Processing of Powder Metals, Ceramics, Glass, and Superconductors

Typical Applications for Metal Powders

TABLE 17.1

Application	**Metals**	**Uses**
Abrasives	Fe, Sn, Zn	Cleaning, abrasive wheels
Aerospace	Al, Be, Nb	Jet engines, heat shields
Automotive	Cu, Fe, W	Valve inserts, bushings, gears
Electrical/electronic	Ag, Au, Mo	Contacts, diode heat sinks
Heat treating	Mo, Pt, W	Furnace elements, thermocouples
Joining	Cu, Fe, Sn	Solders, electrodes
Lubrication	Cu, Fe, Zn	Greases, abradable seals
Magnetic	Co, Fe, Ni	Relays, magnets
Manufacturing	Cu, Mn, W	Dies, tools, bearings
Medical/dental	Ag, Au, W	Implants, amalgams
Metallurgical	Al, Ce, Si	Metal recovery, alloying
Nuclear	Be, Ni, W	Shielding, filters, reflectors
Office equipment	Al, Fe, Ti	Electrostatic copiers, cams

Source: R. M. German.

Powder-Metallurgy

(a)

(b)

(c)

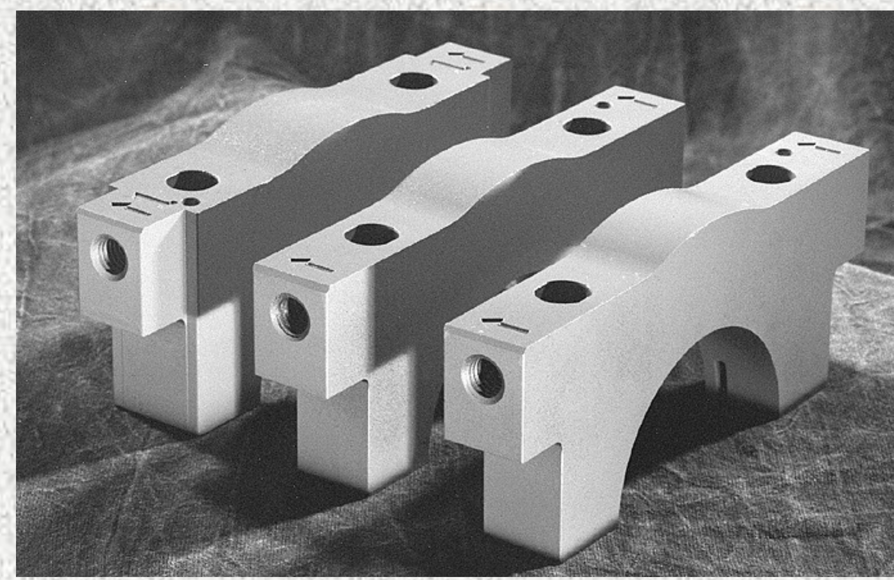


Figure 17.1 (a) Examples of typical parts made by powder-metallurgy processes. (b) Upper trip lever for a commercial irrigation sprinkler, made by P/M. This part is made of unleaded brass alloy; it replaces a die-cast part, with a 60% savings. *Source*: Reproduced with permission from *Success Stories on P/M Parts*, 1998. Metal Powder Industries Federation, Princeton, New Jersey, 1998. (c) Main-bearing powder metal caps for 3.8 and 3.1 liter General Motors automotive engines. *Source*: Courtesy of Zenith Sintered Products, Inc., Milwaukee, Wisconsin.

Powder Metallurgy Video

Powder Metallurgy – basics & applications

Powder metallurgy– science of producing metal powders and making finished/semifinished objects from mixed or alloyed powders with or without the addition of nonmetallic constituents

Steps in powder metallurgy:

- Powder production,
- Compaction
- Sintering
- Secondary operations

Making Powder-Metallurgy Parts

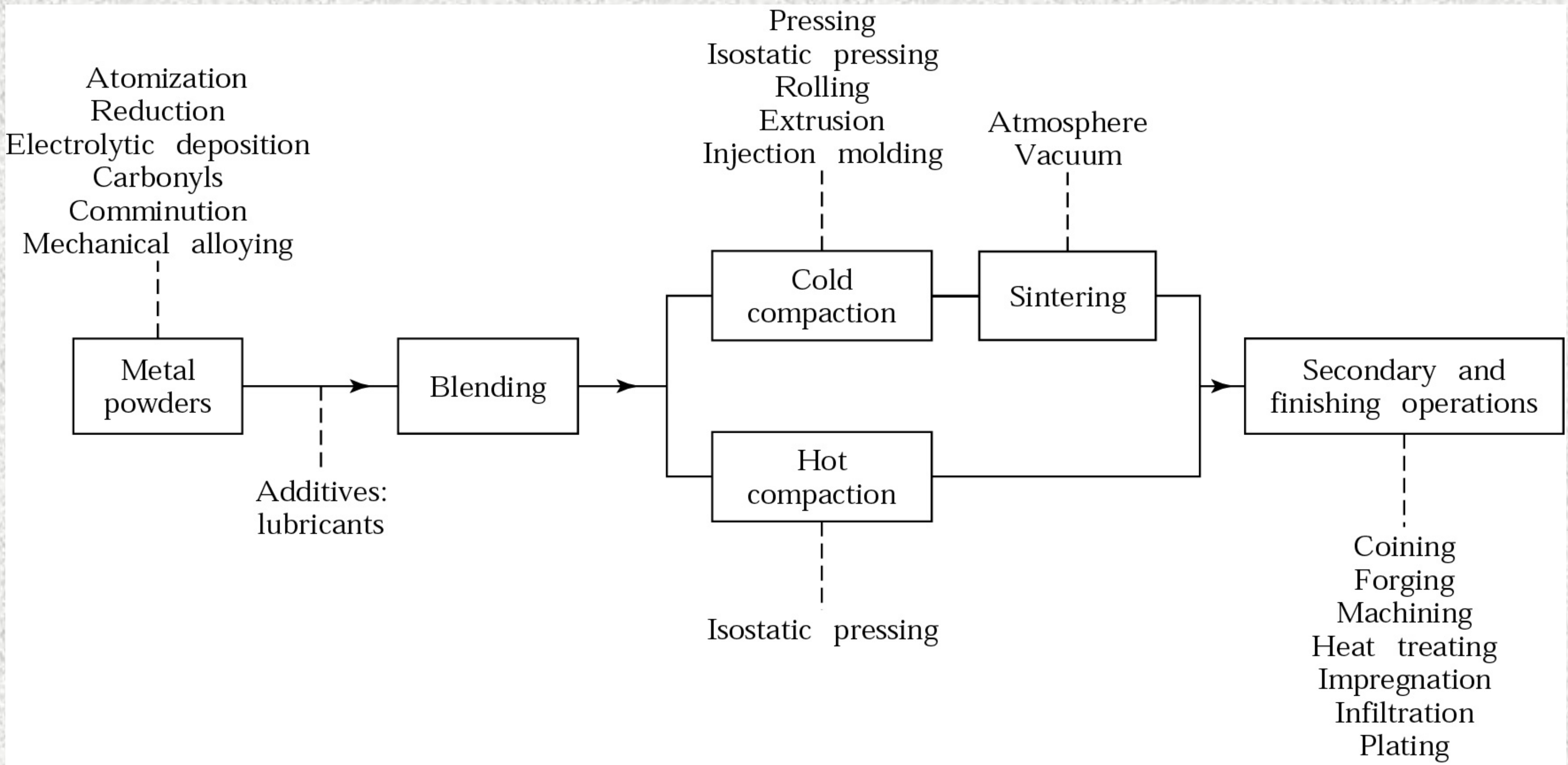


Figure 17.2 Outline of processes and operations involved in making powder-metallurgy parts.

Powder Processing

Raw materials => Powder: pure elements or pre-alloyed powders

Methods for making powders

- Atomization: Produces powders of both ferrous and non-ferrous powders like stainless steel, superalloys, Ti alloy powders;
- Reduction of compounds: Production of iron, Cu, tungsten, molybdenum
- Electrolysis: for making Cu, iron, silver powders
- Powders along with additives are mixed using mixers

Lubricants are added prior to mixing to facilitate easy ejection of compact and to minimize wear of tools; Waxes, metallic stearates, graphite etc.

Powder characterization – size, flow, density, compressibility tests

Powder Production

- Compaction: compaction is performed using dies machined to close tolerances
- Dies are made of cemented carbide, die/tool steel; pressed using hydraulic or mechanical press
- The basic purpose of compaction is to obtain a green compact with sufficient strength to withstand further handling operations
- The green compact is then taken for sintering, hot extrusion, hot pressing, hot isostatic pressing => consolidation at high temperatures

Sintering

- Performed at controlled atmosphere to bond atoms metallurgically; Bonding occurs by diffusion of atoms; done at 70% of abs. melting point of materials.,
- It serves to consolidate the mechanically bonded powders into a coherent body having desired on service behavior
- Densification occurs during the process and improvement in physical and mechanical properties are seen
- Furnaces – mesh belt furnaces (up to 1200C), walking beam, pusher type furnace, batch type furnaces are also used
- Protective atmosphere: Nitrogen (widely used)

Particle Shapes in Metal Powders

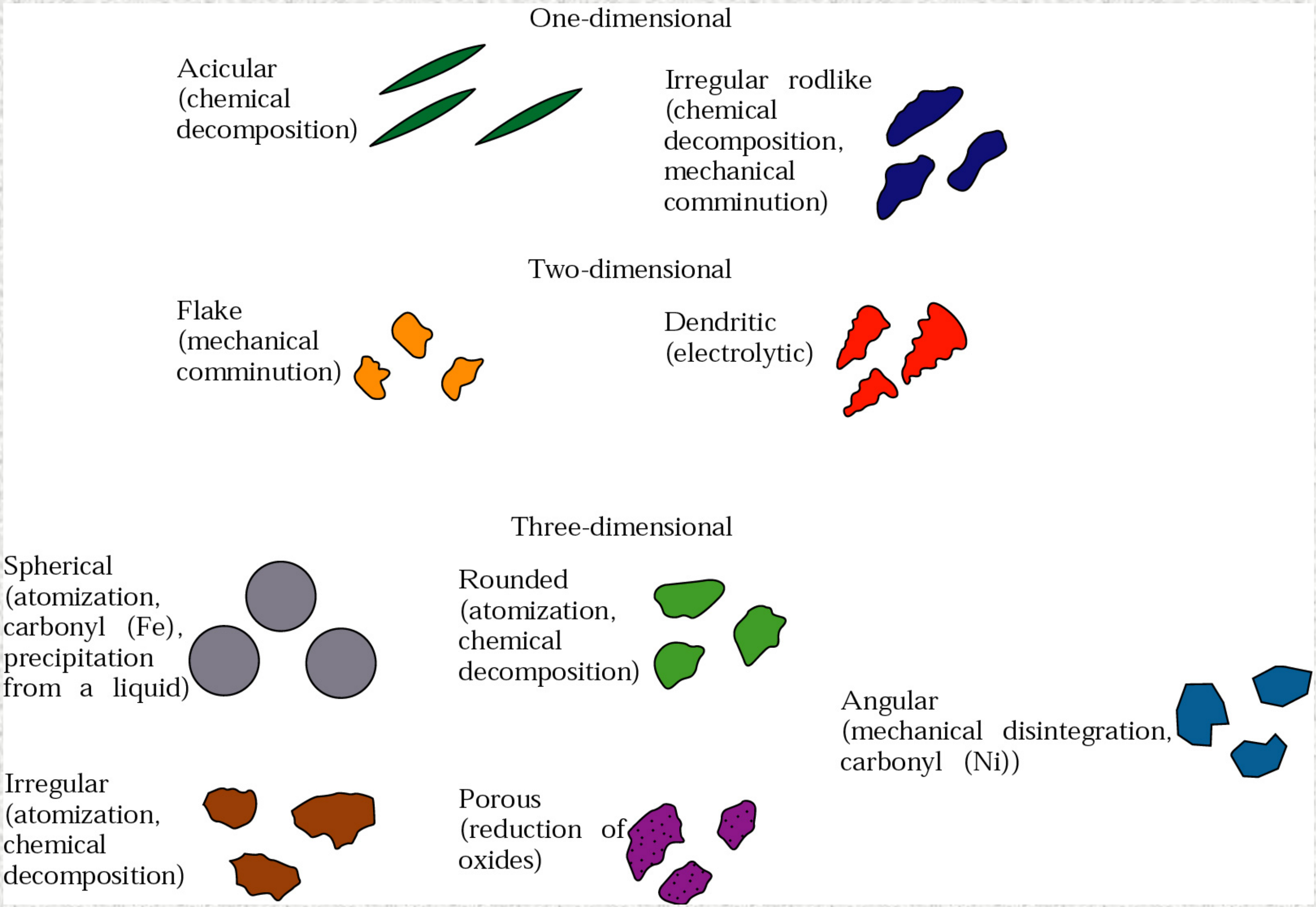


Figure 17.3 Particle shapes in metal powders, and the processes by which they are produced. Iron powders are produced by many of these processes.

Powder Particles

(a) (b)

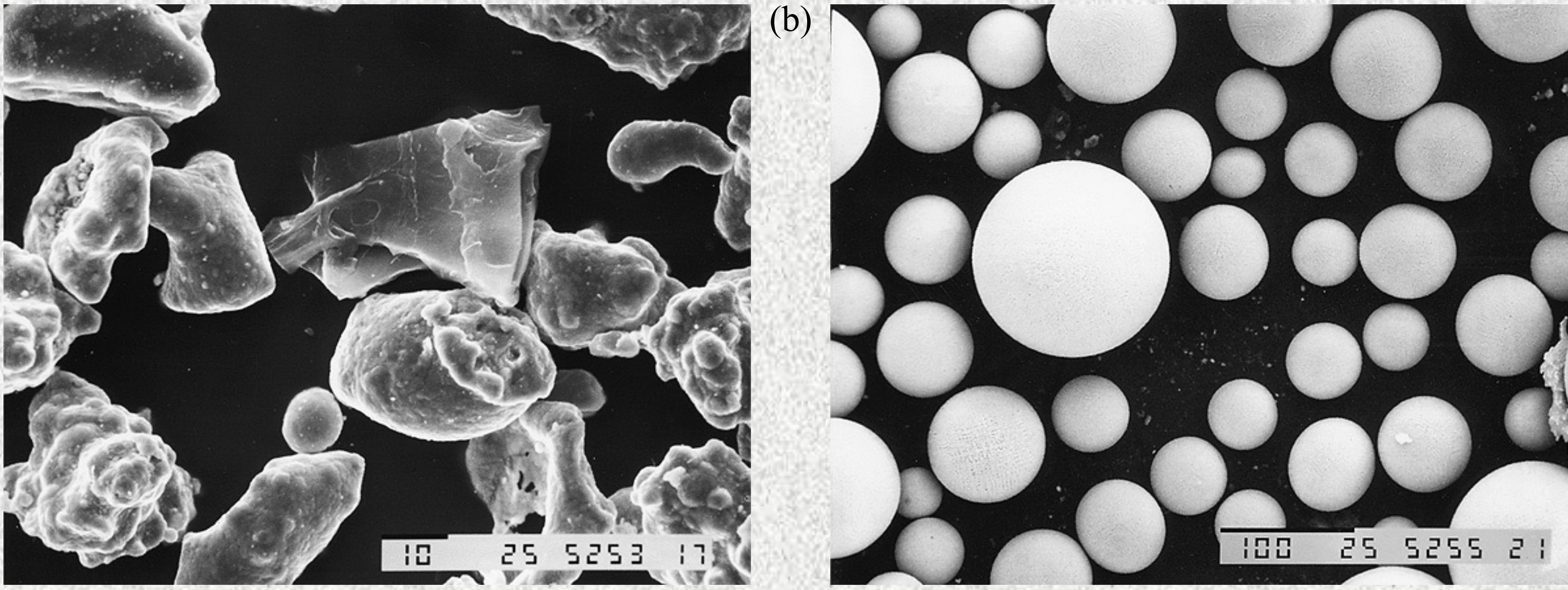


Figure 17.4 (a) Scanning-electron-microscopy photograph of iron-powder particles made by atomization. (b) Nickel-based superalloy (Udimet 700) powder particles made by the rotating electrode process; see Fig. 17.5b. *Source*: Courtesy of P. G. Nash, Illinois Institute of Technology, Chicago.

Atomization and Mechanical Comminution

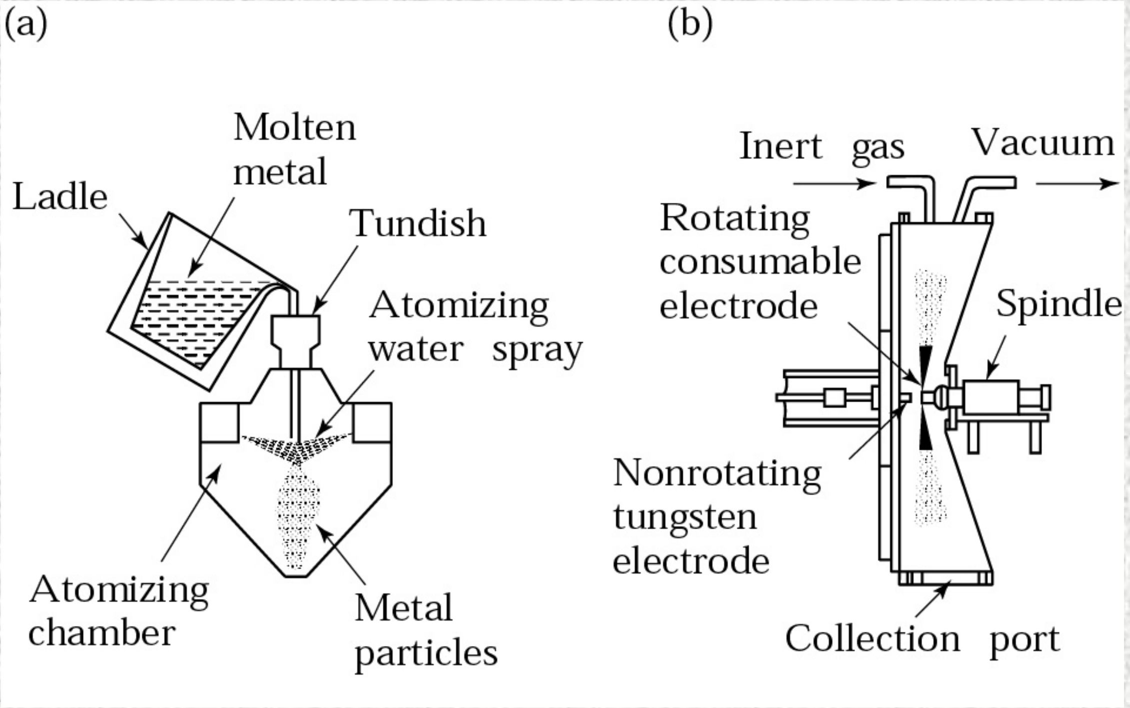


Figure 17.5 Methods of metal-powder production by atomization; (a) melt atomization; (b) atomization with a rotating consumable electrode.

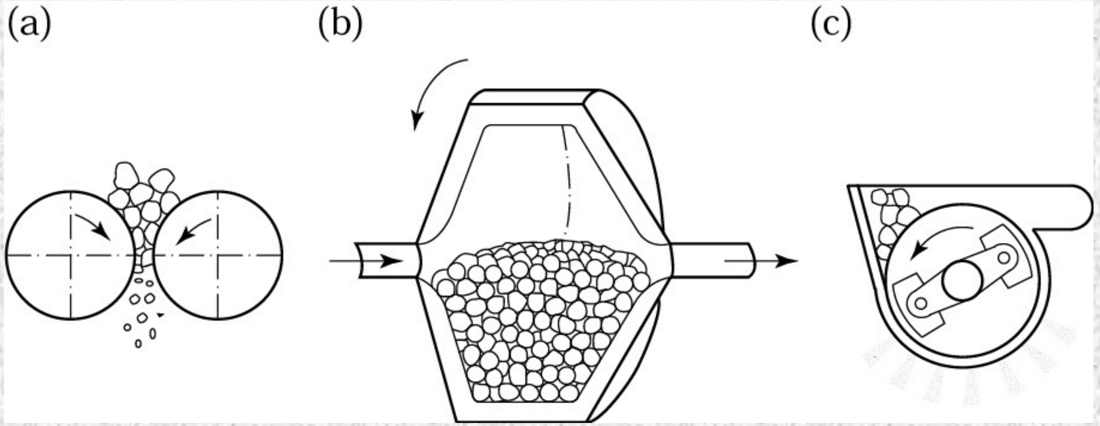


Figure 17.6 Methods of mechanical comminution, to obtain fine particles: (a) roll crushing, (b) ball mill, and (c) hammer milling.

Geometries of Powders

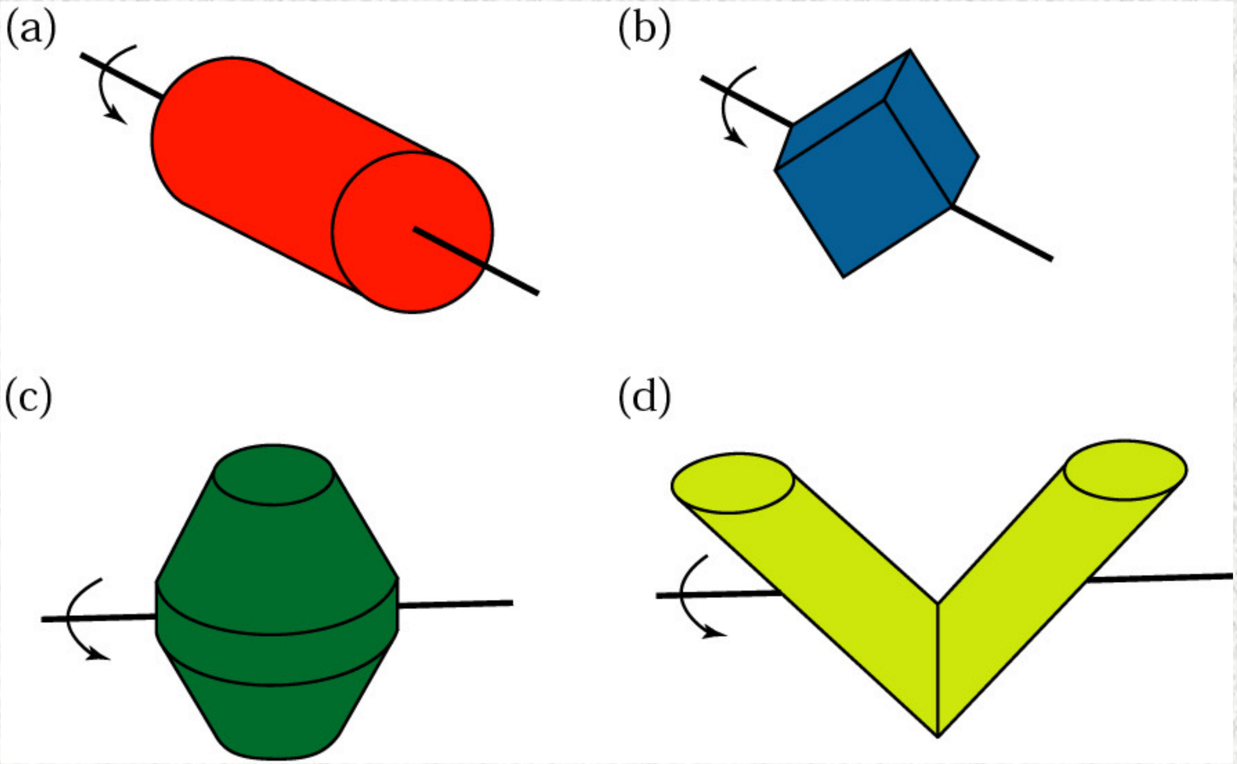


Figure 17.7 Some common equipment geometries for mixing or blending powders: (a) cylindrical, (b) rotating cube, (c) double cone, and (d) twin shell. *Source*: Reprinted with permission from R. M. German, *Powder Metallurgy Science*. Princeton, NJ; Metal Powder Industries Federation, 1984.

Compaction

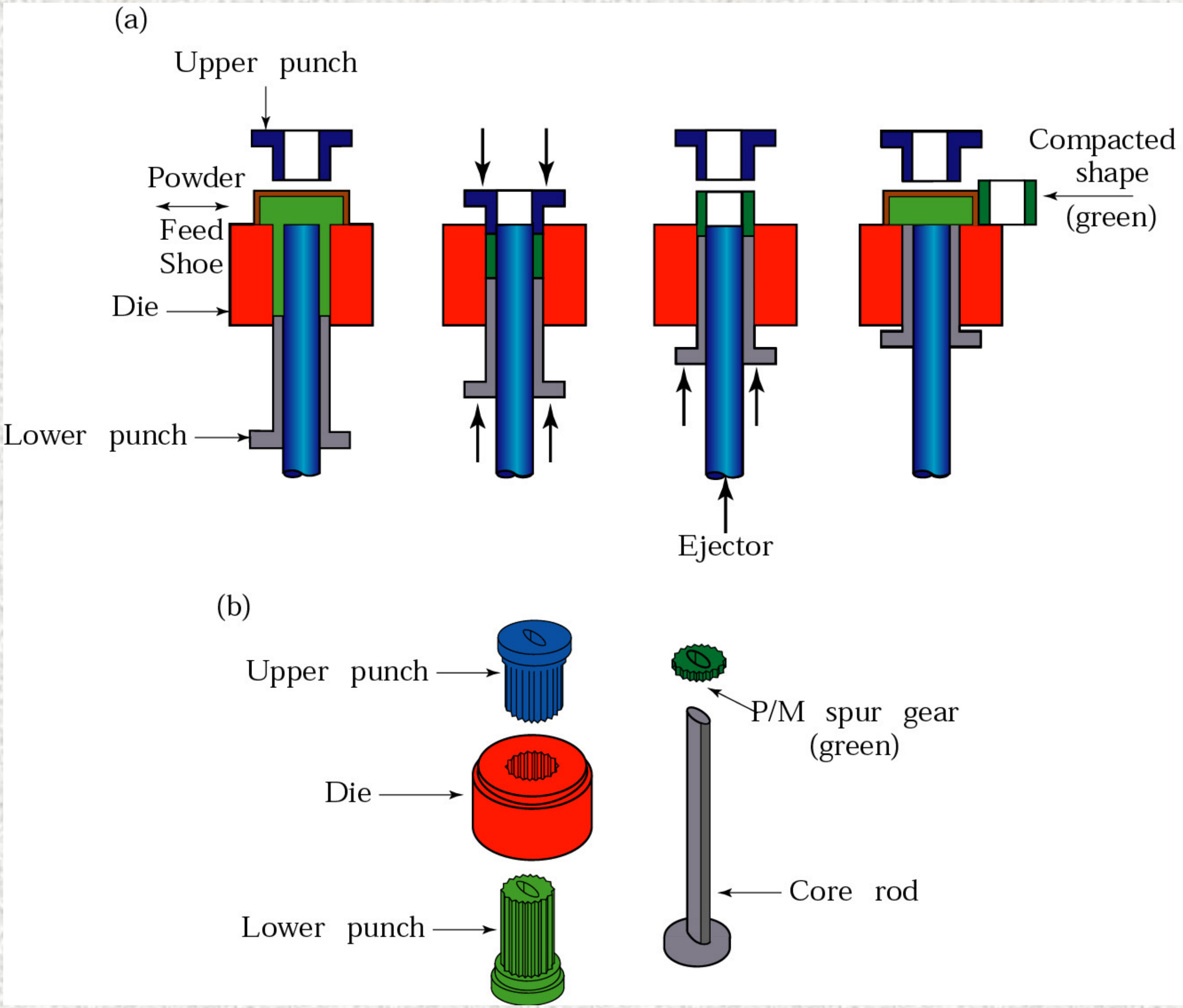
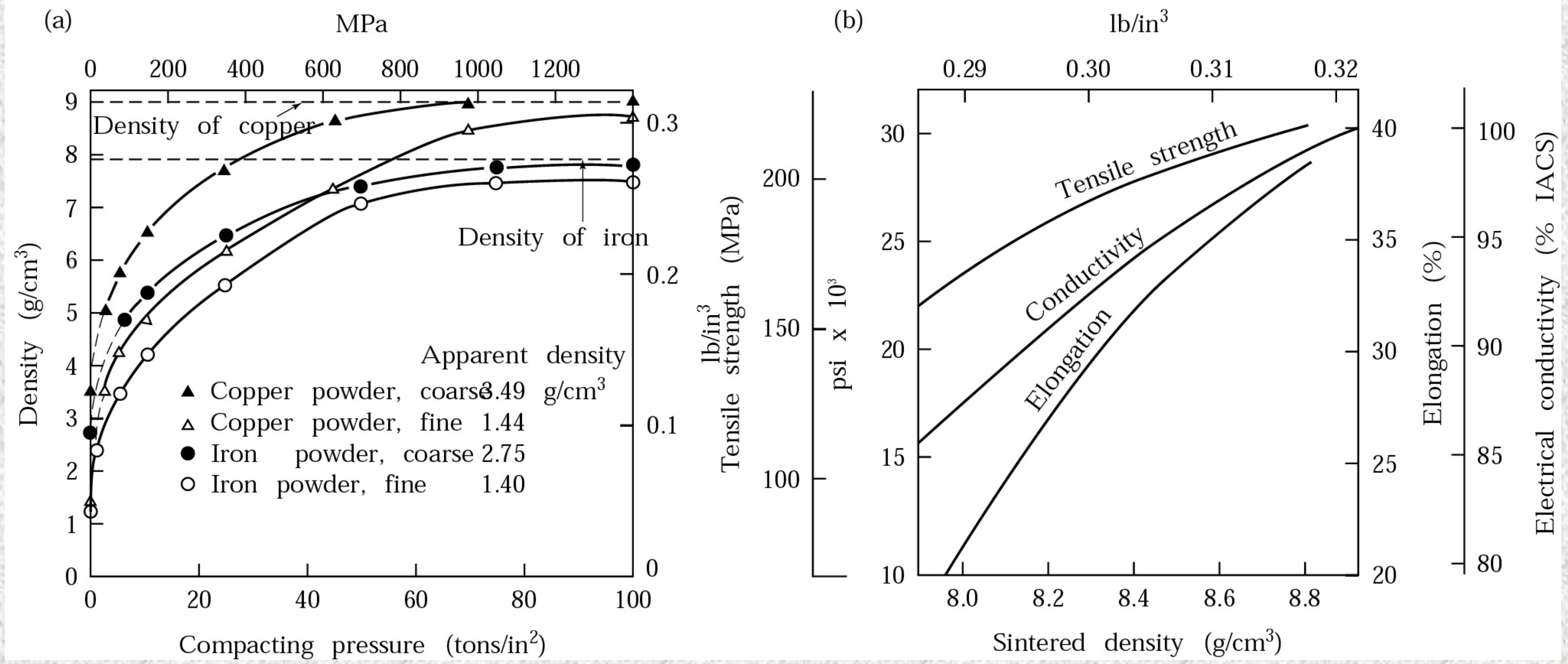


Figure 17.8 (a) Compaction of metal powder to form a bushing. The pressed powder part is called green compact. (b) Typical tool and die set for compacting a spur gear. *Source*: Metal Powder Industries Federation.

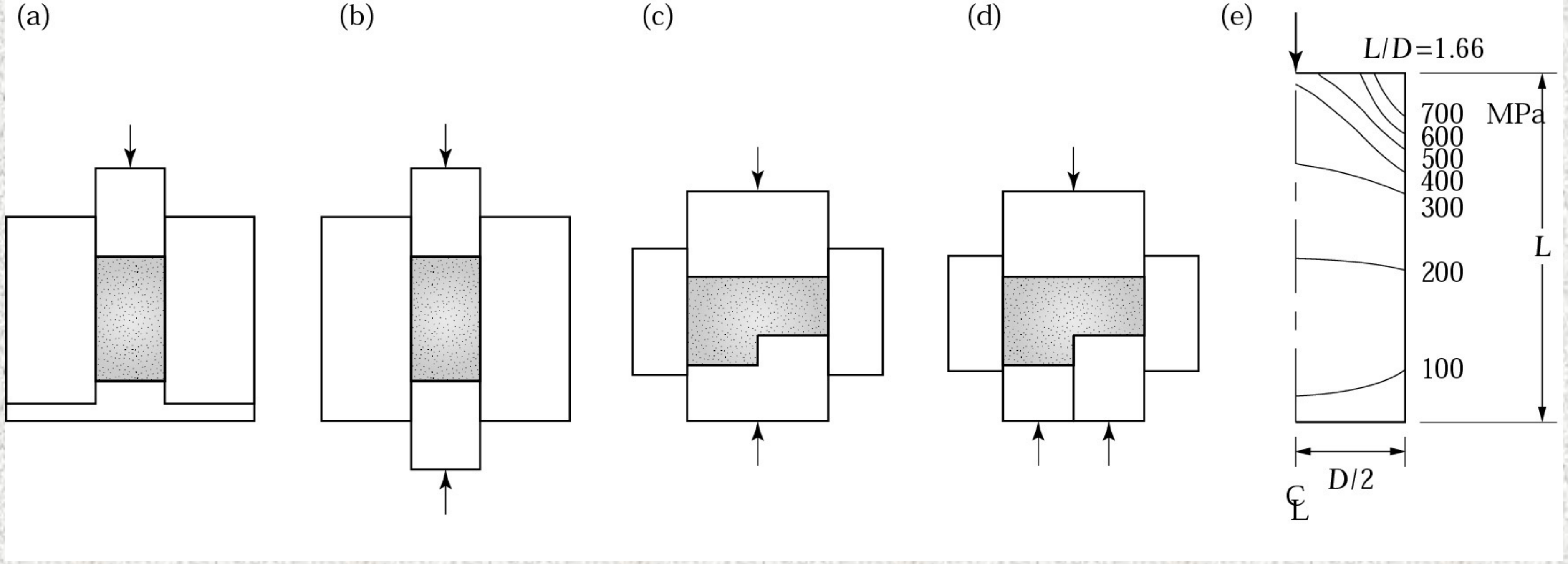
Density Effects

Figure 17.9 (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*: F. V. Lenel, *Powder Metallurgy: Principles and Applications*. Princeton, NJ; Metal Powder Industries Federation, 1980. (b) Effects of density on tensile strength, elongation, and electrical conductivity of copper powder. IACS means International Annealed Copper Standard for electrical conductivity.



Density Variations in Dies

Figure 17.10 Density variation in compacting metal powders in various dies: (a) and (c) single-action press; (b) and (d) double-action press. Note in (d) the greater uniformity of density, from pressing with two punches with separate movements, compared with (c). (e) Pressure contours in compacted copper powder in a single-action press. *Source*: P. Duwez and L. Zwell.



Compacting Pressures for Various Metal Powders

Metal	Pressure (MPa)
Aluminum	70–275
Brass	400–700
Bronze	200–275
Iron	350–800
Tantalum	70–140
Tungsten	70–140
Other materials	
Aluminum oxide	110–140
Carbon	140–165
Cemented carbides	140–400
Ferrites	110–165

Mechanical Press

Figure 17.11 A 7.3 MN (825 ton) mechanical press for compacting metal powder. *Source*: Courtesy of Cincinnati Incorporated.

Hot and Cold Isostatic Pressing

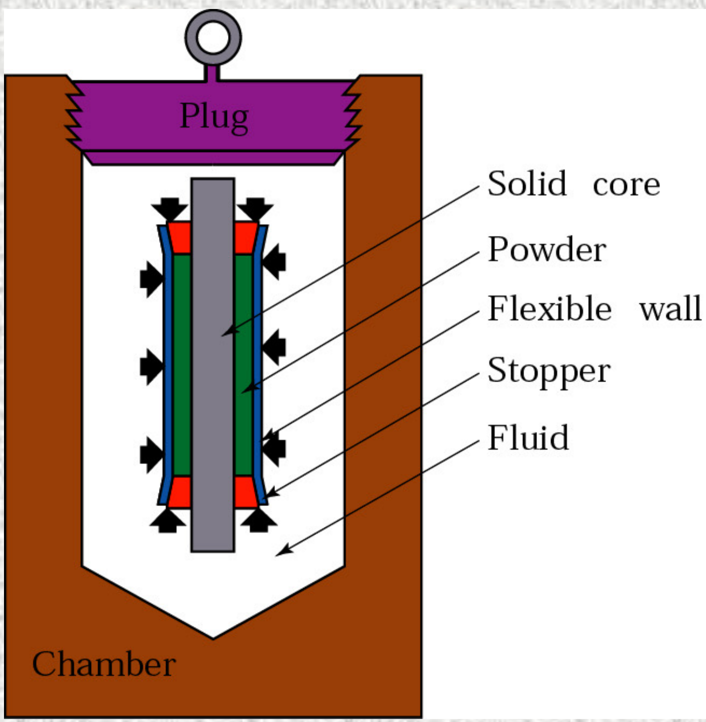


Figure 17.12 Schematic diagram of cold isostatic pressing, as applied to forming a tube. The powder is enclosed in a flexible container around a solid core rod. Pressure is applied isostatically to the assembly inside a high-pressure chamber. *Source*: Reprinted with permission from R.M. German, *Powder Metallurgy Science*. Princeton, NJ; Metal Powder Industries Federation, 1984.

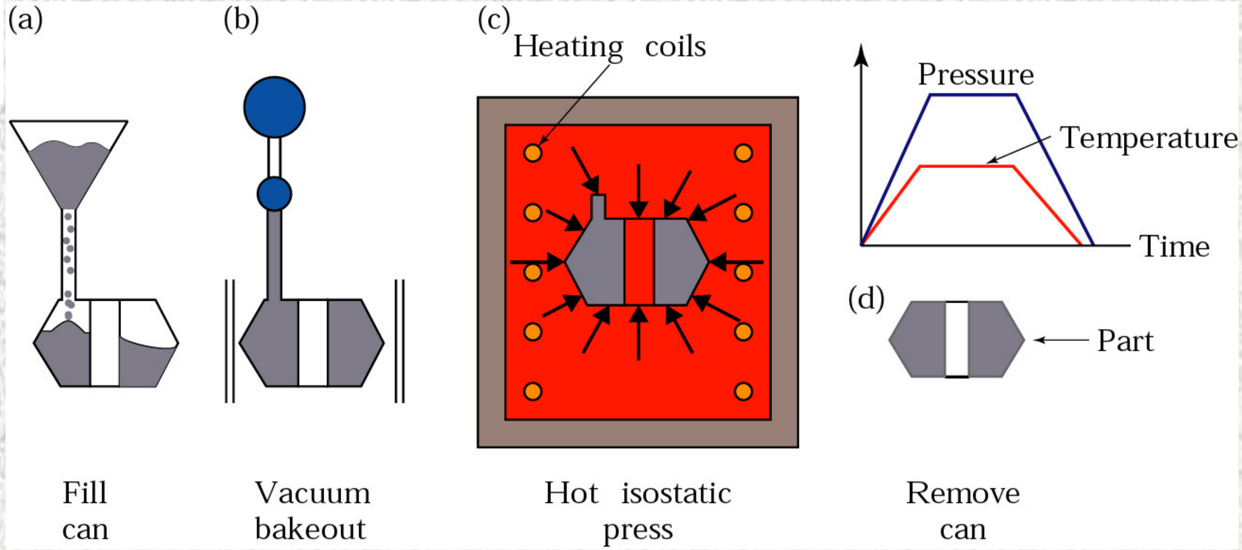


Figure 17.14 Schematic illustration of hot isostatic pressing. The pressure and temperature variation vs. time are shown in the diagram. *Source*: Preprinted with permission from R.M. German, *Powder Metallurgy Science*. Princeton, NJ; Metal Powder Industries Federation, 1984.

CIP

CIP is a compaction process in which isostatic fluid pressure is applied to a powder mass at room temperature to compact it into desired shape. The powder parts can be compacted up to 80-90 % of their theoretical densities. Water or oil can be used as pressuring medium.

• Process details: High density near-net shape green parts, long thin walled cylinders, parts with undercuts can be readily fabricated. In this process, pressure is applied simultaneously and equally in all directions using a fluid to an elastomeric fluid with powder at room temperature. Sintered CIP component can reach up to 97 % of theoretical density. Steps in this process is shown in flowchart.

CIP Flowchart

Select elemental or pre-alloyed powders → Fill mould with powder → Load mould into press → Pressurise & hold → De-pressurise & remove mould → Remove compact sample & sinter

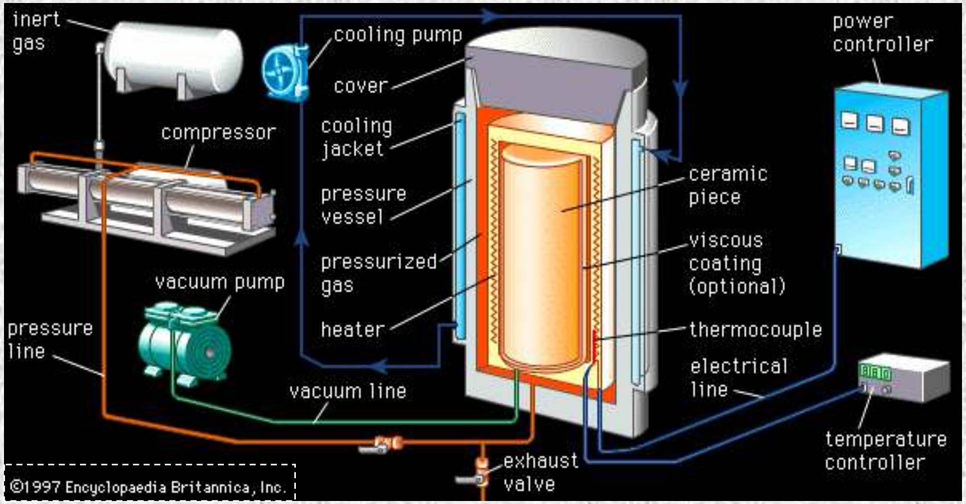
HIP

- Ideal method for consolidation of powders of nickel and cobalt base super alloys, tool steels, maraging steels, titanium alloys, refractory metal powders, cermets. It has got variety of applications including bonding of dissimilar materials, consolidation of plasma coatings, processing hard and soft magnetic materials etc.
- HIP is the application of pressure at elevated temperatures to obtain net or near net shape parts from metal, ceramic, cermet powders.
- HIP unit consists of a pressure vessel, high temperature furnace, pressurizing system, controls and auxiliary systems (material handling, vacuum pumps, metering pumps).

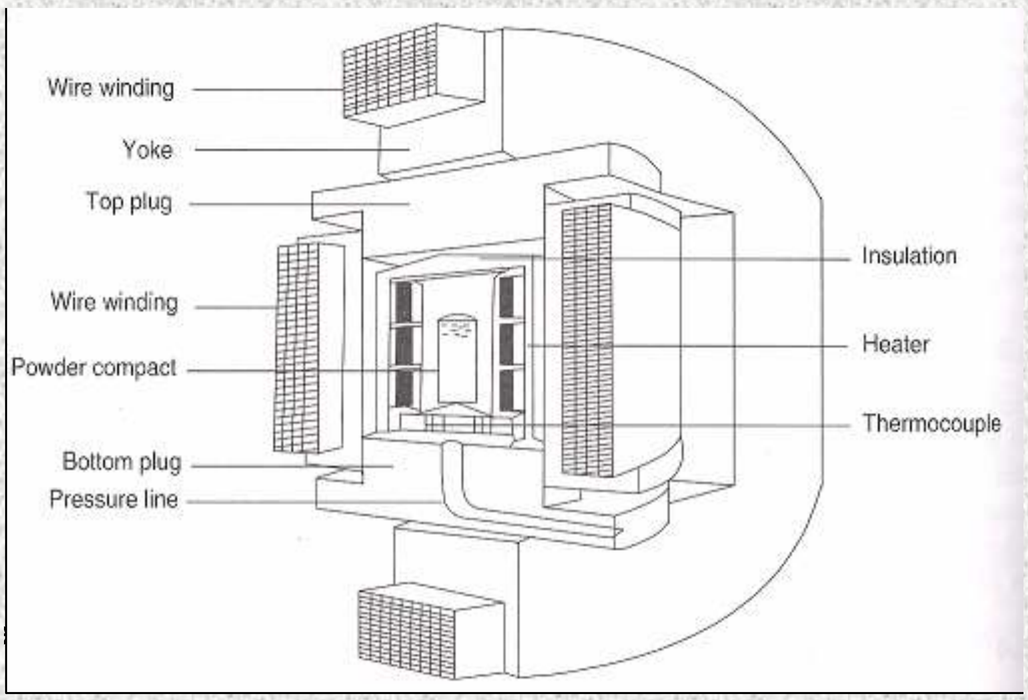
HIP

- The pressure vessel is made of low alloy steel. Its function is to heat the powders while applying uniform gas pressure on all the sides. Furnaces are of radiation or convection type heating furnaces with graphite or molybdenum heating elements. Nichrome is also used.
- The furnace heats the powder part, while pressurizing medium (a gas) is used to apply a high pressure during the process. Generally, argon, nitrogen, helium or even air is used as pressurizing medium.
- The pressurizing gas, usually argon, is let into the vessel and then a compressor is used to increase the pressure to the desired level. The furnace is then started and both temperature and pressure are increased to a required value.

HIP



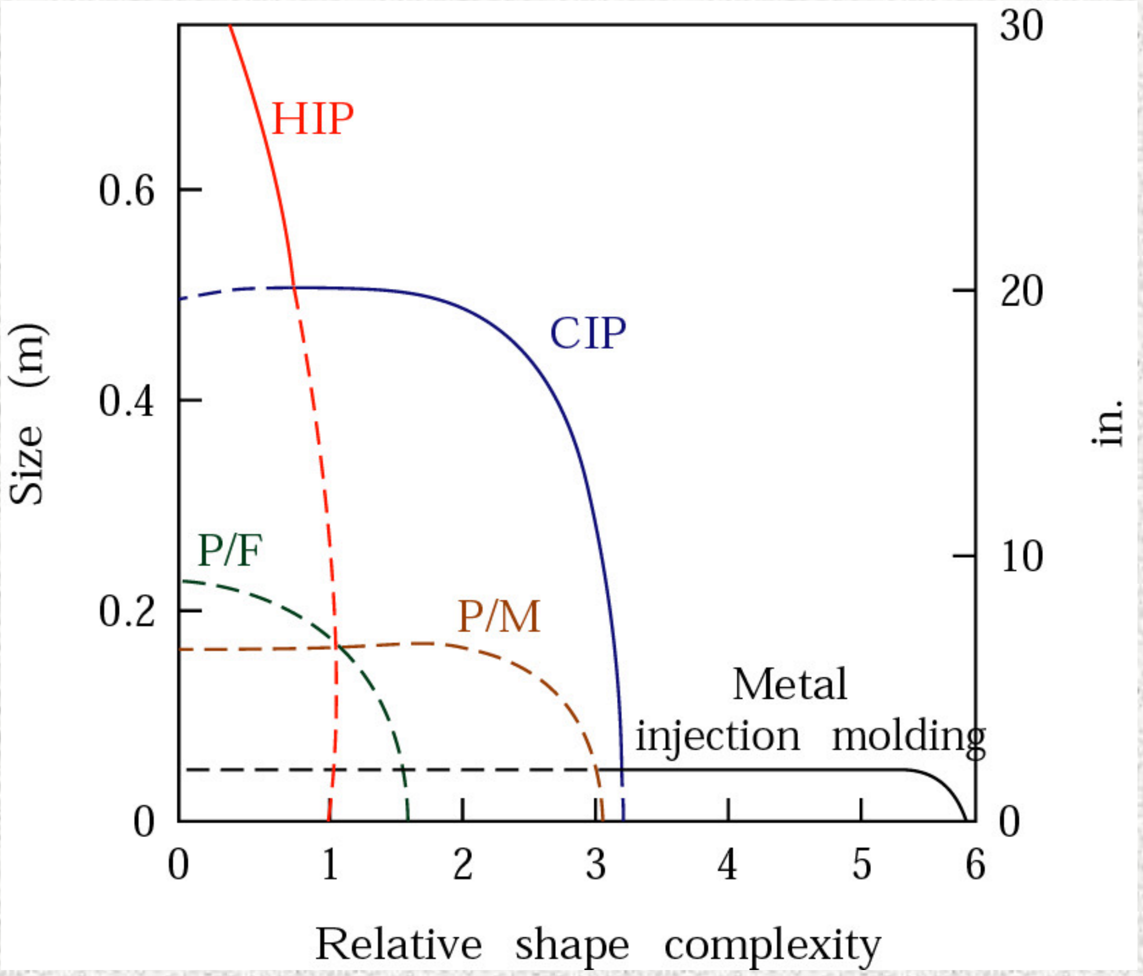
HIP UNIT– used for ceramic material (photo from public domain)



HIP Video

Capabilities Available from P/M Operations

Figure 17.13 Capabilities, with respect to part size and shape complexity, available from various P/M operations. P/F means powder forging. *Source*: Metal Powder Industries Federation.



Powder Rolling

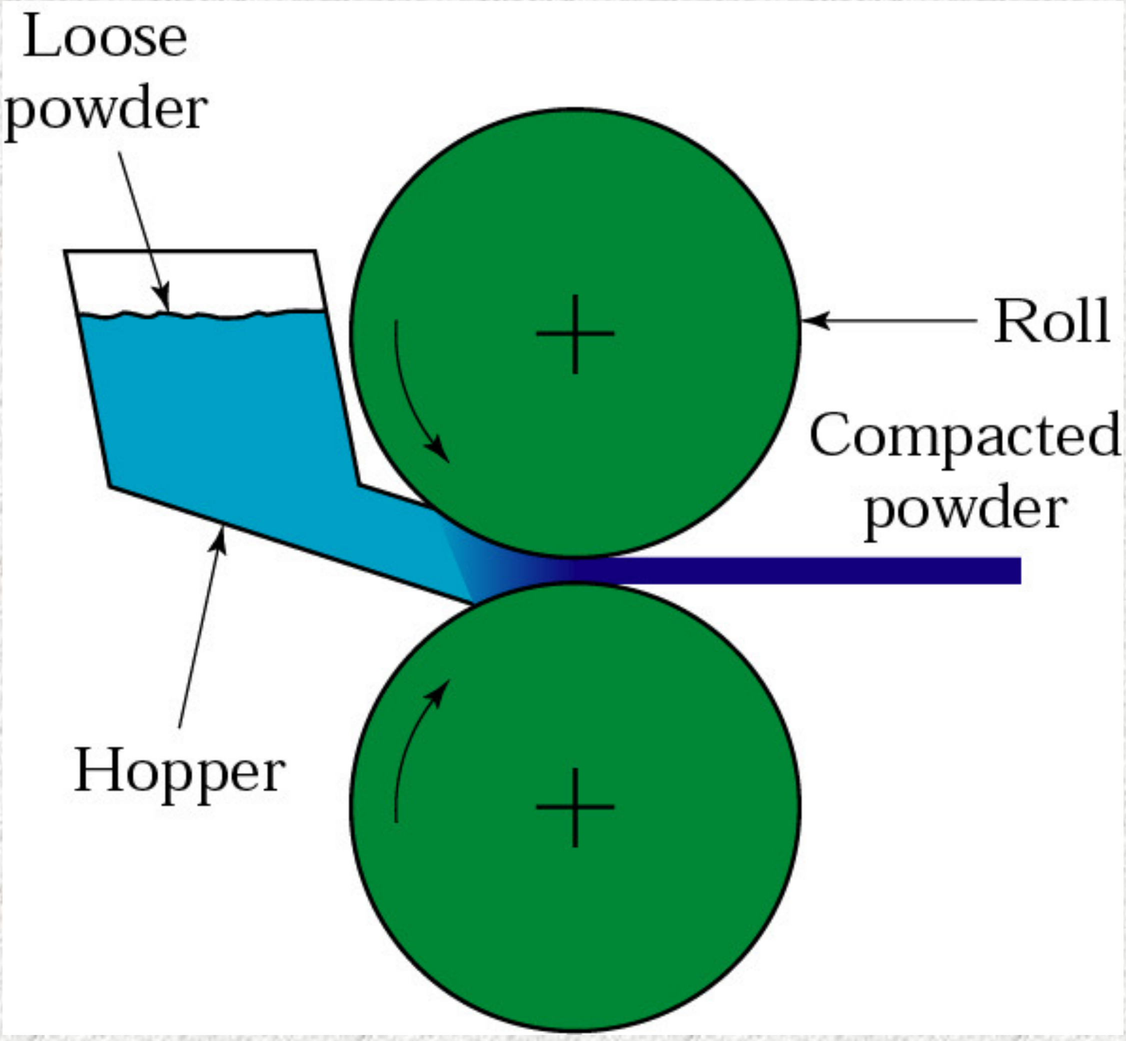


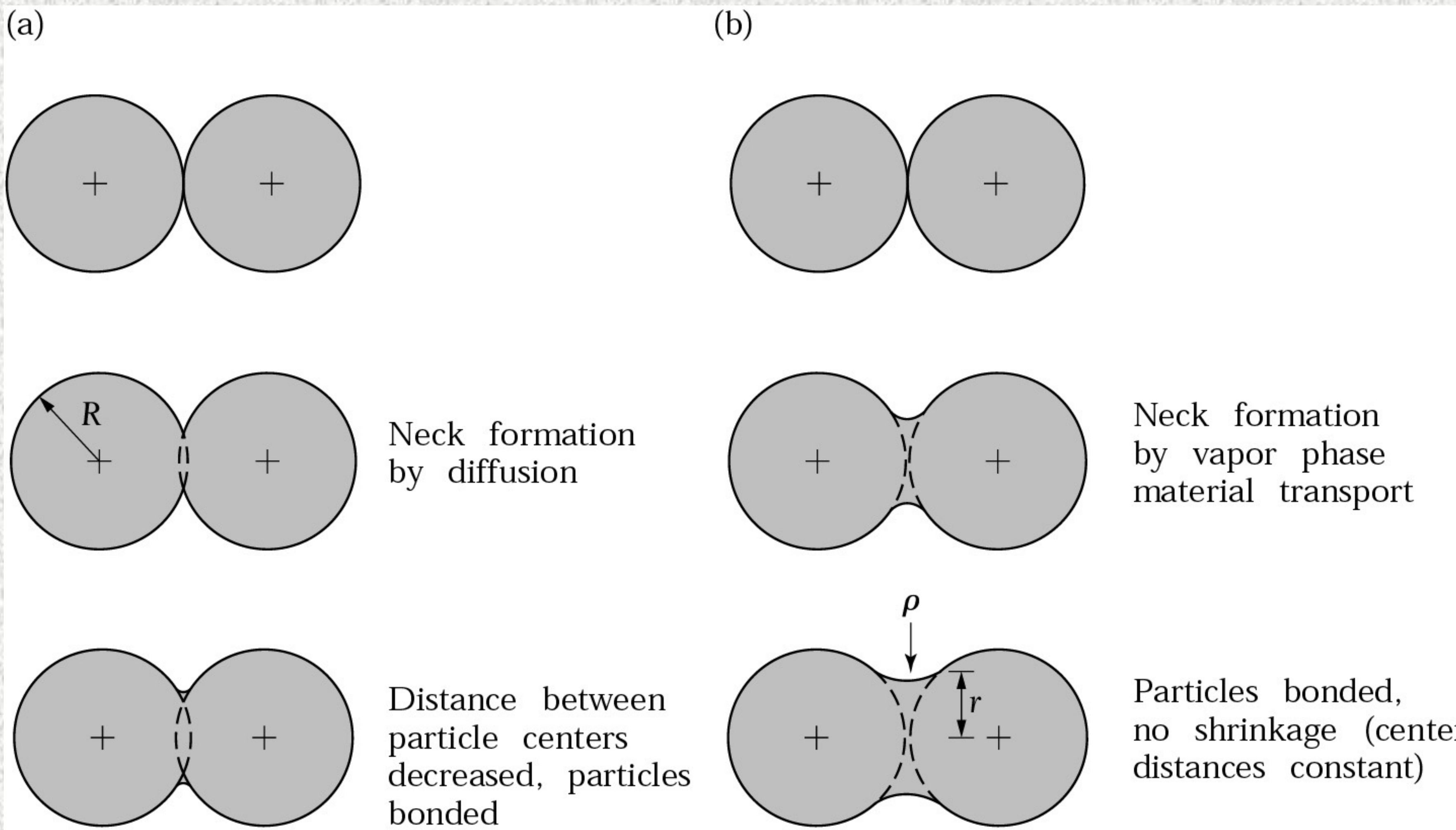
Figure 17.15 An example of powder rolling. *Source*: *Metals Handbook* (9th ed.), Vol. 7. American Society for Metals.

Sintering Temperature and Time for Various Metals

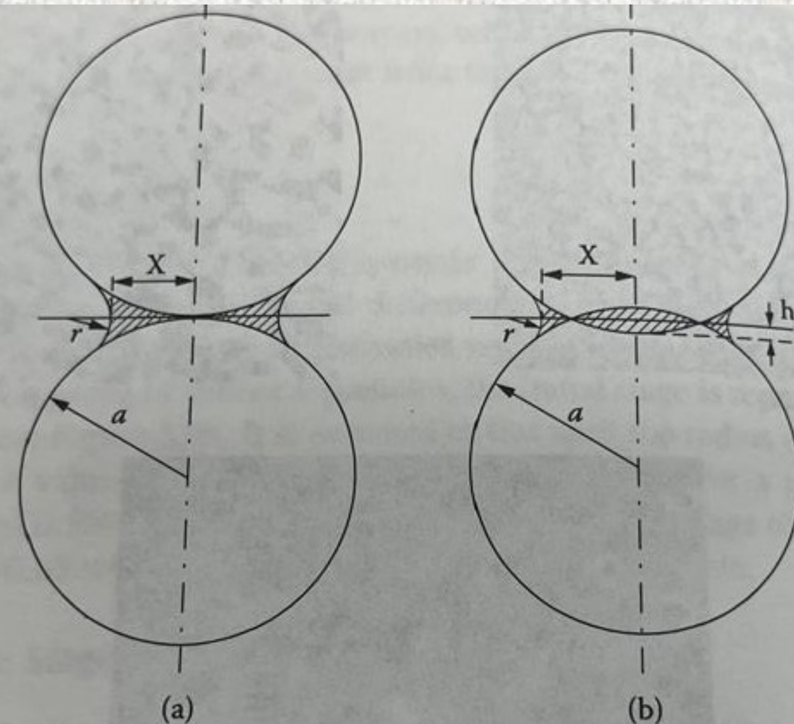
Material	Temperature (° C)	Time (Min)
Copper, brass, and bronze	760–900	10–45
Iron and iron-graphite	1000–1150	8–45
Nickel	1000–1150	30–45
Stainless steels	1100–1290	30–60
Alnico alloys (for permanent magnets)	1200–1300	120–150
Ferrites	1200–1500	10–600
Tungsten carbide	1430–1500	20–30
Molybdenum	2050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

Sintering

Figure 17.16 Schematic illustration of two mechanisms for sintering metal powders: (a) solid-state material transport; (b) liquid-phase material transport. R = particle radius, r = neck radius, and ρ = neck profile radius.



Simple Geometric Model



(a)		(b)
$r \approx \frac{X^2}{2a}$	Radius of neck	$r \approx \frac{X^2}{4a}$
$A \approx \frac{\pi^2 X^3}{a}$	Area of neck surface	$A \approx \frac{\pi^2 X^3}{2a}$
$V \approx \frac{\pi X^4}{2a}$	Volume transported into neck	$V \approx \frac{\pi X^4}{8a}$

Mechanical Properties of Selected P/M Materials

TABLE 17.4

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

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, pressed bar		AS	110	48	60 HRH	6	—
		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-6AI-4V		HIP	917	827	—	13	—
Superalloys							
Stellite 19		—	1035	—	49 HRC <1	—	

Mechanical Property Comparison for Ti-6Al-4V

TABLE 17.5
(*) P+S = pressed and sintered, HIP = hot isostatically pressed.
Source: R.M. German.

Process(*)	Density (%)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	Reduction of area (%)
Cast	100	840	930	7	15
Cast and forged	100	875	965	14 40	14
Blended elemental	98	786	875	8	17
(P+S)	> 99	805	875	9	26
Blended elemental	100	880	975	14	
(HIP)					
Prealloyed (HIP)					

Examples of P/M Parts

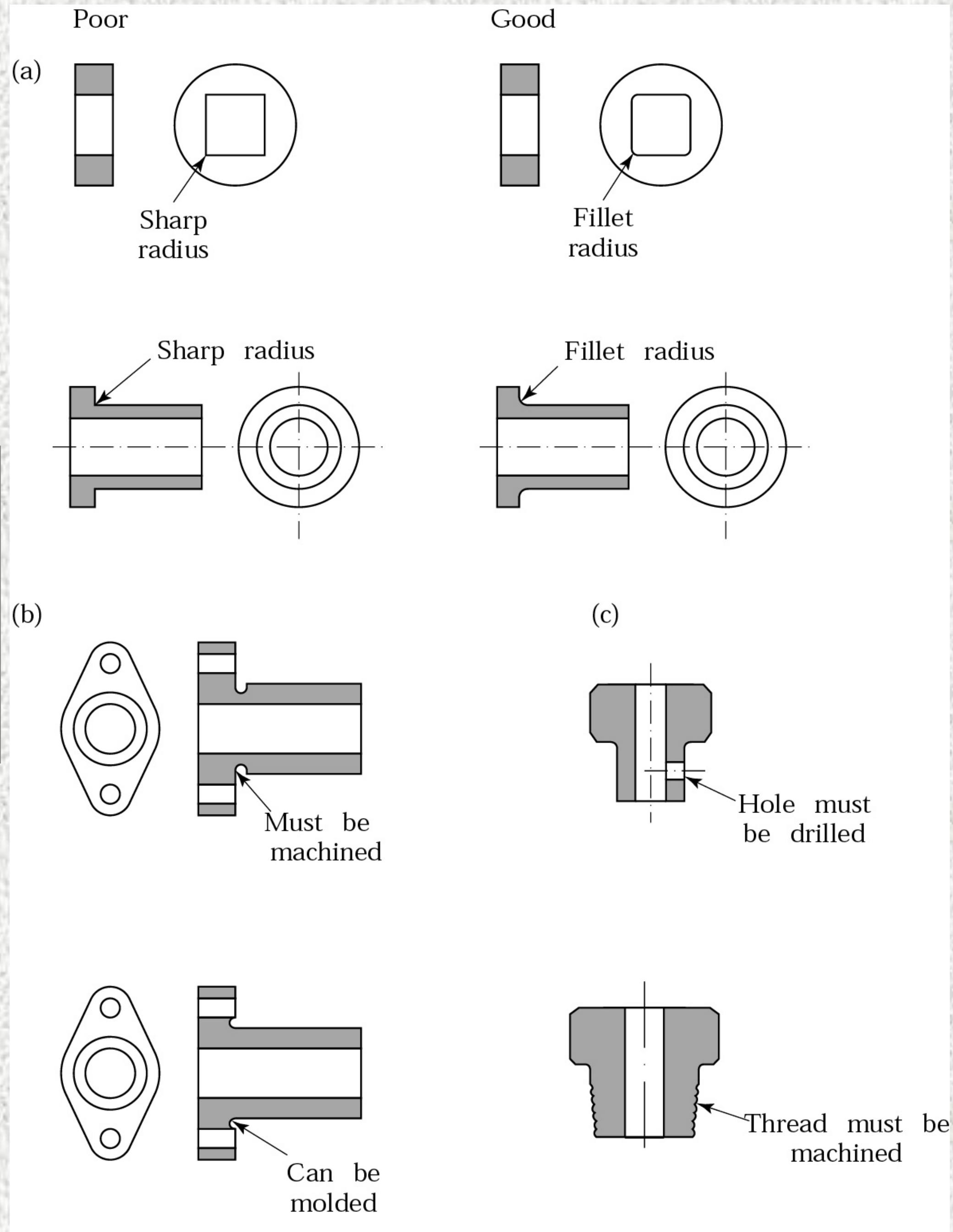


Figure 17.17 Examples of P/M parts, showing poor designs and good ones. Note that sharp radii and reentry corners should be avoided and that threads and transverse holes have to be produced separately by additional machining operations.

Forged and P/M Titanium Parts and Potential Cost Saving

Part	Weight (kg) Forged billet	P/M	Final part	Potential cost saving (%)
F-14 Fuselage brace	2.8	1.1	0.8	50
F-18 Engine mount support	7.7	2.5	0.5	20
F-18 Arrestor hook support fitting	79.4	25.0	12.9	25
F-14 Nacelle frame	143	82	24.2	50

Characteristics of Ceramics Processing

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.	Part size limited; limited 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 can be costly.

Steps in Making Ceramic Parts

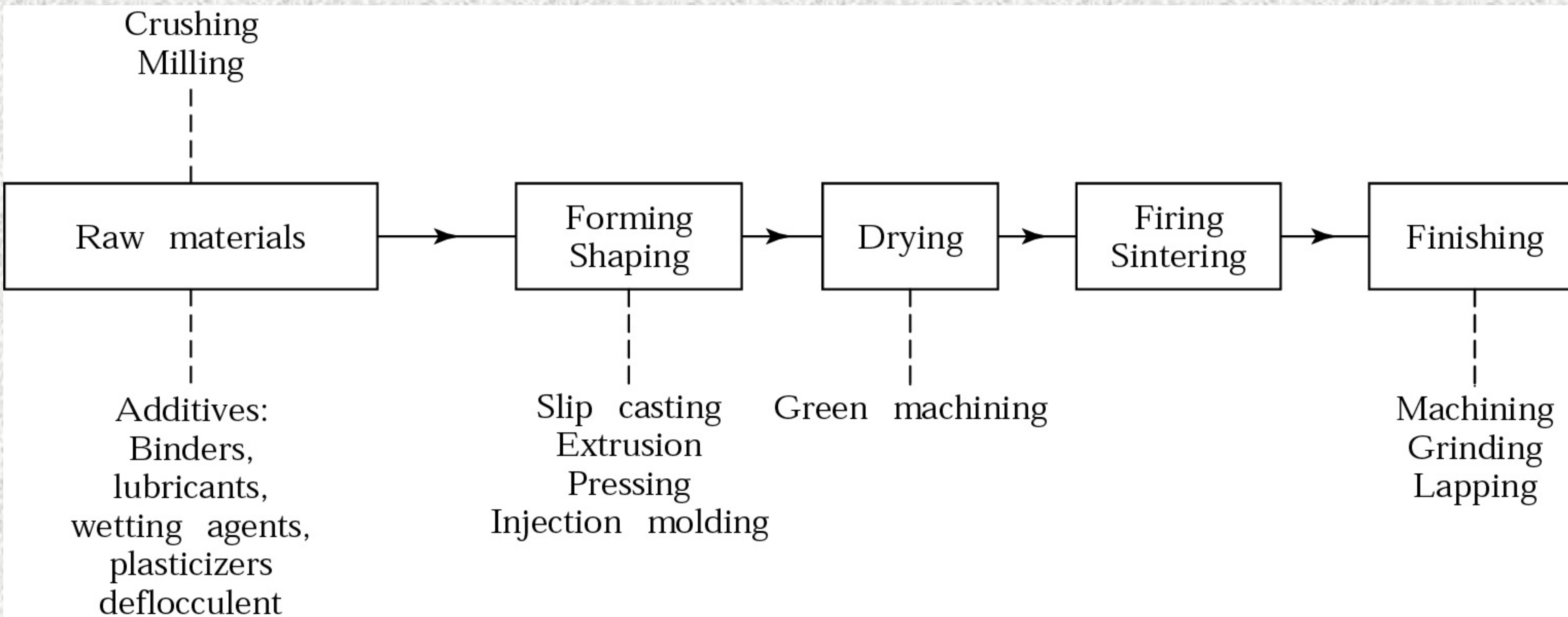


Figure 17.18 Processing steps involved in making ceramic parts.

Slip-Casting

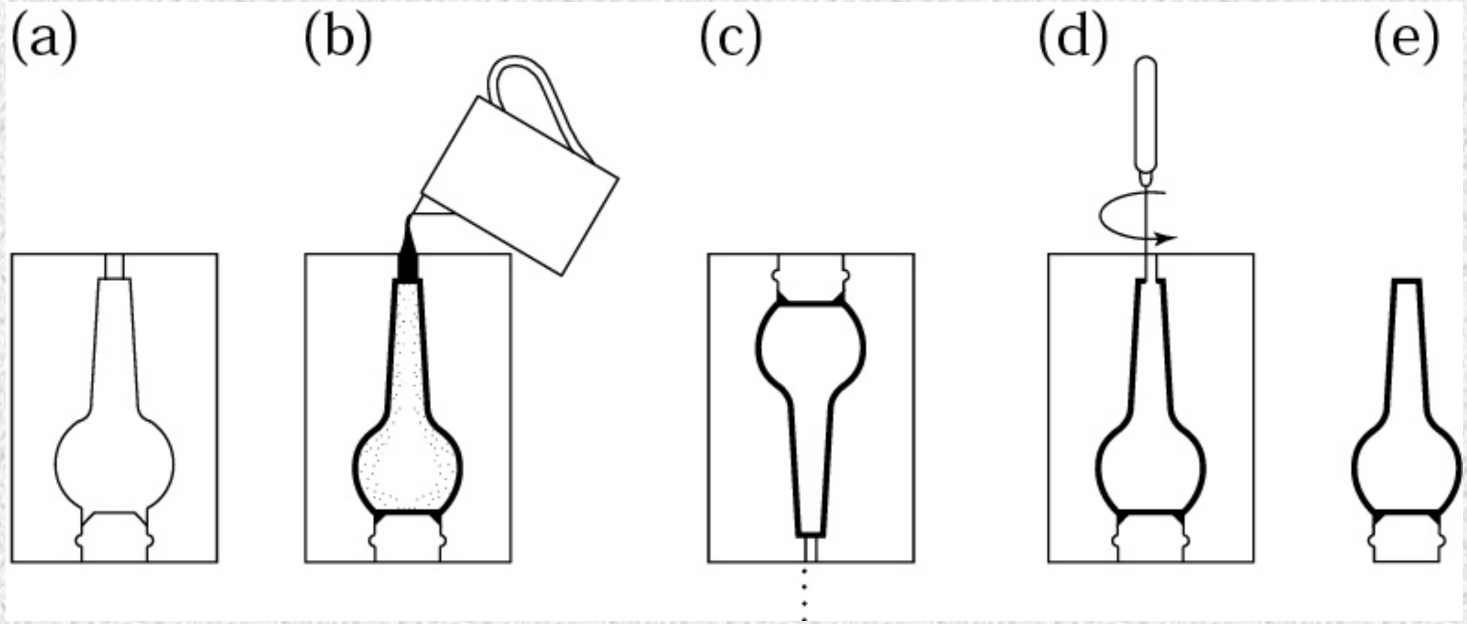
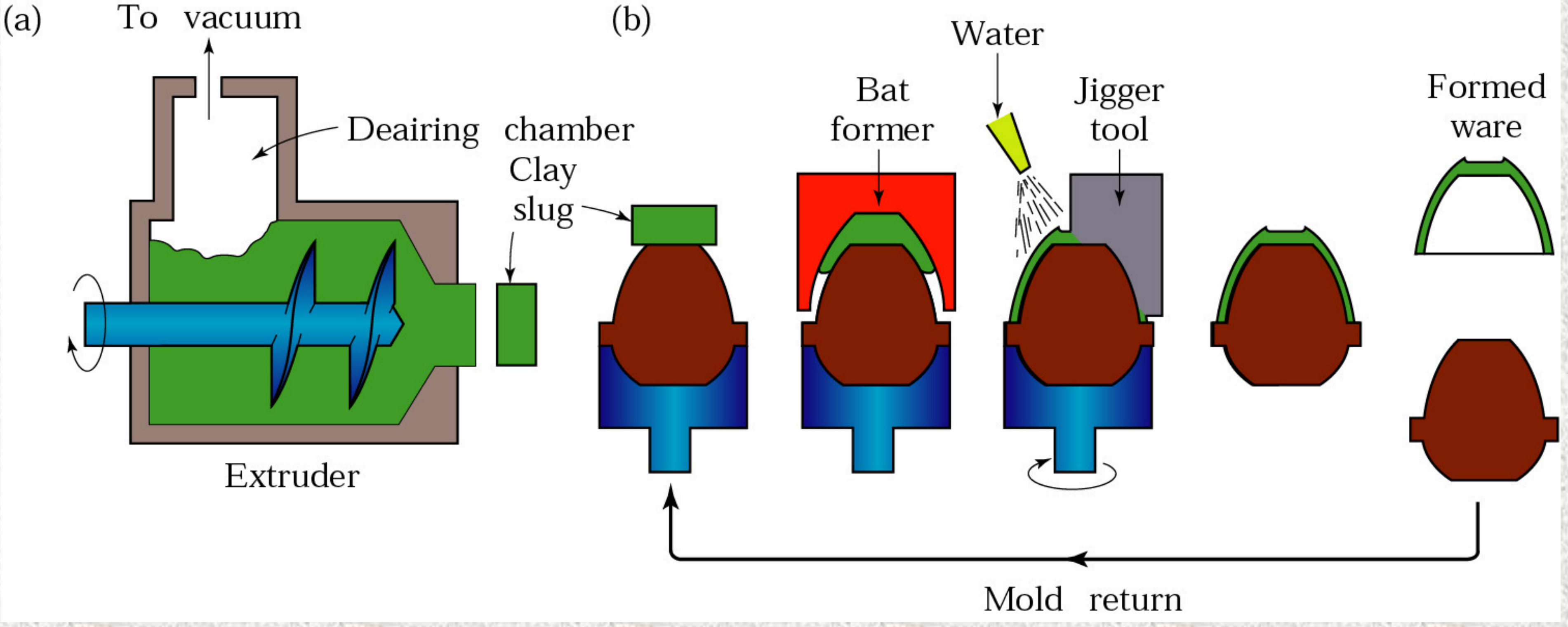


Figure 17.19 Sequence of operations in slip-casting a ceramic part. After the slip has been poured, the part is dried and fired in an oven to give it strength and hardness. *Source*: F. H. Norton, *Elements of Ceramics*. Addison-Wesley Publishing Company, Inc. 1974.

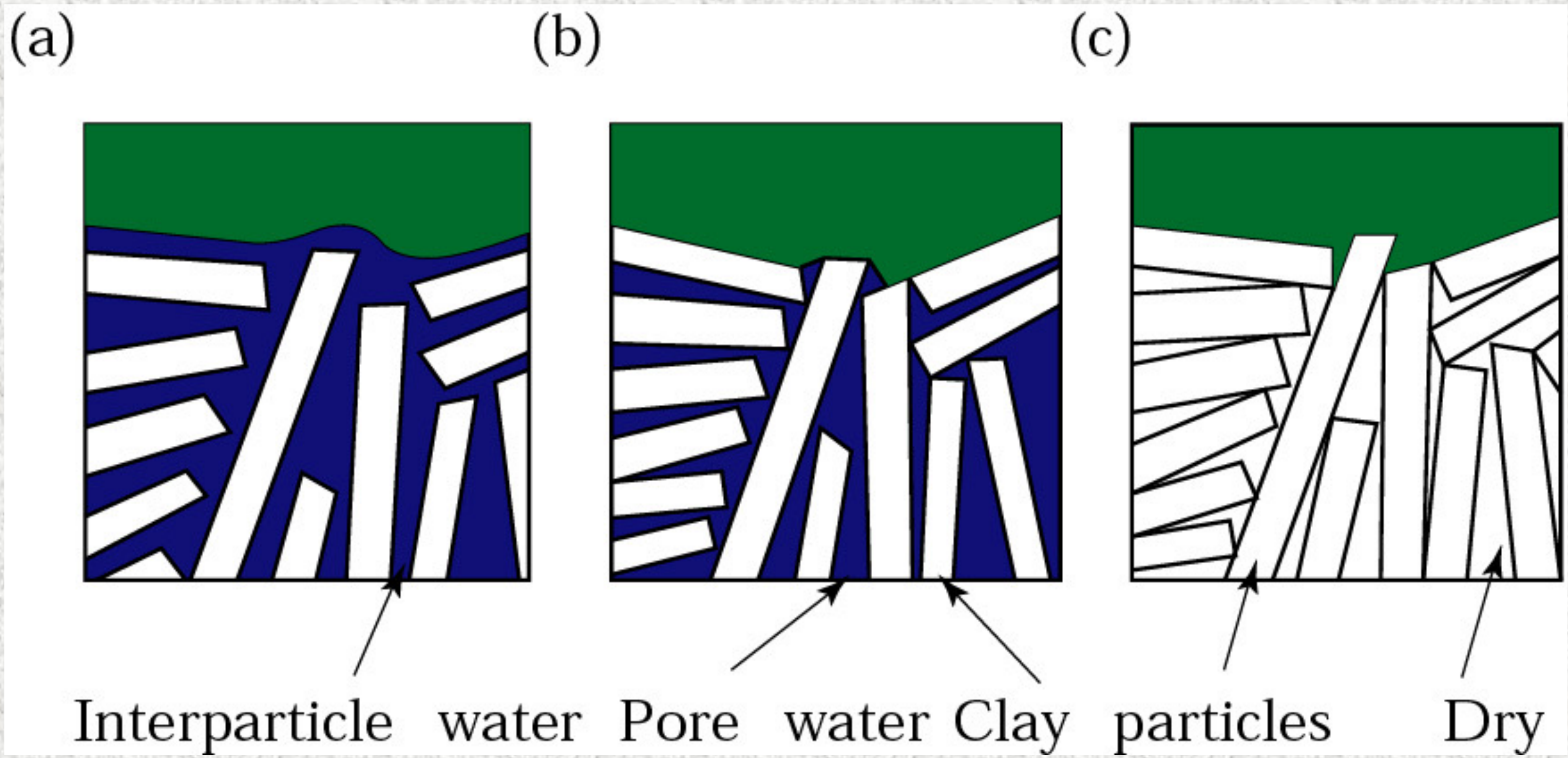
Extruding and Jiggering

Figure 17.20 (a) Extruding and (b) jiggering operations. *Source*: R. F. Stoops.



Shrinkage

Figure 17.21 Shrinkage of wet clay caused by removal of water during drying. Shrinkage may be as much as 20% by volume. *Source*: F. H. Norton, *Elements of Ceramics*. Addison-Wesley Publishing Company, Inc. 1974.



Sheet Glass Formation

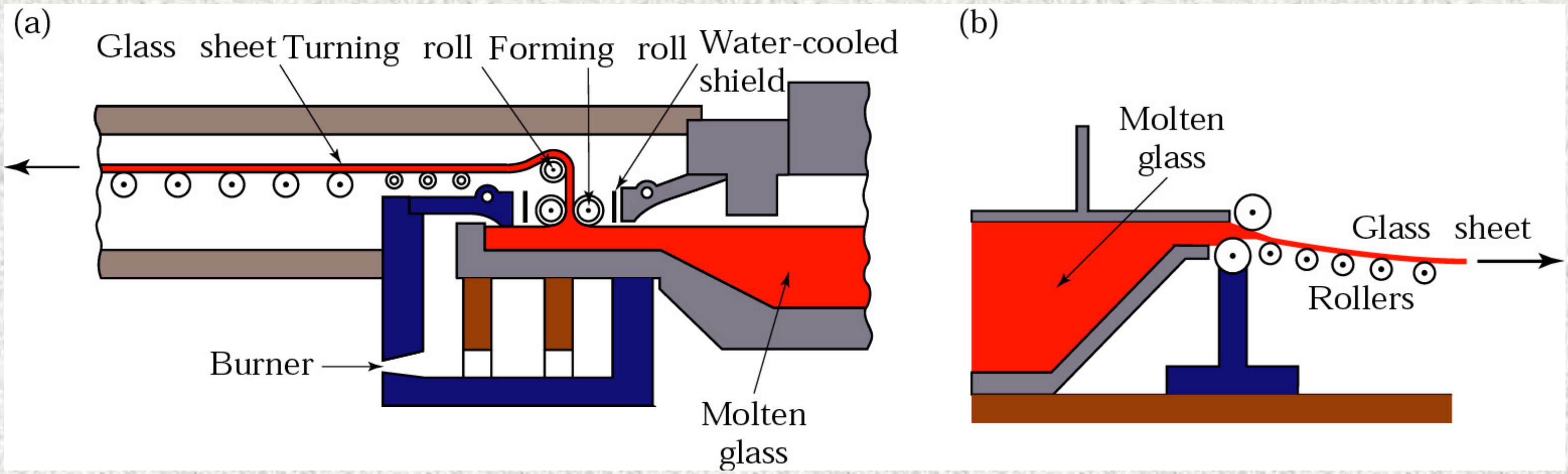


Figure 17.22 (a) Continuous process for drawing sheet glass from a molten bath. *Source*: W. D. Kingery, *Introduction to Ceramics*. Wiley, 1976. (b) Rolling glass to produce flat sheet.

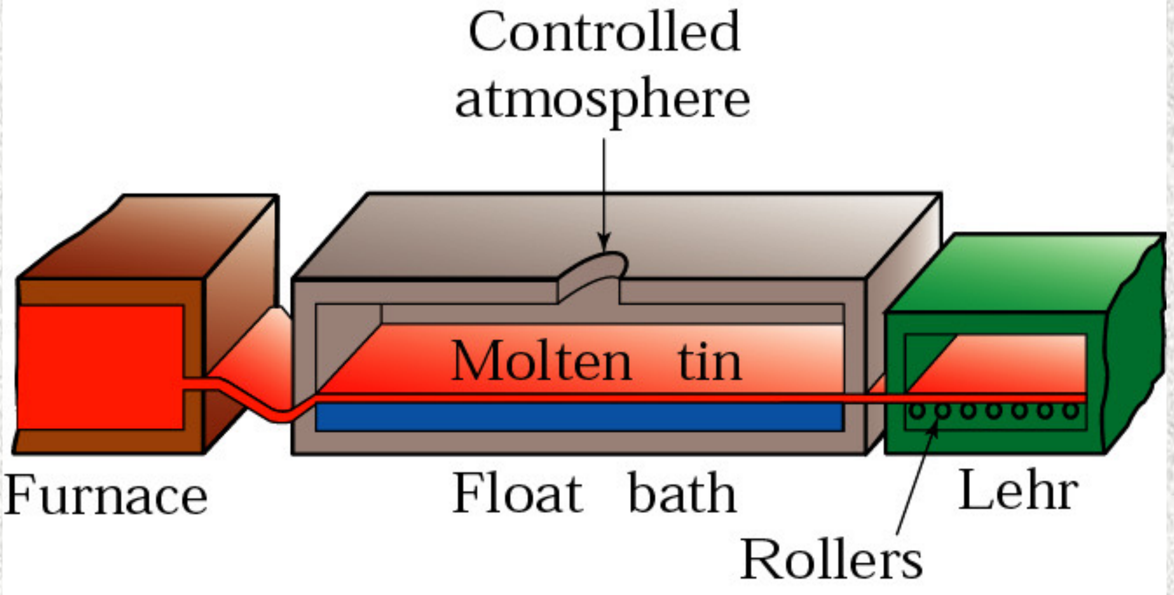


Figure 17.23 The float method of forming sheet glass. *Source*: Corning Glass Works.

Glass Tubing

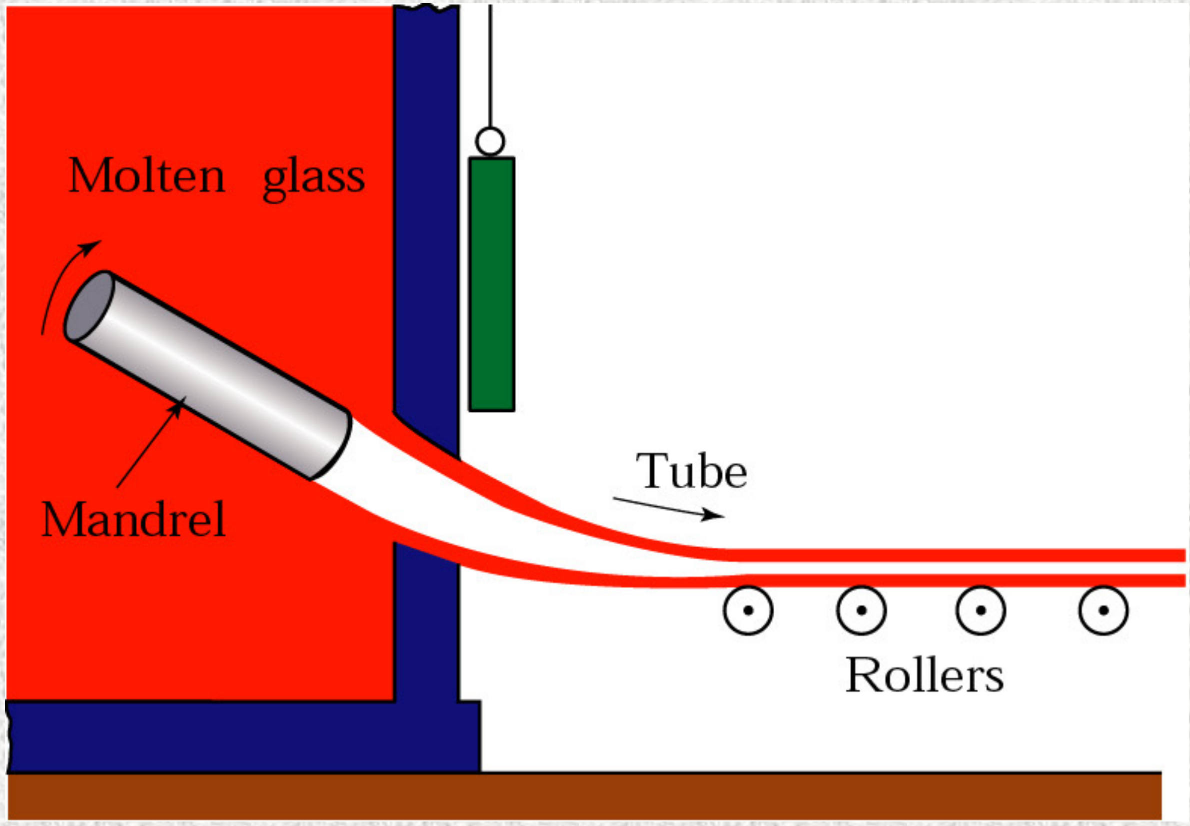


Figure 17.24 Manufacturing process for glass tubing. Air is blown through the mandrel to keep the tube from collapsing. *Source*: Corning Glass Works.

Steps in Manufacturing a Glass Bottle

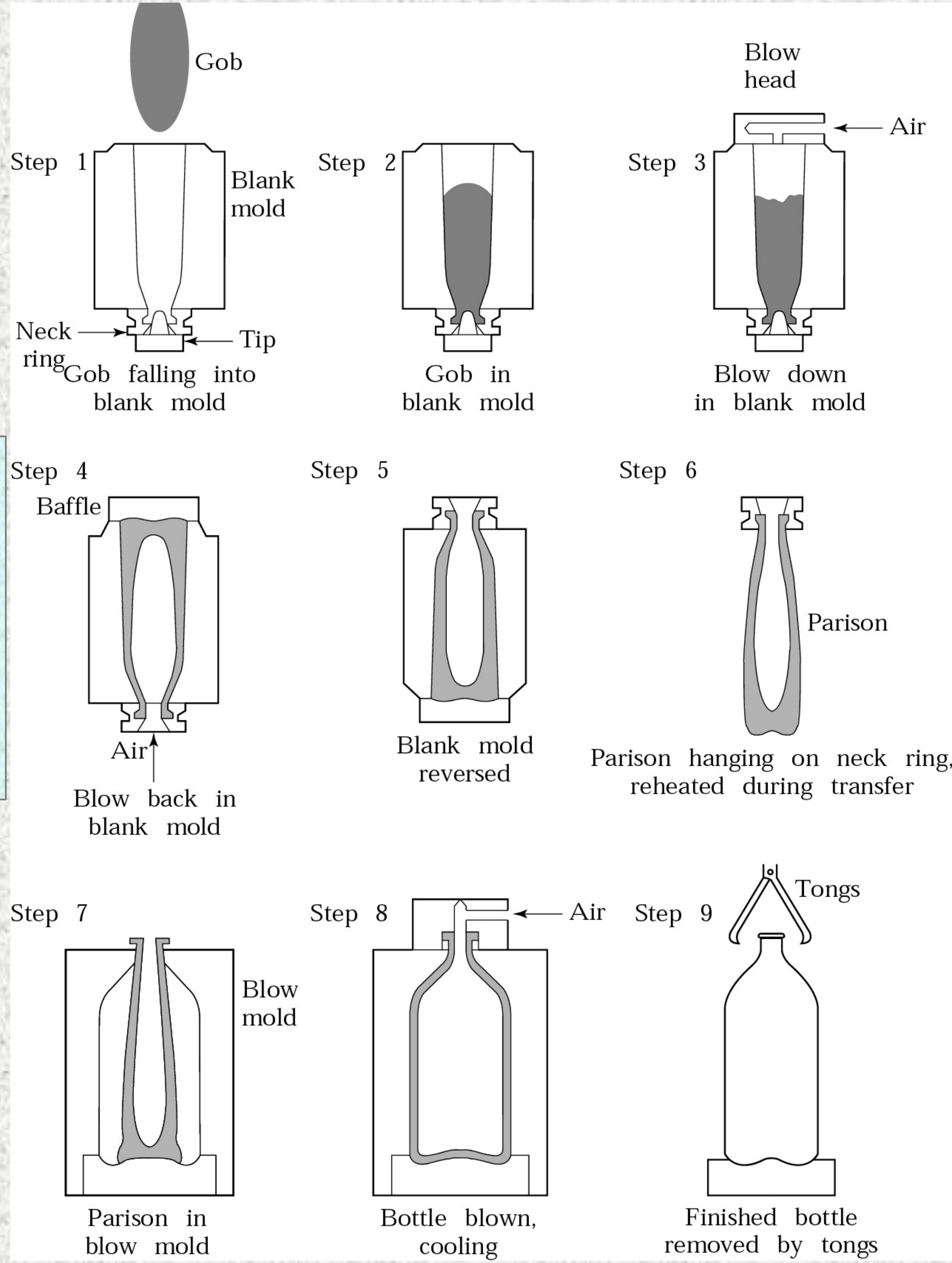


Figure 17.25 Stages in manufacturing an ordinary glass bottle. *Source*: F.H. Norton, *Elements of Ceramics*. Addison-Wesley Publishing Company, Inc. 1974.

Glass Molding

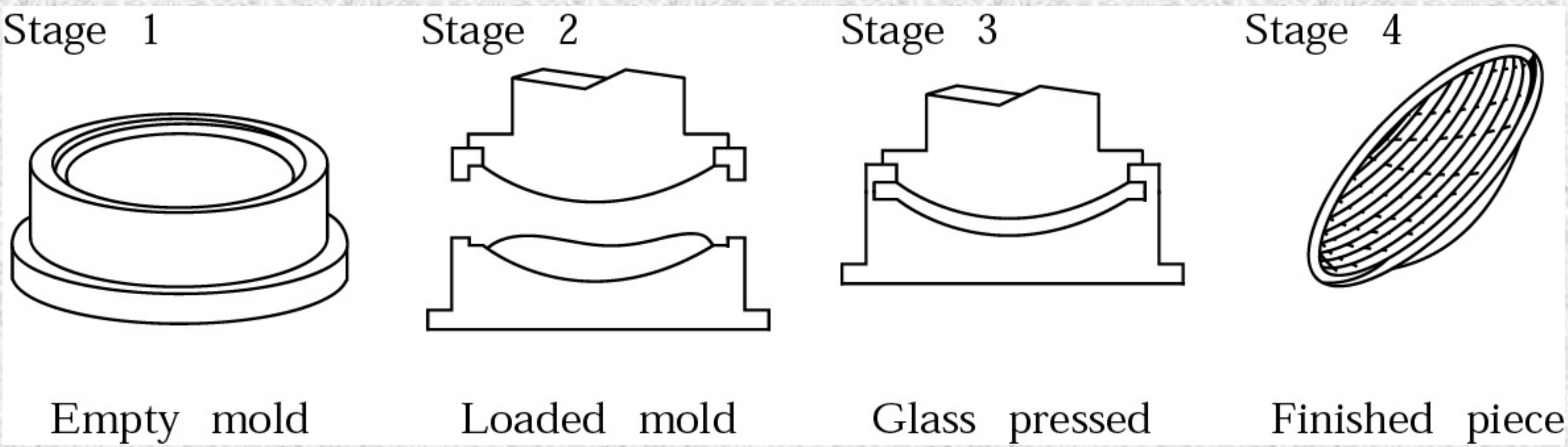


Figure 17.26 Manufacturing a glass item by pressing glass in a mold. *Source*: Corning Glass Works.

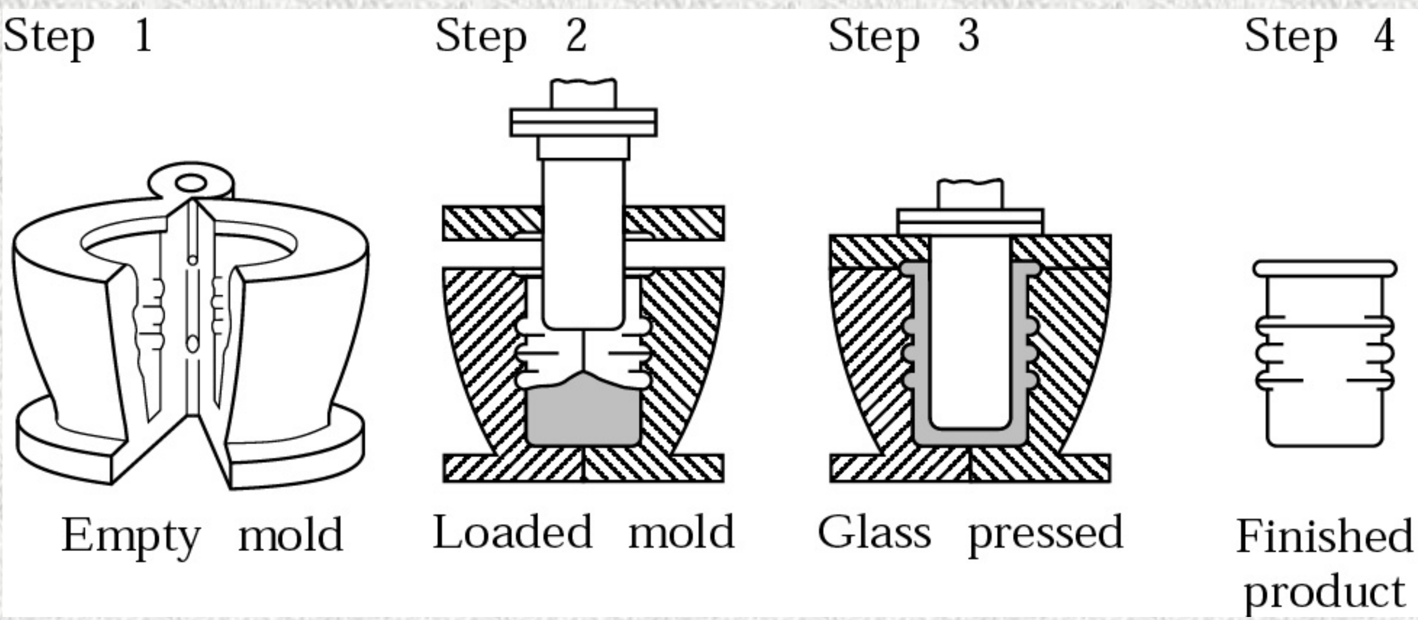
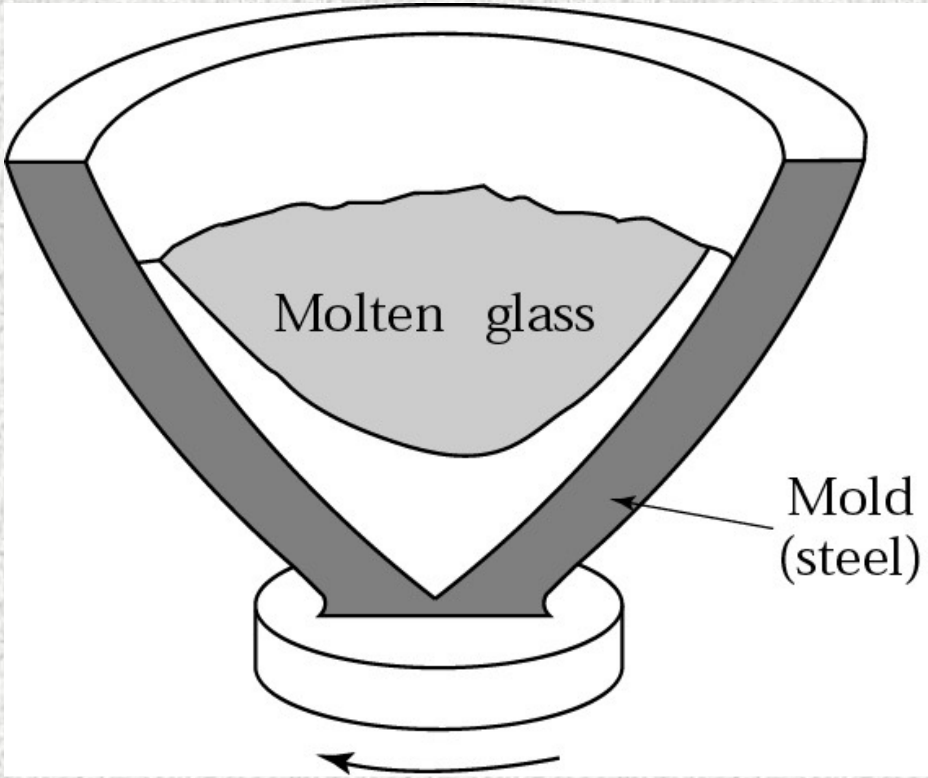


Figure 17.27 Pressing glass in a split mold. *Source*: E.B. Shand, *Glass Engineering Handbook*. McGraw-Hill, 1958.

Centrifugal Glass Casting

Figure 17.28 Centrifugal casting of glass. Television-tube funnels are made by this process. *Source*: Corning Glass Works.



Residual Stresses

Figure 17.29 Residual stresses in tempered glass plate, and stages involved in inducing compressive surface residual stresses for improved strength.