Powder Metallurgy

by
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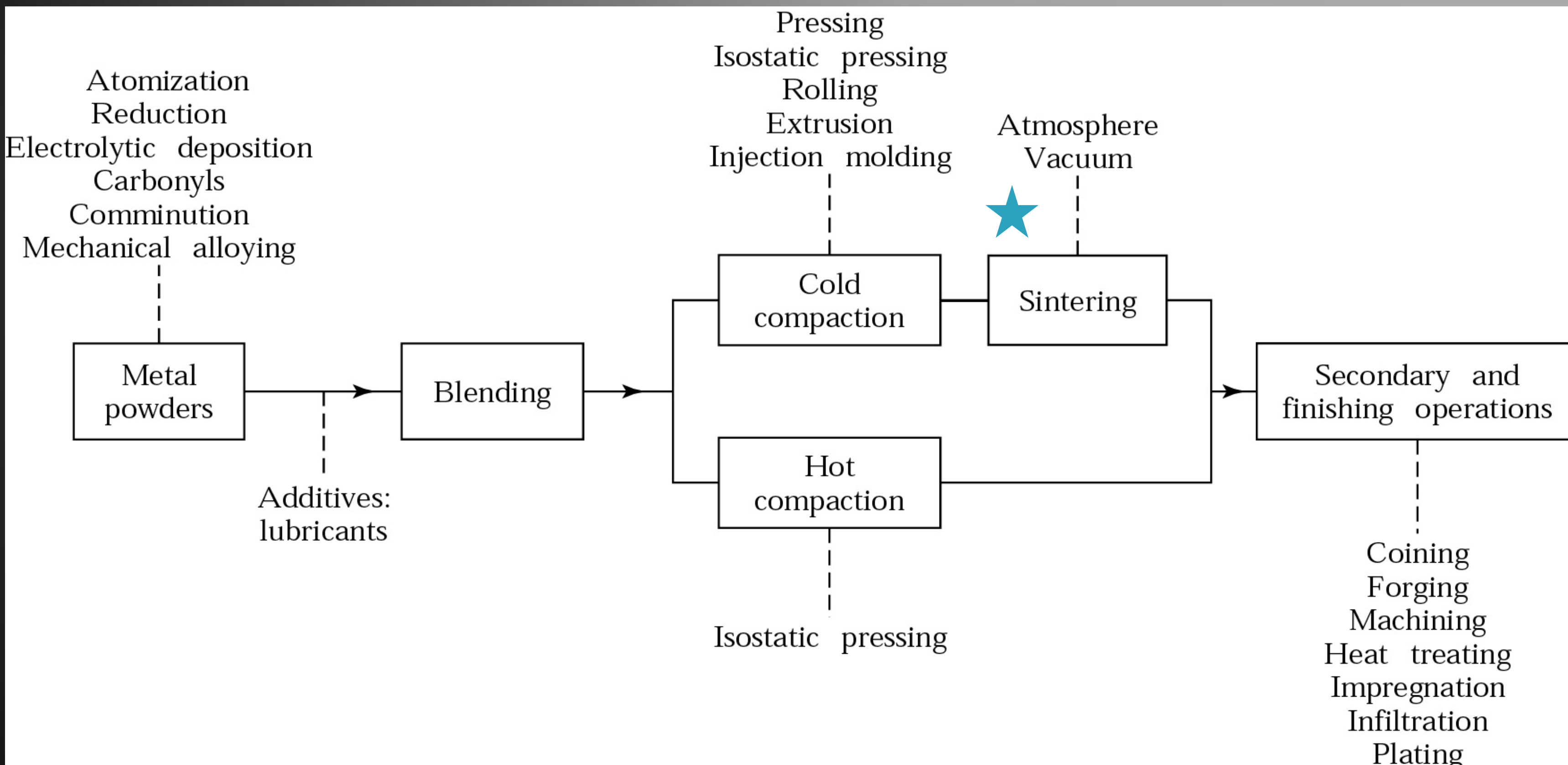
Making Powder-Metallurgy Parts



Sintering

- In the sintering operation, the pressed-powder compacts are heated in a controlled atmosphere to right below the melting point (70%–90% of melting point of metals or alloy)
- Sintered density depends on its “green density” and sintering conditions (temperature, time and furnace atmosphere).
- Times range from 10 minutes for iron and copper to 8 hours for tungsten and tantalum

Sintering

- Three stages of sintering
  - Burn-off (purge)- combusts any air and removes lubricants or binders that would interfere with good bonding
  - High-temperature- desired solid-state diffusion and bonding occurs
  - Cooling period- lowers the temperature of the products in a controlled atmosphere

- All three stages must be conducted in oxygen-free conditions

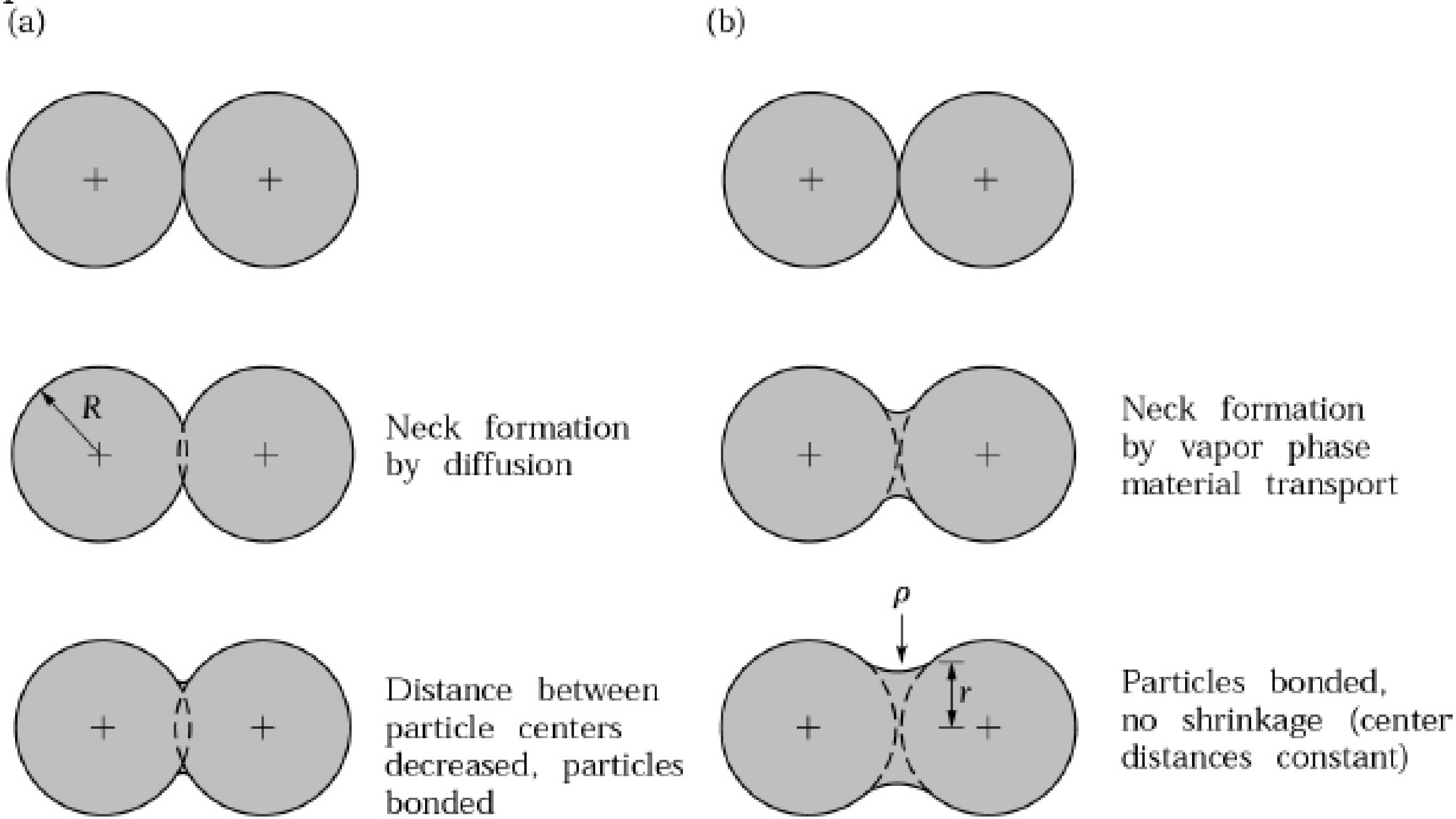
Sintering

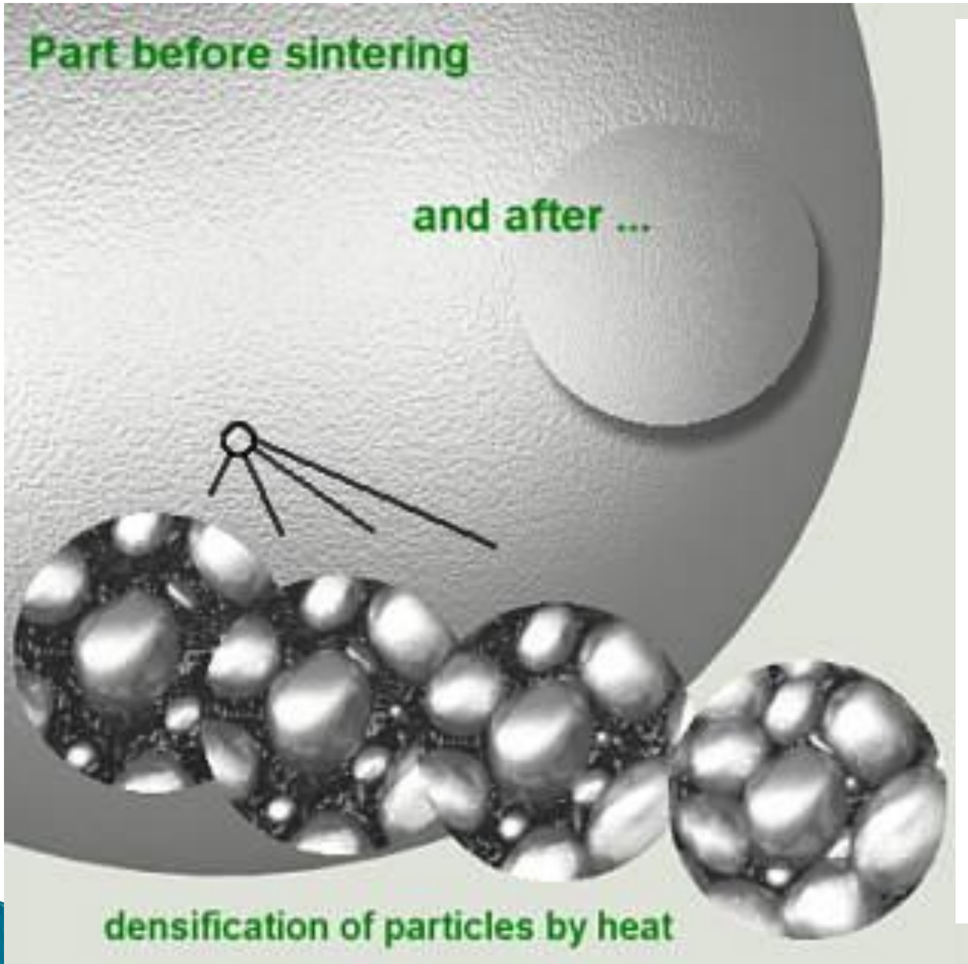
- Sintering mechanisms are complex and depend on the composition of metal particles as well as processing parameters. As temperature increases two adjacent particles begin to form a bond by diffusion (solid-state bonding).
- If two adjacent particles are of different metals, alloying can take place at the interface of two particles. One of the particles may have a lower melting point than the other. In that case, one particle may melt and surround the particle that has not melted (liquid-phase sintering).

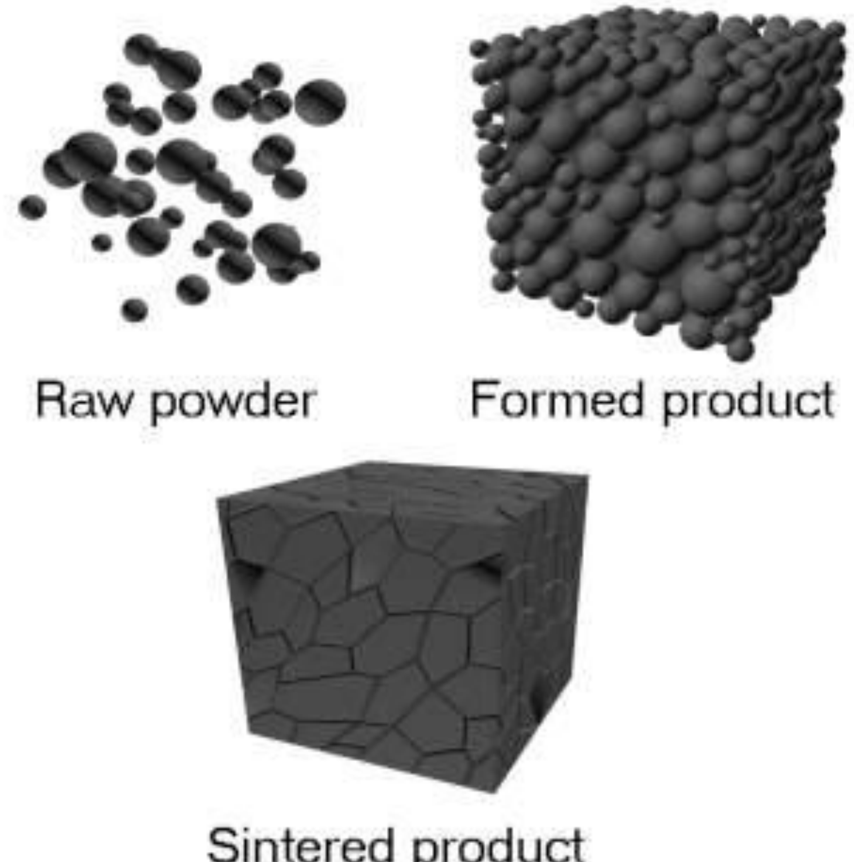
Sintering Temperature and Time for Various Powder Metals

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

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.

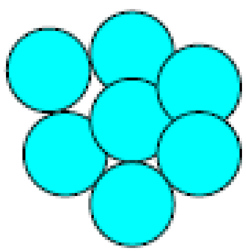



Part before sintering
and after ...
densification of particles by heat

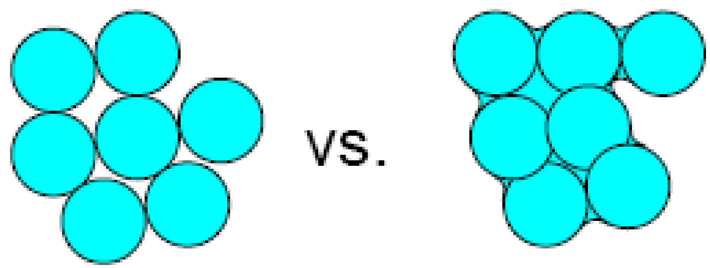

Raw powder
Formed product
Sintered product

Sintering Problem

Voids



Incomplete fusion



Mechanical Properties of Selected P/M Materials

TABLE 11.5

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	—	

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

Mechanical Properties Comparison for Ti-6Al-4V

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
Blended elemental (P+S)	98	786	875	8	14
Blended elemental (HIP)	> 99	805	875	9	17
Prealloyed (HIP)	100	880	975	14	26

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

Example 11.4: Shrinkage in sintering

In solid-state bonding during sintering of a powder-metal green compact, the linear shrinkage is 4 percent. If the desired sintered density is 95 percent of the theoretical density of the metal, what should be the density of the green compact? Ignore the small changes in mass during sintering.

SOLUTION. We define linear shrinkage as $\Delta L/L_o$, where L_o is the original length. We can then express the volume shrinkage during sintering as

$$V_{\text{sint}} = V_{\text{green}}\left(1 - \frac{\Delta L}{L_o}\right)^3. \tag{11.3}$$

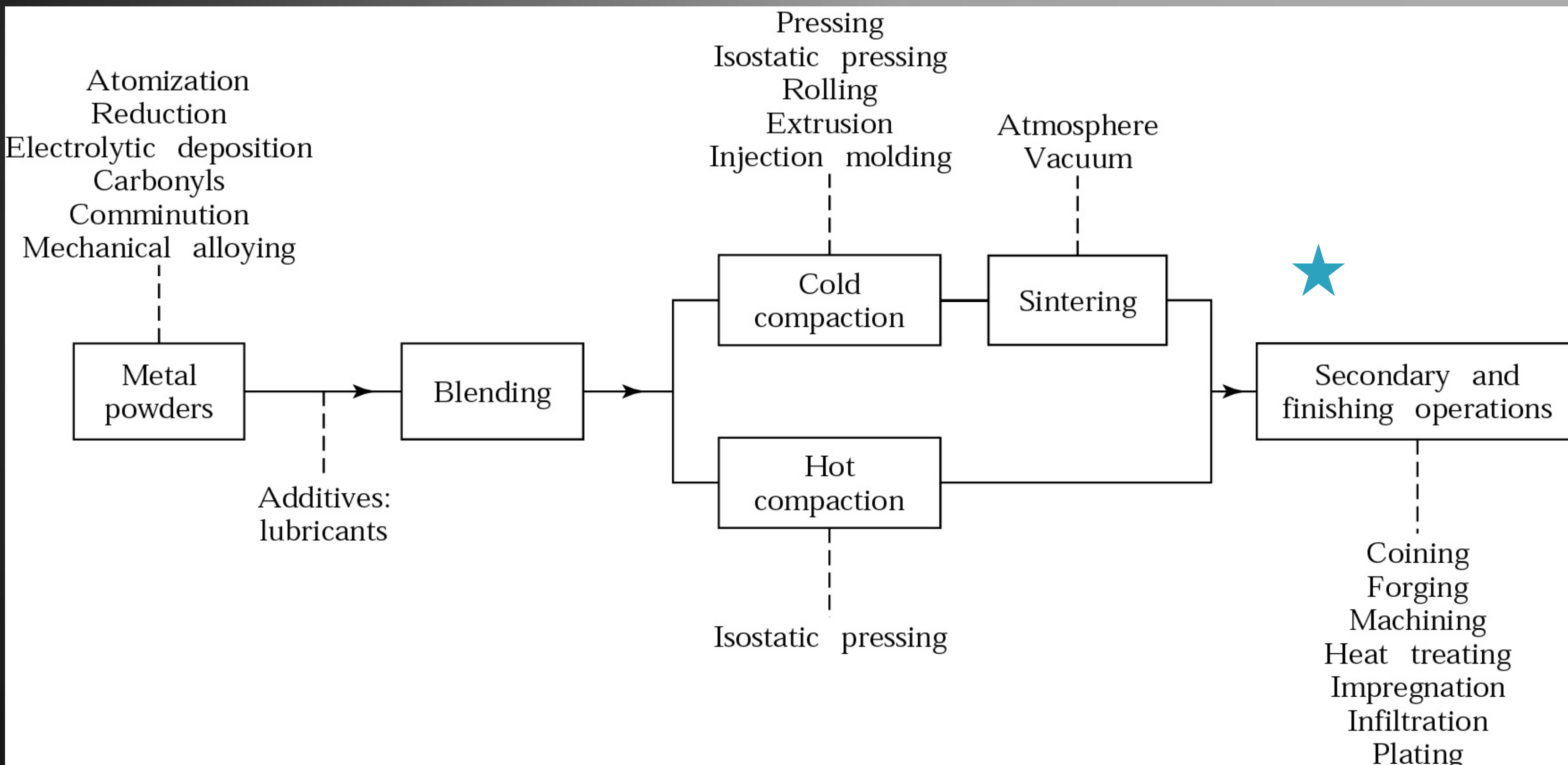
The volume of the green compact must be larger than that of the sintered part. However, the mass does not change during sintering, so we can rewrite this expression in terms of the density ρ as

$$\rho_{\text{green}} = \rho_{\text{sint}}\left(1 - \frac{\Delta L}{L_o}\right)^3. \tag{11.4}$$

Thus,

$$\rho_{\text{green}} = 0.95(1 - 0.04)^3 = 0.84, \text{ or } 84 \text{ percent}.$$

Making Powder-Metallurgy Parts



Finishing

- Repressing
  - Additional compacting operations, performed under high pressure in presses (coining, sizing)
- Impregnation
  - Utilizes inherent porosity of PM components by impregnating them with a fluid (oil)
- Infiltration
  - A slug of lower melting point metal is placed against the sintered part, the assembly is heated to melt slug. By capillary action, the liquid slug fills the pores of the sintered part.

Secondary Operations

- Most powder metallurgy products are ready to use after the sintering process
- Some products may use secondary operation to provide enhanced precision, improved properties, or special characteristics
- Distortion may occur during nonuniform cool-down so the product may be repressed, coined, or sized to improve dimensional precision

Secondary Operations

- If massive metal deformation takes place in the second pressing, the operation is known as P/M forging
  - Increases density and adds precision
- Infiltration and impregnation– oil or other liquid is forced into the porous network to offer lubrication over an extended product lifetime
- Metal infiltration fills in pores with other alloying elements that can improve properties
- P/M products can also be subjected to the conventional finishing operations: heat treatment, machining, and surface treatments

Figure 18-14 (Right) Comparison of conventional forging and the forging of a powder metallurgy preform to produce a gear blank (or gear). Moving left to right, the top sequence shows the sheared stock, upset section, forged blank, and exterior and interior scrap associated with conventional forging. The finished gear is generally machined from the blank with additional generation of scrap. The bottom pieces are the powder metallurgy preform and forged gear produced entirely without scrap by P/M forging. (*Courtesy of GKN Sinter Metals, Auburn Hills, MI.*)

Figure 18-15 P/M forged connecting rods have been produced by the millions. (Courtesy of Metal Powder Industries Federation, Princeton, NJ.)

Properties of P/M Products

- The properties of P/M products depend on multiple variables
  - Type and size of powder
  - Amount and type of lubricant
  - Pressing pressure
  - Sintering temperature and time
  - Finishing treatments
- Mechanical properties are dependent on density
- Products should be designed (and materials selected) so that the final properties will be achieved with the anticipated final porosity

P/M Materials

TABLE 18-5 Comparison of Properties of Powder Metallurgy Materials and Equivalent Wrought Metals (Note how porosity diminishes mechanical performance)

Material[a]	Form and Composition	Condition[b]	Percent of Theoretical Density	Tensile Strength		Elongation in 2 in. (%)
				10^3 psi	Mpa	
Iron	Wrought	HR	—	48	331	30
	P/M—49% Fe min	As sintered	89	30	207	9
	P/M—99% Fe min	As sintered	94	40	276	15
Steel	Wrought AISI 1025	HR	—	85	586	25
	P/M—0.25% C, 99.75% Fe	As sintered	84	34	234	2
Stainless steel	Wrought type 303	Annealed	—	90	621	50
	P/M type 303	As sintered	82	52	358	2
Aluminum	Wrought 2014	T6	—	70	483	20
	P/M 201 AB	T6	94	48	331	2
	Wrought 6061	T6	—	45	310	15
	P/M 601 AB	T6	94	36.5	252	2
Copper	Wrought OFHC	Annealed	—	34	234	50
	P/M copper	As sintered	89	23	159	8
		Repressed	96	35	241	18
Brass	Wrought 260	Annealed	—	44	303	65
	P/M 70% Cu-30% Zn	As sintered	89	37	255	26

[a]Equivalent wrought metal shown for comparison. [b]HR, hot rolled; T6, age hardened.

Design of Powder Metallurgy Parts

- Basic rules for the design of P/M parts
  - Shape of the part must permit ejection from die
  - Powder should not be required to flow into small cavities
  - The shape of the part should permit the construction of strong tooling
  - The thickness of the part should be within the range for which P/M parts can be adequately compacted
  - The part should be designed with as few changes in section thickness as possible

Basic Rules for P/M Parts

- Parts can be designed to take advantage of the fact that certain forms and properties can be produced by P/M that are impossible, impractical, or uneconomical by any other method
- The design should be consistent with available equipment
- Consideration should be made for product tolerances
- Design should consider and compensate for dimensional changes that will occur after pressing

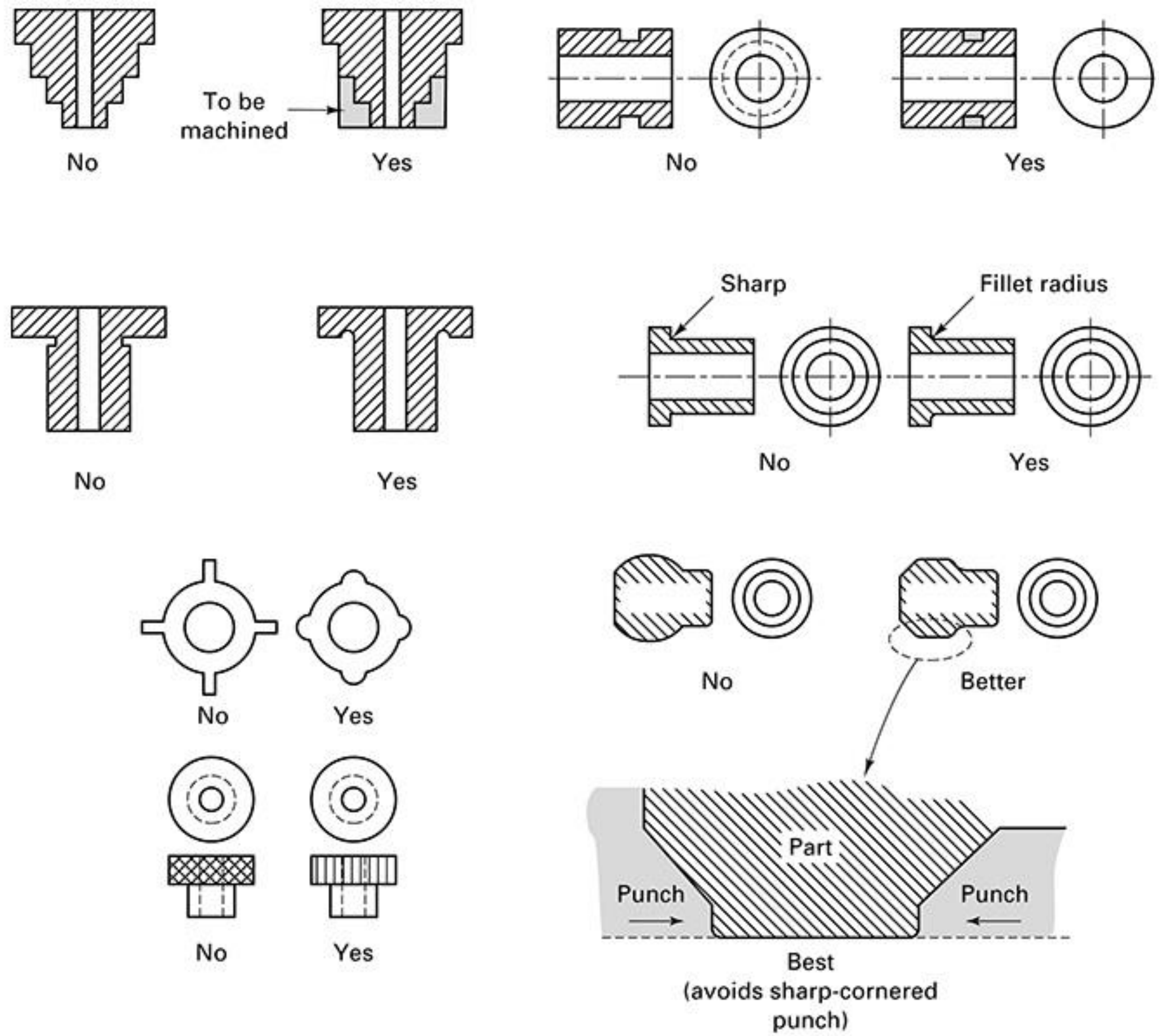


Figure 18-17 Examples of poor and good design features for powder metallurgy products. Recommendations are based on ease of pressing, design of tooling, uniformity of properties, and ultimate performance.

Powder Metallurgy Products

- Porous or permeable products such as bearings, filters, and pressure or flow regulators
- Products of complex shapes that would require considerable machining when made by other processes
- Products made from materials that are difficult to machine or materials with high melting points
- Products where the combined properties of two or more metals are desired
- Products where the P/M process produces clearly superior properties
- Products where the P/M process offers and economic advantage

Advantages and Disadvantages of Powder Metallurgy

- Advantages
  - Elimination or reduction of machining
  - High production rates
  - Complex shapes
  - Wide variations in compositions
  - Wide property variations
  - Scrap is eliminated or reduced
- Disadvantages
  - Inferior strength properties
  - High tooling costs
  - High material cost
  - Size and shape limitations
  - Dimensional changes during sintering
  - Density variations
  - Health and safety hazards

Metal Injection Molding (MIM) or Powder Injection Molding (PIM)

- Ultra-fine spherical-shaped metal, ceramic, or carbide powders are combined with a thermoplastic or wax
  - Becomes the feedstock for the injection process
- The material is heated to a pastelike consistency and injected into a heated mold cavity
- After cooling and ejection, the binder material is removed
  - Most expensive step in MIM and PIM

MIM

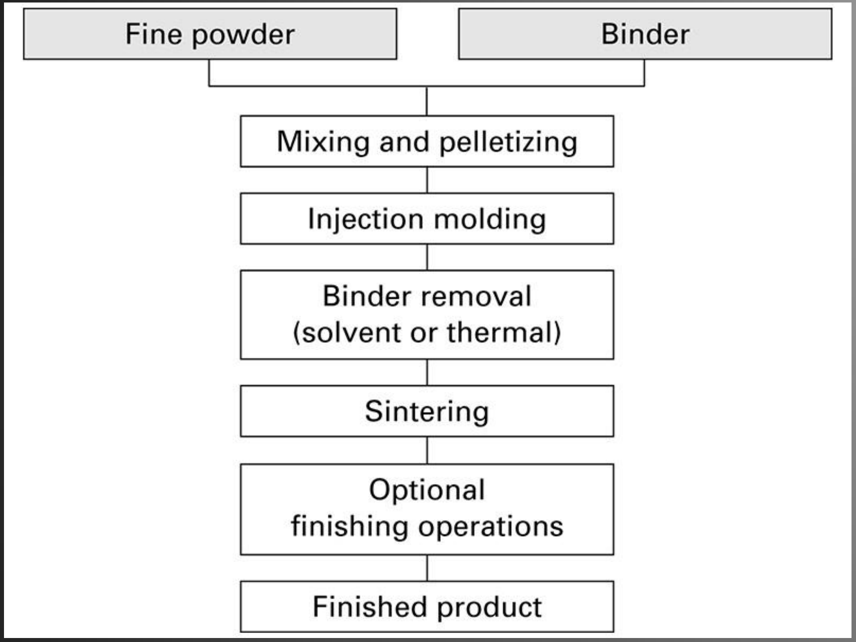


Figure 18-12 Flow chart of the metal injection molding process (MIM) used to produce small, intricate-shaped parts from metal powder.

Figure 18-13 Metal injection molding (MIM) is ideal for producing small, complex parts. (Courtesy of Megamet Solid Metals, Inc., St. Louis, MO.)

Properties of P/M products

- The properties of P/M products depend on multiple variables
  - Type and size of powder
  - Amount and type of lubricant
  - Pressing pressure
  - Sintering temperature and time
  - Finishing treatments
- Mechanical properties are dependent on density
- Products should be designed (and materials selected) so that the final properties will be achieved with the anticipated final porosity

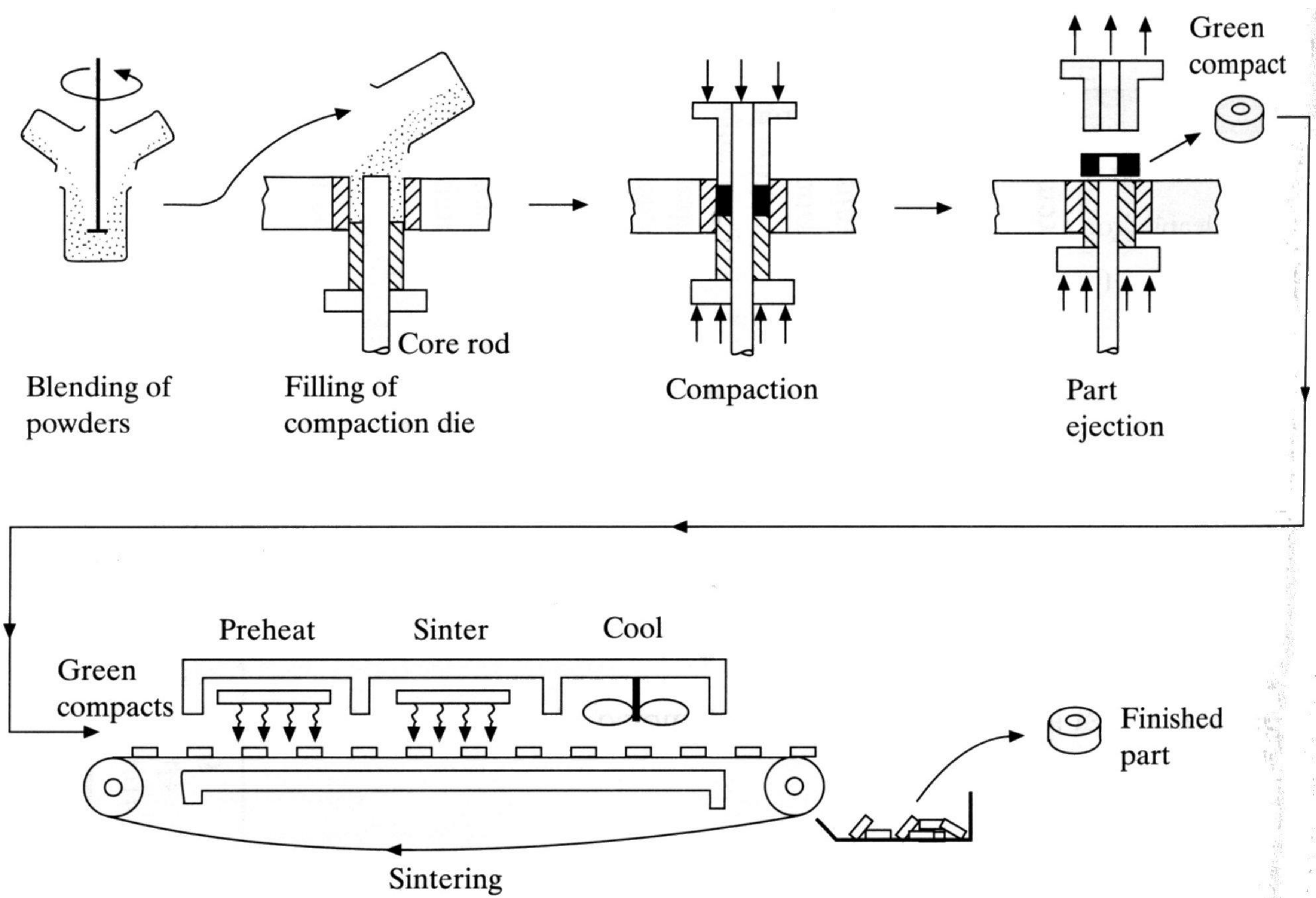
TABLE 18-6 Comparison of Four Powder Processing Methods

Characteristic	Conventional Press and Sinter	Metal Injection Molding (MIM)	Hot-Isostatic Pressing (HIP)	P/M Forging
Size of workpiece	Intermediate <5 pounds	Smallest <1/4 pounds	Largest 1–1000 pounds	Intermediate <5 pounds
Shape complexity	Good	Excellent	Very good	Good
Production rate	Excellent	Good	Poor	Excellent
Production quantity	>5000	>5000	1–1000	>10,000
Dimensional precision	Excellent ±0.001 in./in.	Good ±0.003 in./in.	Poor ±0.020 in./in.	Very good ±0.0015 in./in.
Density	Fair	Very good	Excellent	Excellent
Mechanical properties	80–90% of wrought	90–95% of wrought	Greater than wrought	Equal to wrought
Cost	Low \$0.50–5.00/lb	Intermediate \$1.00–10.00/lb	High >\$100.00/lb	Somewhat low \$1.00–5.00/lb

Summary

- Powder metallurgy can produce products out of materials that are otherwise very difficult to manufacture
- P/M products can be designed to provide the targeted properties
- Variations in product size, production rate, quantity, mechanical properties, and cost

Basic Processing Steps



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