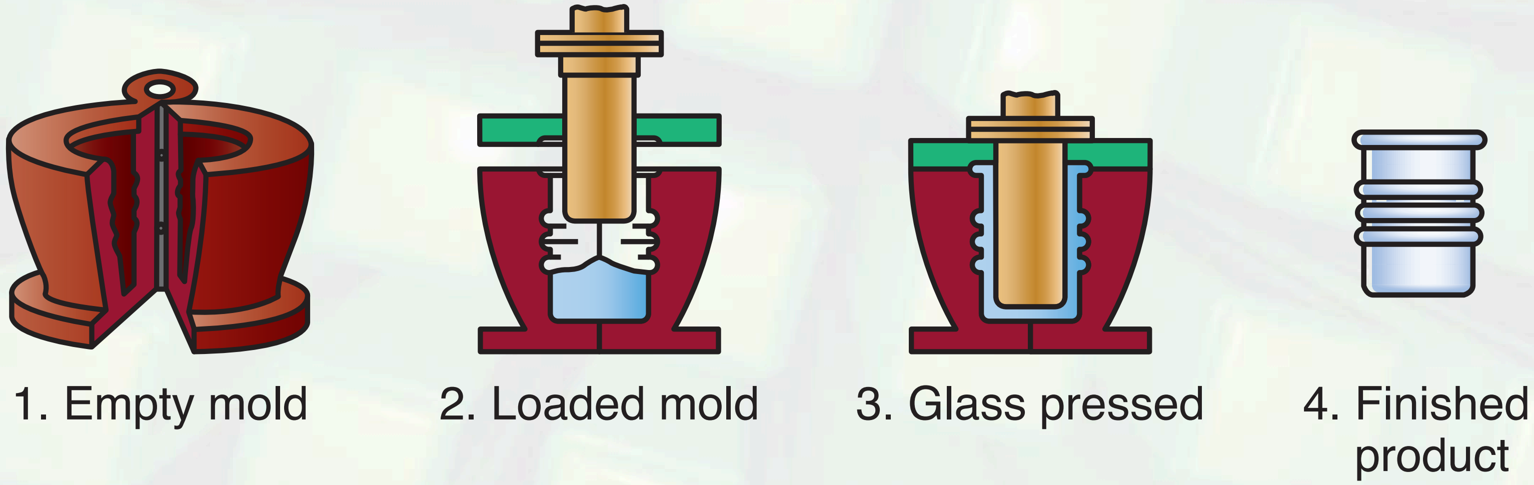

FIGURE 11.36 Pressing glass in a split mold. Note that the use of a split mold is essential to be able to remove the part; see also Figs. 10.34, 10.35, and 10.36. *Source:* After E.B. Shand.

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Residual Stresses in Glass

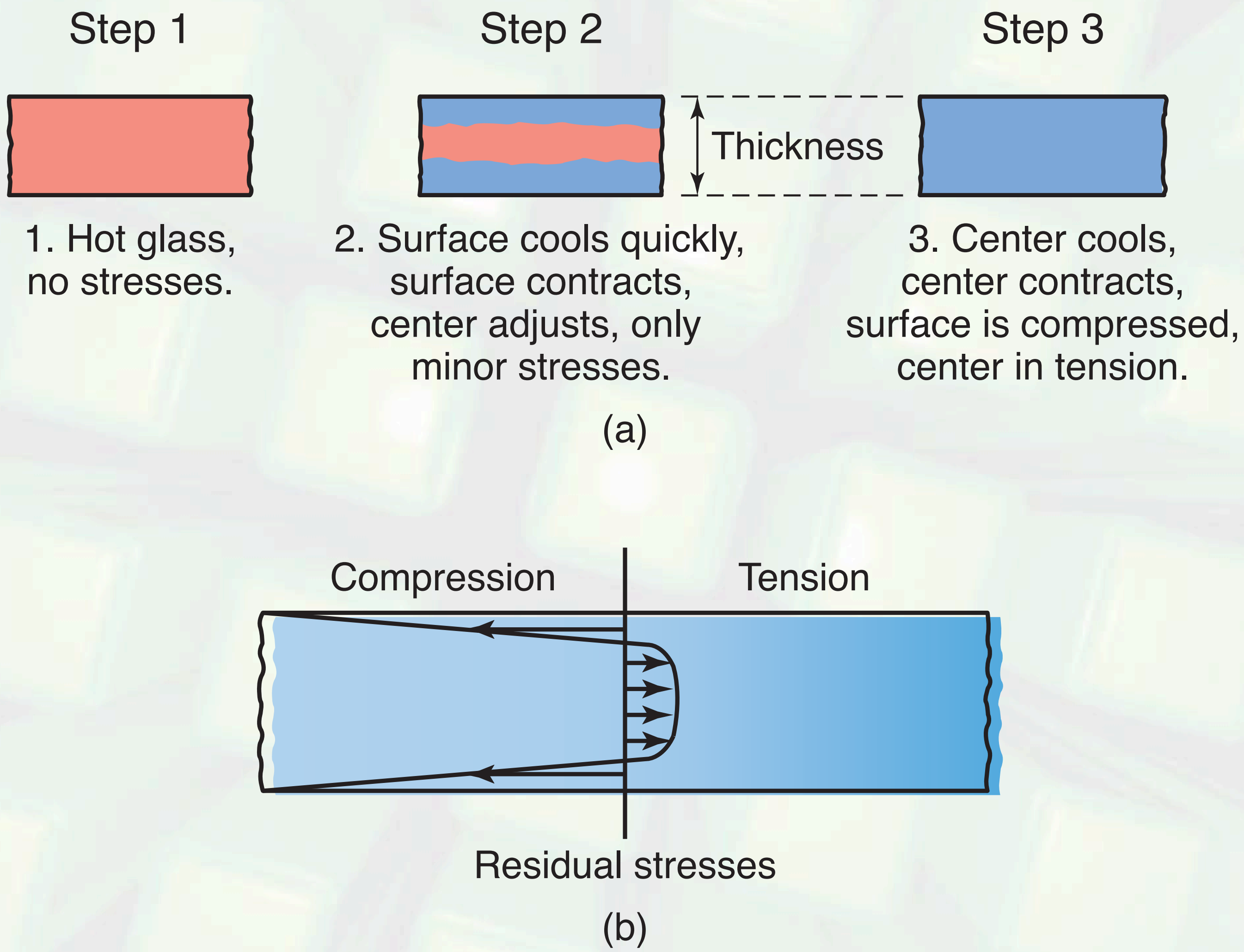

FIGURE 11.37 Stages in the development of residual stresses in tempered glass plate.

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Metal-Matrix Composites

Fiber	Matrix	Typical Applications
Graphite	Aluminum	Satellite, missile, and helicopter structures
	Magnesium	Space and satellite structures
	Lead	Storage-battery plates
	Copper	Electrical contacts and bearings
Boron	Aluminum	Compressor blades and structural supports
	Magnesium	Antenna structures
	Titanium	Jet-engine fan blades
Alumina	Aluminum	Superconductor restraints in fusion power reactors
	Lead	Storage-battery plates
	Magnesium	Helicopter transmission structures
Silicon carbide	Aluminum, titanium	High-temperature structures
	Superalloy (cobalt base)	High-temperature engine components
Molybdenum, tungsten	Superalloy	High-temperature engine components

TABLE 11.10 Metal-matrix composite materials and typical applications.

Example: Brake Caliper

FIGURE 11.38 Aluminum-matrix composite brake caliper, using nanocrystalline alumina-fiber reinforcement. *Source:* Courtesy of 3M Specialty Materials Division.

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Powder-in-Tube Process

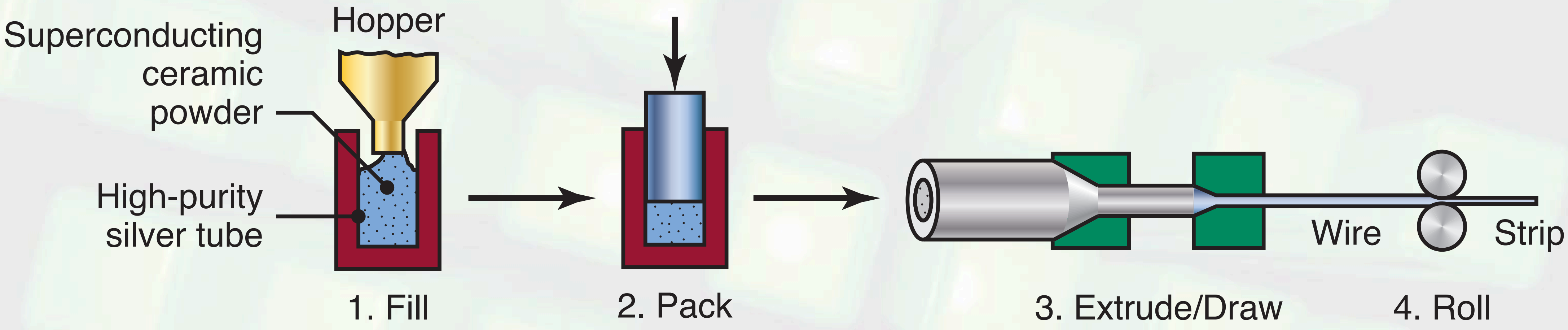

FIGURE 11.39 Schematic illustration of the steps involved in the powder-in-tube process. *Source:* Courtesy of Concurrent Technologies Corporation.

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Case Study: Engine Valves

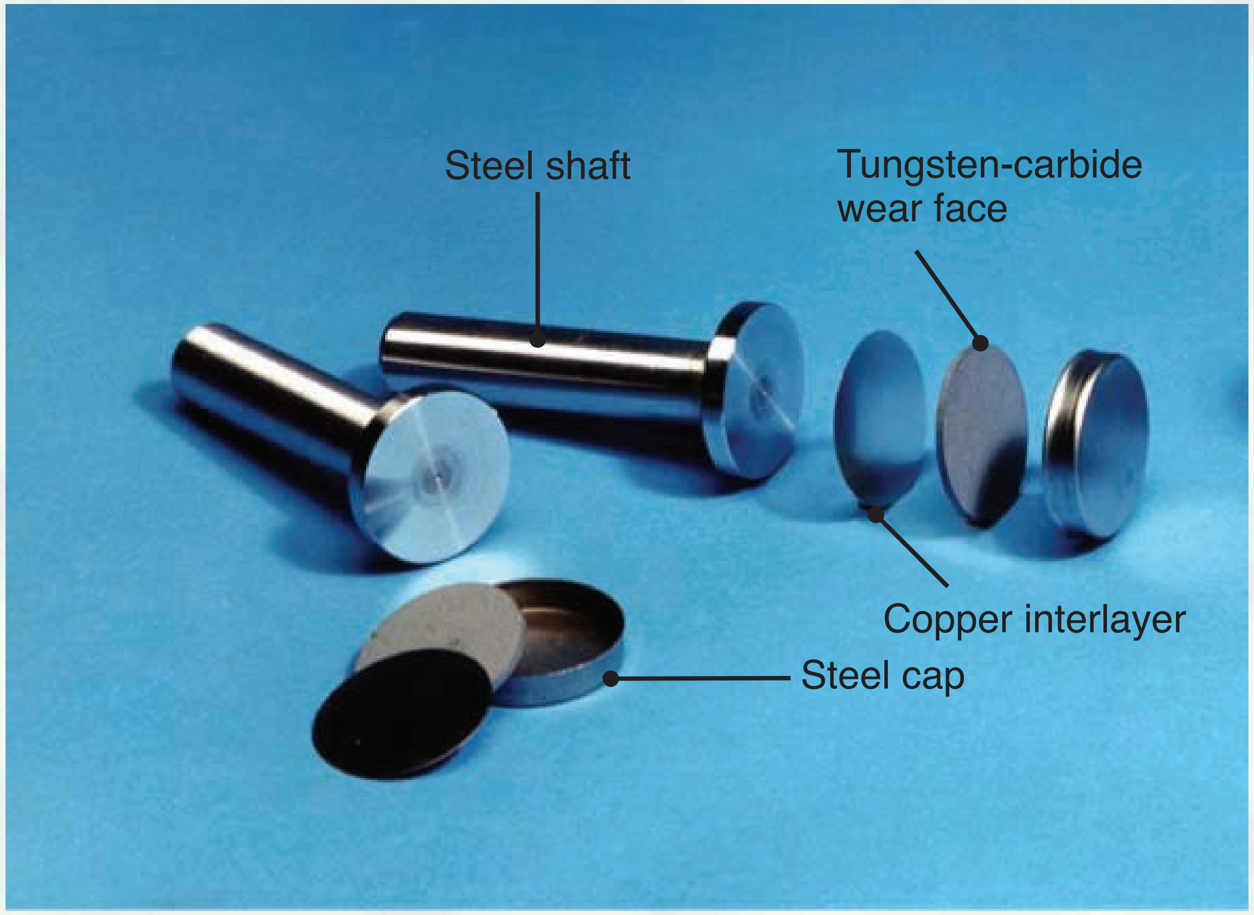

FIGURE 11.40 A valve lifter for heavy-duty diesel engines, produced from a hot-isostatically-pressed carbide cap on a steel shaft. *Source:* Courtesy of Metal Powder Industries Federation and Bodycote, Inc.