Powder Metallurgy

General Description

- Powder metallurgy, or PM, is a process for forming metal parts by heating compacted metal powders to just below their melting points. Although the process has existed for more than 100 years, over the past quarter century it has become widely recognized as a superior way of producing high-quality parts for a variety of important applications

Powder Metallurgy (P/M)

- Competitive with processes such as casting, forging, and machining.
- Used when
  - melting point is too high (W, Mo).
  - reaction occurs at melting (Zr).
  - too hard to machine.
  - very large quantity.
- Near 70% of the P/M part production is for automotive applications.
- Good dimensional accuracy.
- Controllable porosity.
- Size range from tiny balls for ball-point pens to parts weighing 100 lb. Most are around 5 lb

Advantages

- High strength parts with low ductility metals and metals with very high melting temperatures.
- High tolerance parts possible with minimum processing.
- High alloy contents possible; often alloy content exceeds solubility limits of conventional wrought metallurgical processing.
- Relatively low processing temperatures. Sintering is generally a diffusion driven process rather than a melting process, although some alloy metals may become molten at sintering temperatures

Limitations

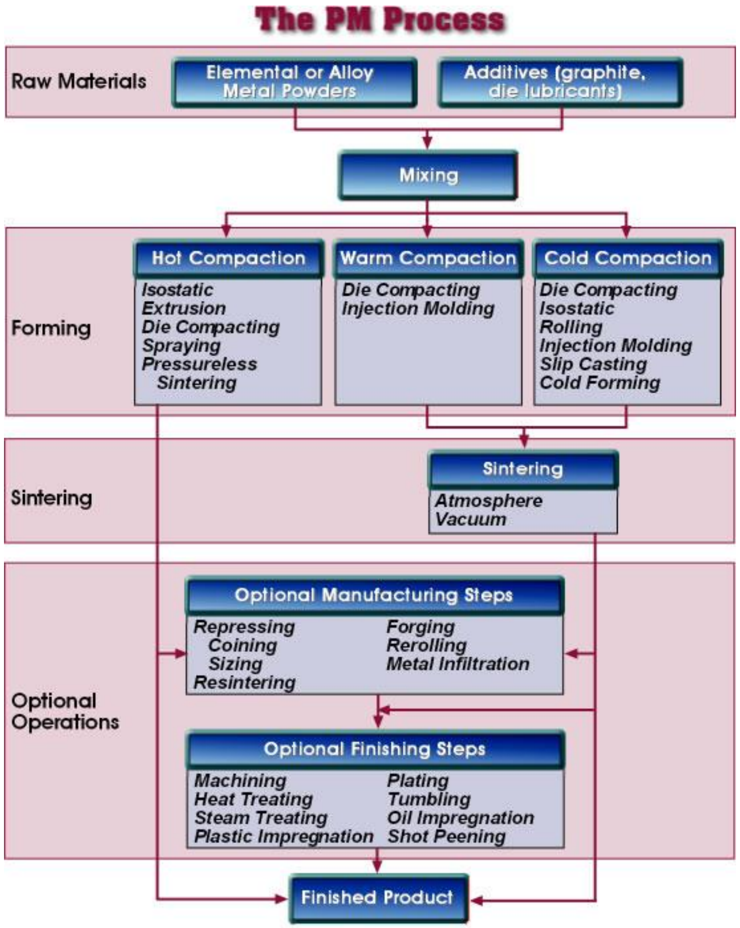
- Size and complexity limitations
- High cost of powder metals compared to other raw materials
- High cost of tooling and equipment for small production runs
- Start-up costs may be high relative to conventional processing.
- Strength and stiffness may be inferior to wrought alloys of similar composition.
- Porosity and low ductility may impair durability.
- Fracture Toughness may be low.

Examples of P/M materials

- Typical metals used to take advantage of P/M technology include:
  - Fe-based alloys (plain-carbon, low alloy, high alloy and stainless steels)
  - Al-based alloys
  - Cu-based alloys
  - Co-based alloys
  - Ni-based alloys
  - Ti-based alloys
  - W-based alloys
  - Refractory metal alloys (Rhenium, tantalum).

Basic Steps In Powder Metallurgy

- Powder Production
- Blending or Mixing
- Powder Consolidation
- Sintering
- Finishing
- The PM process, depicted in the diagram below, consists of mixing elemental or alloy powders, compacting the mixture in a die, and then sintering, or heating, the resultant shapes in a controlled-atmosphere furnace to bond the particles metallurgically.



1. Powder Production

- Many methods: extraction from compounds, deposition, atomization, fiber production, mechanical powder production, etc.
- Atomization is the dominant process

- **Atomization**
- In this process, molten metal is separated into small droplets and frozen rapidly before the drops come into contact with each other or with a solid surface. Typically, a thin stream of molten metal is disintegrated by subjecting it to the impact of high-energy jets of gas or liquid. In principle, the technique is applicable to all metals that can be melted and is used commercially for the production of iron; copper; alloy steels; brass; bronze; low-melting-point metals such as aluminum, tin, lead, zinc, and cadmium; and, in selected instances, tungsten, titanium, rhenium, and other high-melting-point materials.

Atomization Equipments

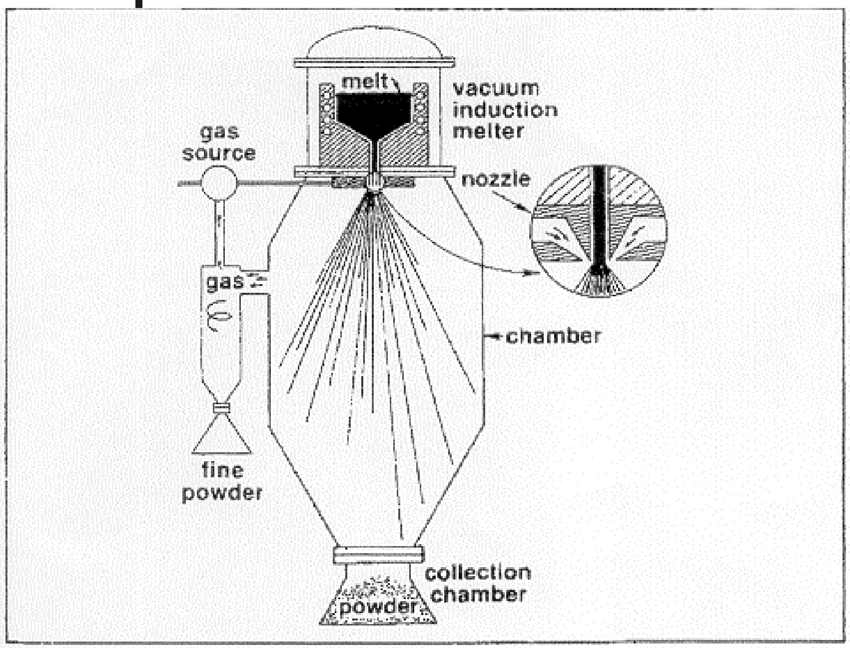
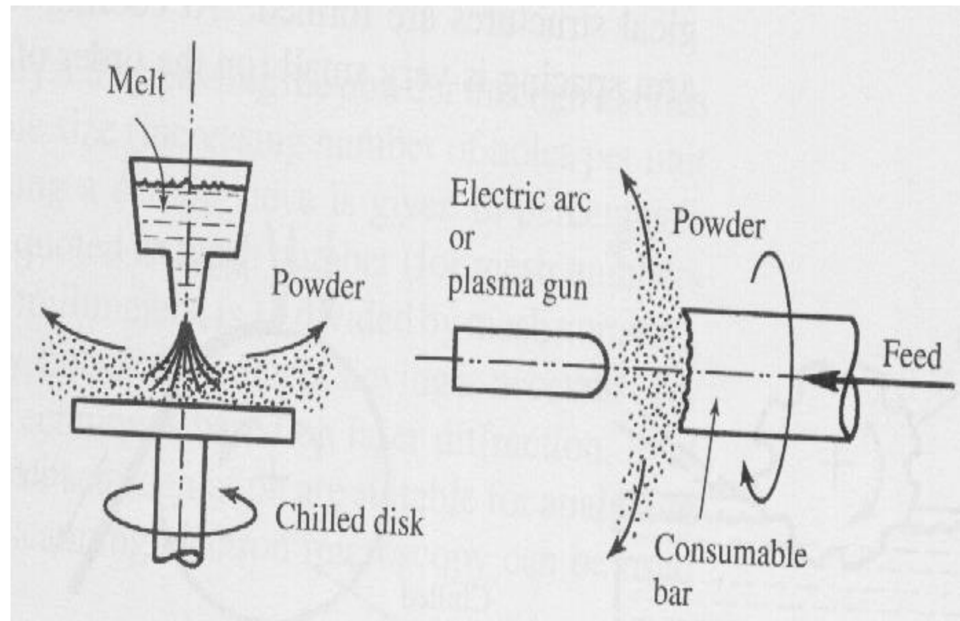


Figure 3.15. A vertical gas atomizer. The main features are a vacuum induction melter, gas expansion nozzle, gas recirculation and supply system, free-flight chamber, and powder collection chamber. An expanded view of the nozzle region is given to show the close proximity of the gas and melt streams needed for efficient atomization.

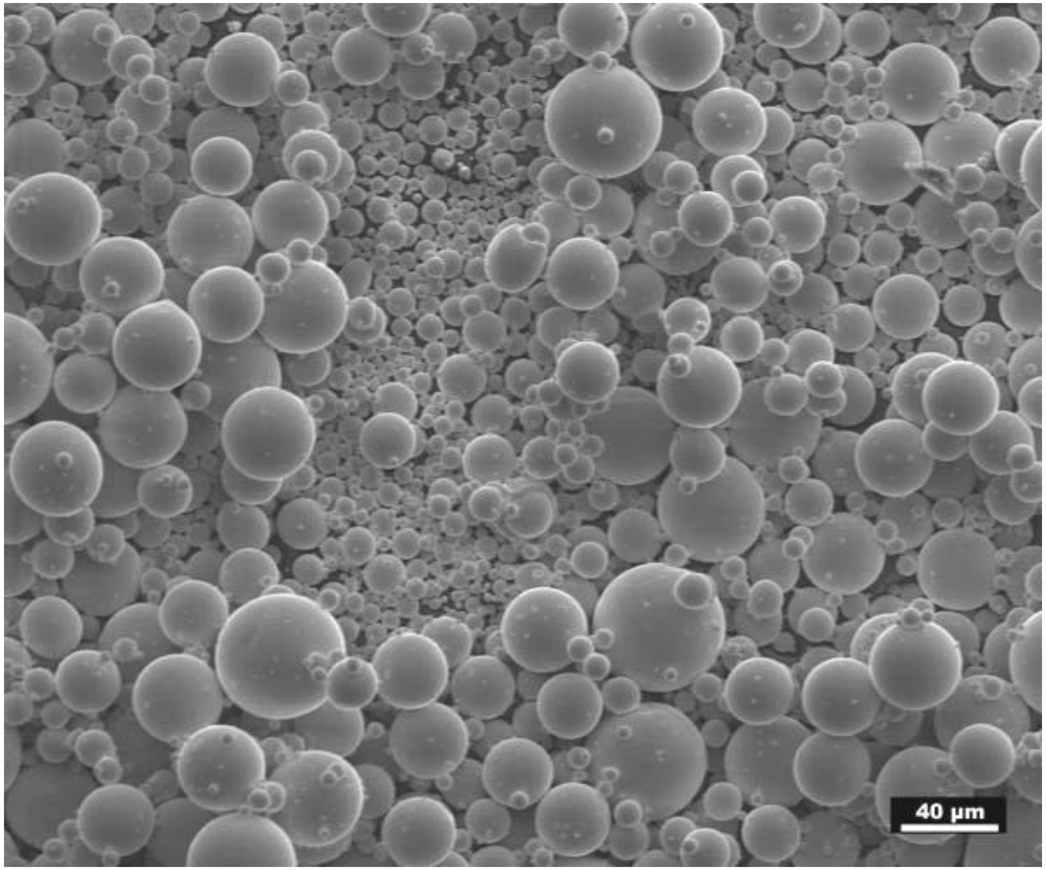


(a) Water or gas atomization; (b) Centrifugal atomization; (c) Rotating electrode

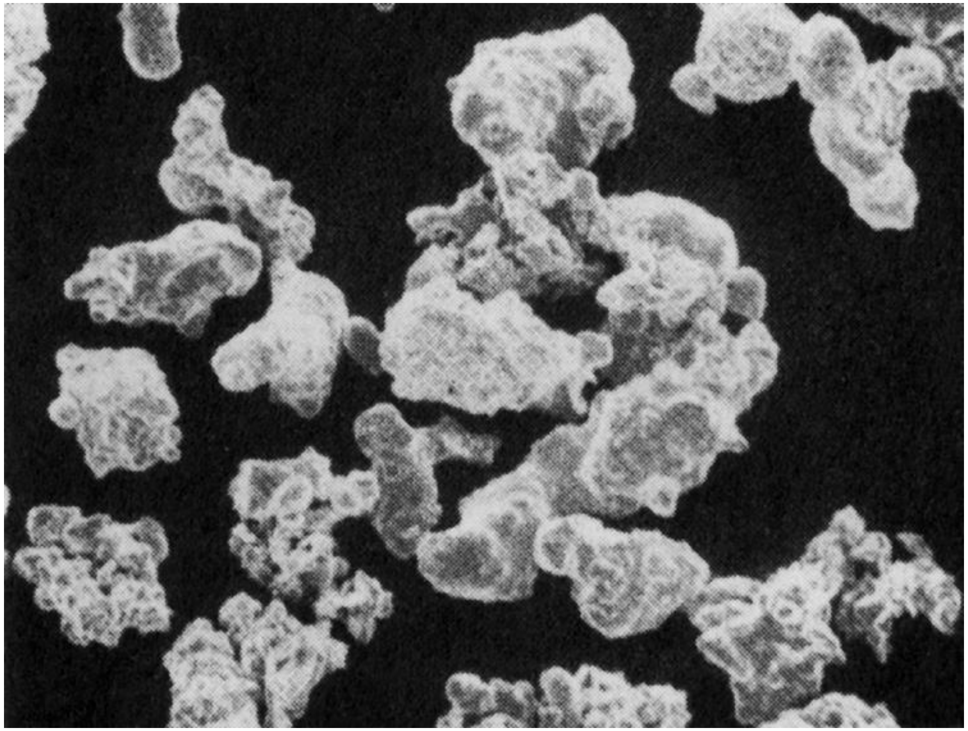
- Gas Atomization
  - Spherical powder particles
  - Good "flowability"
- Water Atomization:
  - Irregular powder particles
  - Good compactability

Microstructure of Gas Atomized Powders

Gas Atomized Silver Alloy



Water Atomized Copper Alloy



ELECTROLYSIS

By choosing suitable conditions, such as electrolyte composition and concentration, temperature, and current density, many metals can be deposited in a spongy or powdery state. Further processing–washing, drying, reducing, annealing, and crushing–is often required, ultimately yielding high-purity and high-density powders. Copper is the primary metal produced by electrolysis but iron, chromium, and magnesium powders are also produced this way. Due to its associated high energy costs, electrolysis is generally limited to high-value powders such as high-conductivity copper powders.

REDUCTION

- Uses gases (hydrogen and CO) to remove oxygen from metal oxides.

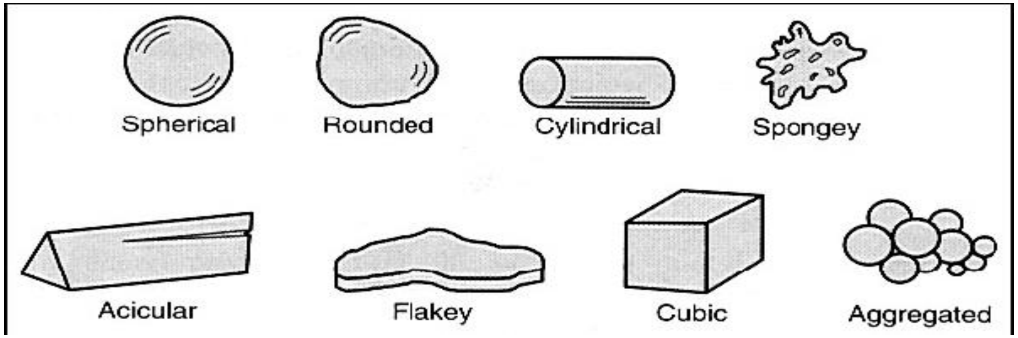
- ***CHEMICAL***

  The most common chemical powder treatments involve oxide reduction, precipitation from solutions, and thermal decomposition. The powders produced can have a great variation in properties and yet have closely controlled particle size and shape. Oxide-reduced powders are often characterized as “spongy,” due to pores present within individual particles. Solution-precipitated powders can provide narrow particle size distributions and high purity. Thermal decomposition is most often used to process carbonyls. These powders, once milled and annealed, exceed 99.5 percent purity.

- **Carbonyls**
  - Are formed by letting iron or nickel react with CO. The reaction products are then decomposed to iron and nickel.
- **Comminution**
  - Mechanical comminution involves crushing, milling in a ball mill.
- **Mechanical alloying**
  - Powders of two or more pure metals are mixed in a ball mill. This process forms alloy powders

Particle's Properties

- **Particle Shape**
- The measure of particle shape is the ratio of maximum dimension to minimum one for a given particle.



- **Surface Area**
- For any particle shape, the shape factor, Ks, defines the area-to-volume ratio,
- Ks= AD/V
- where A is the surface area, V is the volume, and D is the diameter of a sphere of equivalent volume as the non-spherical particle.

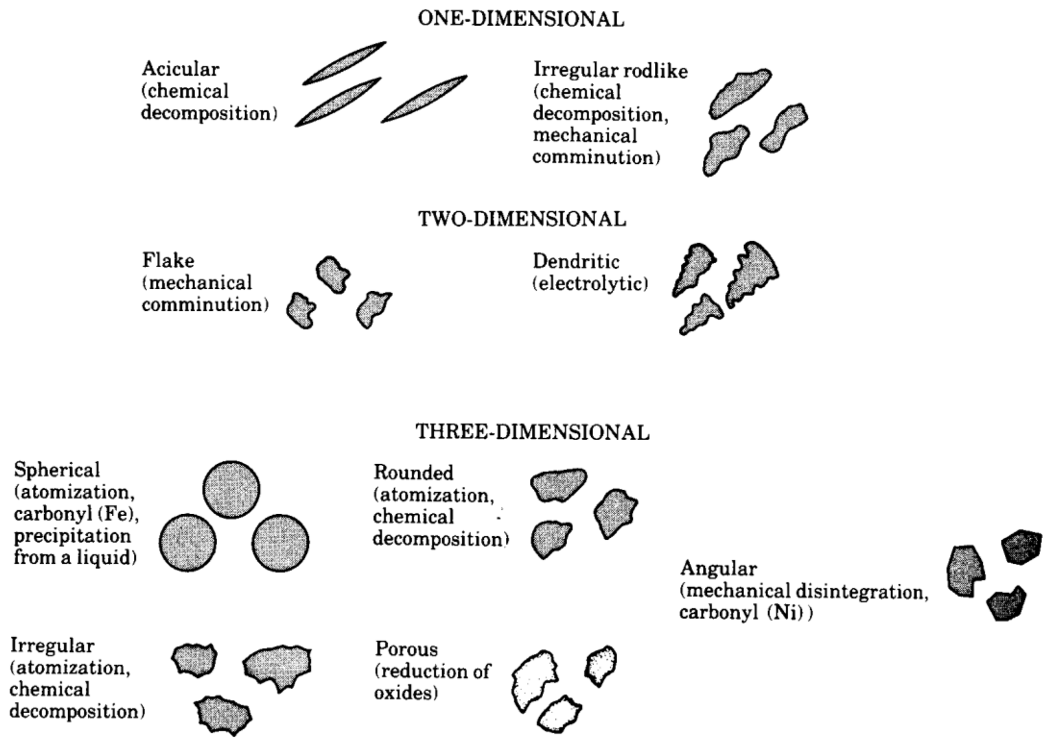


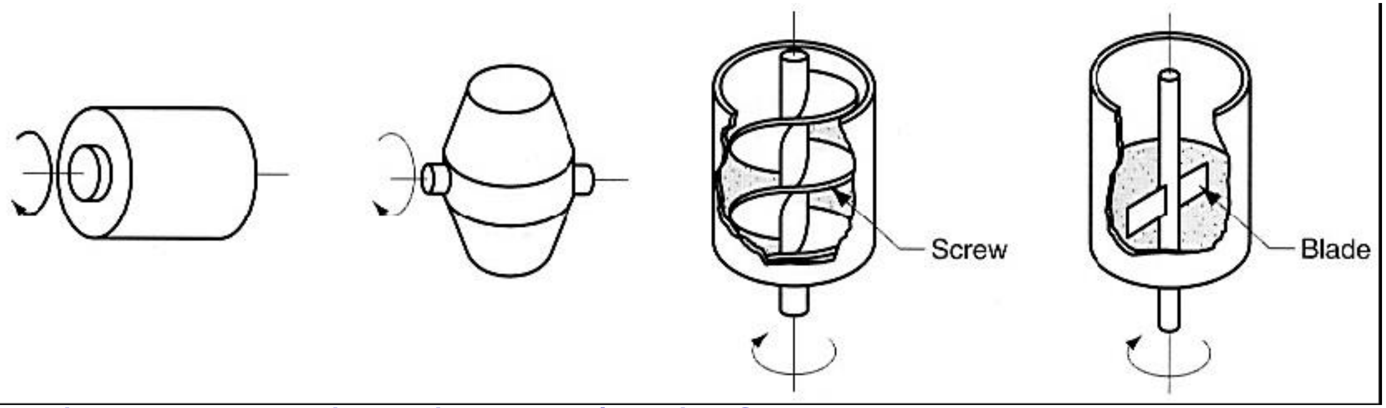
FIGURE 11.2 Particle shapes in metal powders and the processes by which they are produced. Iron powders are produced by many of these processes.

Blending

- The ideal mix is one in which all the particles of each material are distributed uniformly
- Powders of different metals and other materials may be mixed in order to impart special physical and mechanical properties
- Lubricants may be mixed with the powders to improve their flow characteristics.
- Hazards: Over-mixing may wear particles or work-harden them. High surface area to volume ratio – susceptible to oxidation; and may explode!

Blending and Mixing

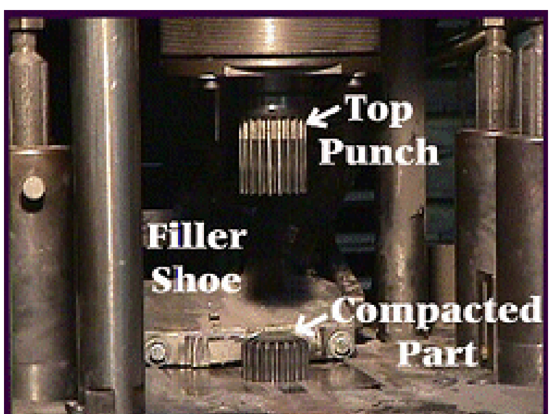
- *Blending*: mixing powder of the same chemical composition but different sizes
- *Mixing*: combining powders of different chemistries
- Blending and mixing are accomplished by mechanical means:
- Several blending and mixing devices: (a) rotating drum, (b) rotating double cone,
- (c) screw mixer, (d) blade mixer



- E
- v *Lubricants*: to reduce the particles-die friction
- v *Binders*: to achieve enough strength before sintering
- v *Deflocculants*: to improve the flow characteristics during feeding

Powder Consolidation

- Cold compaction with 100 – 900 MPa to produce a "Green body".
  - Die pressing
  - Cold isostatic pressing
  - Rolling
  - Gravity



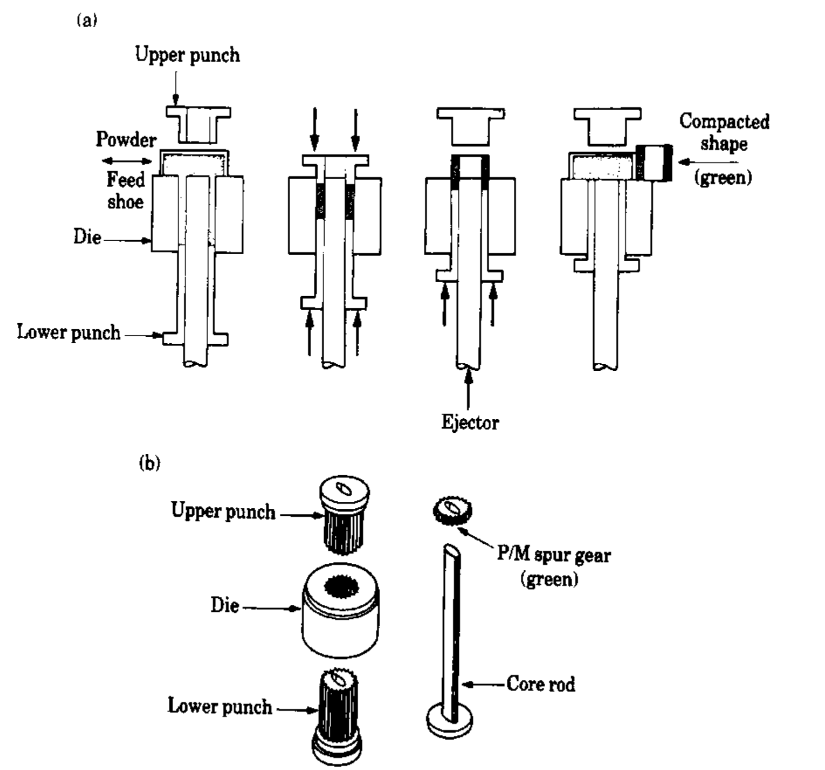
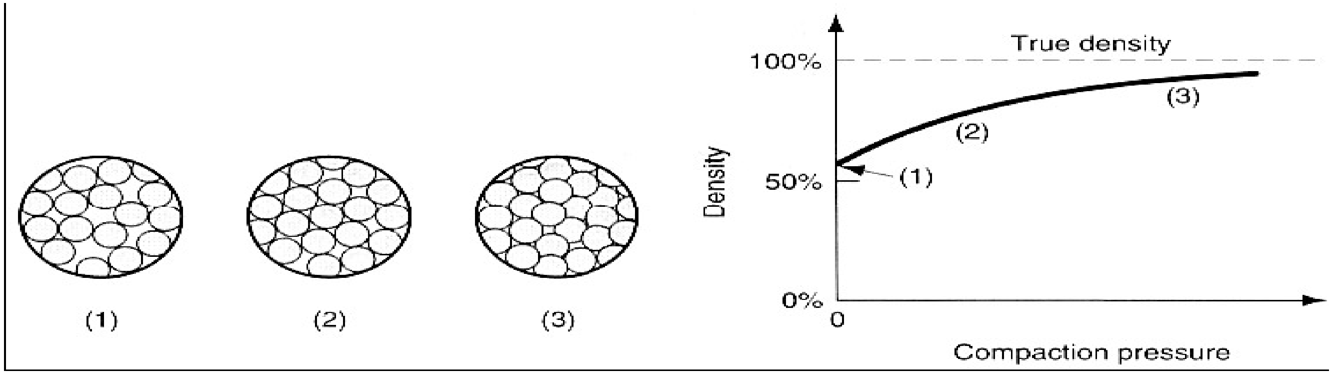


FIGURE 11.6 (a) Compaction of metal powder to form a bushing. The pressed powder part is called green compact. (b) Typical tool and die set for compacting a spur gear. *Source:* Reprinted with the permission of the Metal Powder Industries Federation, 105 College Road East, Princeton, NJ.

- Pressure and density distributions after compaction
- As a result of compaction, the density of the part, called the green density is much greater than the starting material density, but is not uniform in the green. The density and therefore mechanical properties vary across the part volume and depend on pressure in compaction:



- Effect of applied pressure during compaction: (1) initial loose powders after filling, (2) repacking, and (3) deformation of particles.



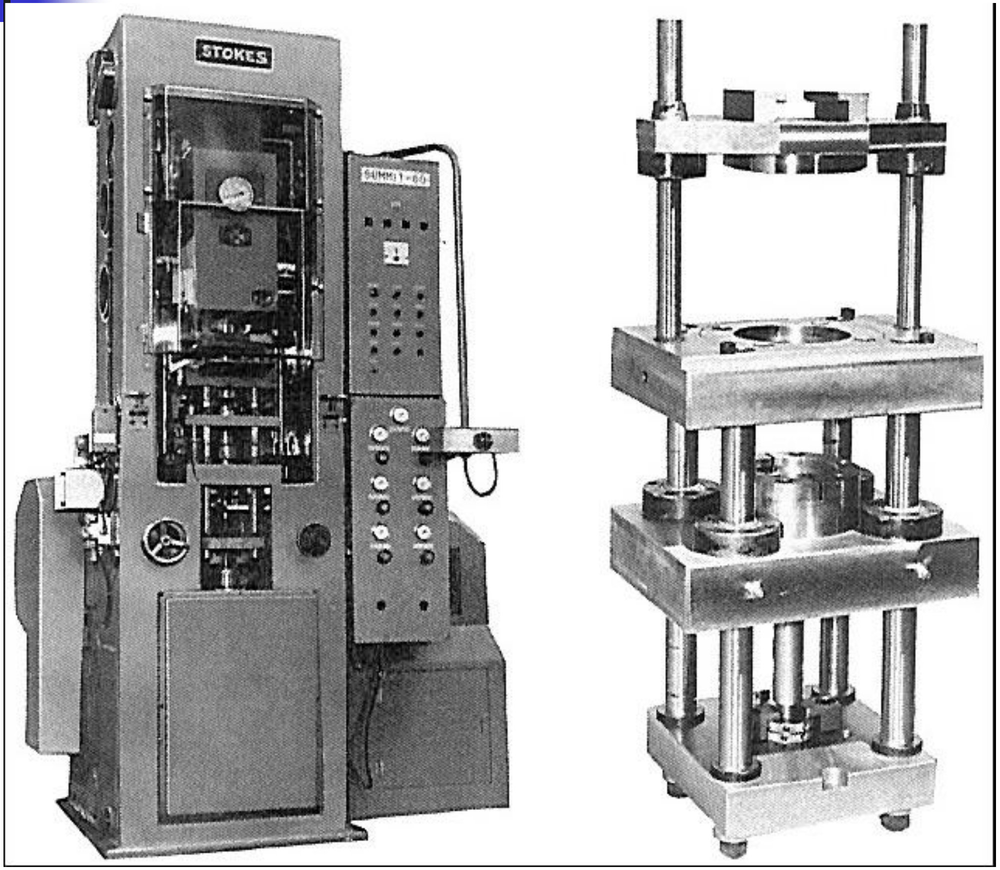
Equipment

- Required pressure ranges from 70 MPa (for aluminum) to 800 MPa (high density iron)

Die Compaction

  - Use water atomized powder (irregular shape)
  - Rigid tooling: tool steel, WC/Co
  - Pressures up to 60 tons/square inch
  - Production > 10,000 parts
  - High tolerance, 0.001 "/" possible
  - High productivity
  - Controlled porosity, density (85% to 90%)

- Isostatic Pressing
  - Cold isostatic pressing (CIP) – the powder is placed in a flexible rubber mold. The assembly is then pressurized hydrostatically in a chamber, usually with water. This results in a pressure of 400 MPa.
  - Hot isostatic pressing (HIP) – the container is usually made of a high melting point sheet metal, and the pressurizing medium is inert gas or vitreous fluid. Pressure is 100 MPa at 1100 C. Results in 100% density.



Typical press for the compaction of metallic powders.

The removable die set (*right*) allows the machine to be producing parts with one die set while another is being fitted to produce a second part

Cold Isostatic Pressing

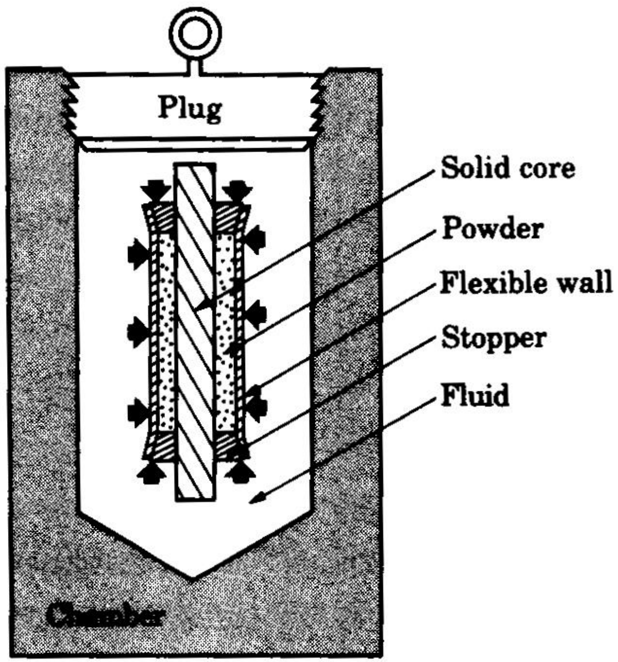


FIGURE 11.10 Schematic diagram of cold isostatic pressing as applied to forming a tube. The powder is enclosed in a flexible container around a solid core rod. Pressure is applied isostatically to the assembly inside a high-pressure chamber. *Source:* Reprinted with permission from Randall M. German, *Powder Metallurgy Science*. Princeton, NJ: Metal Powder Industries Federation, 1984.

Hot Isostatic Pressing

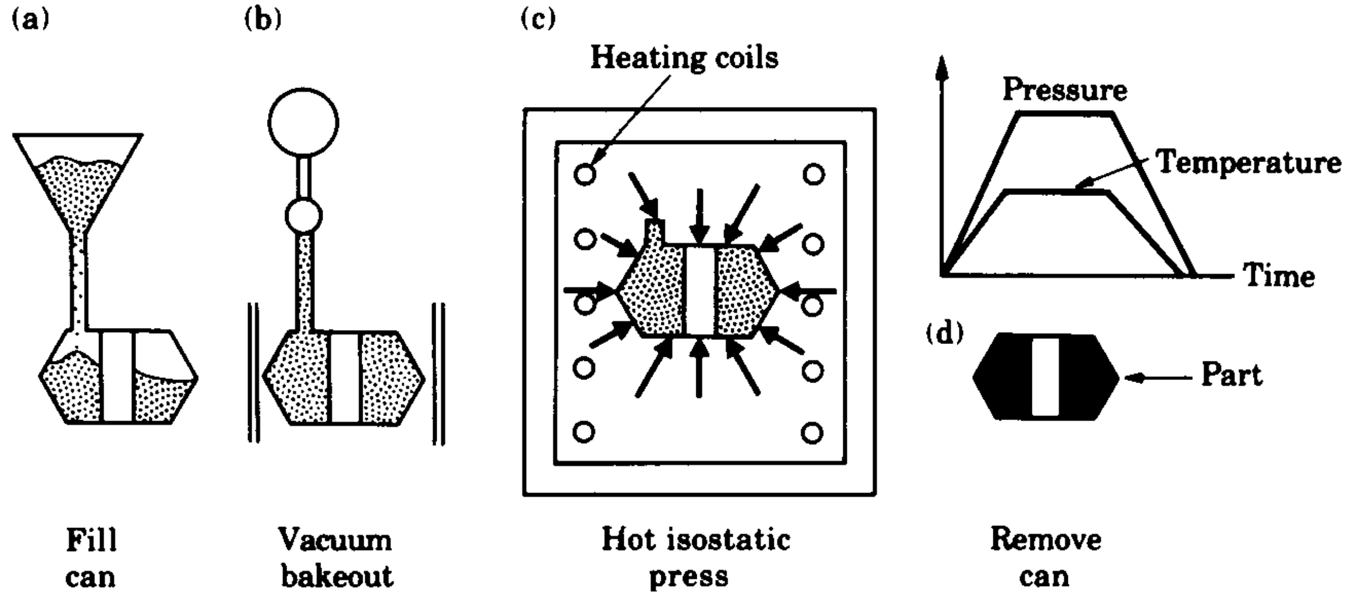


FIGURE 11.12 Schematic illustration of hot isostatic pressing. The pressure and temperature variation versus time are shown in the diagram. *Source:* Reprinted with permission from Randall M. German, *Powder Metallurgy Science.* Princeton, NJ: Metal Powder Industries Federation, 1984.

Other compacting processes

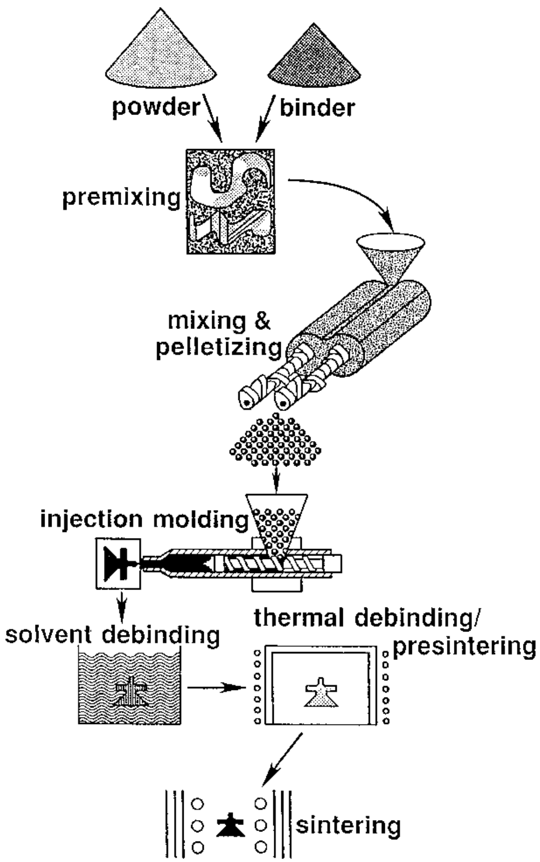
- Forging
- Rolling
- Extrusion
- Injection Molding
- Pressureless compaction
- Ceramic molds

MIM (Metal Injection Molding)

- **Plastic Injection Molding + Powder Metallurgy (P/M)**
- Complex Shapes
- High density metal parts (> 95%)
- Economy of Scale (high productivity)
- Good tolerance, .003 "/" possible, .005-.008 "/" typ.

✓ ***Competes with investment casting***

and discrete machining



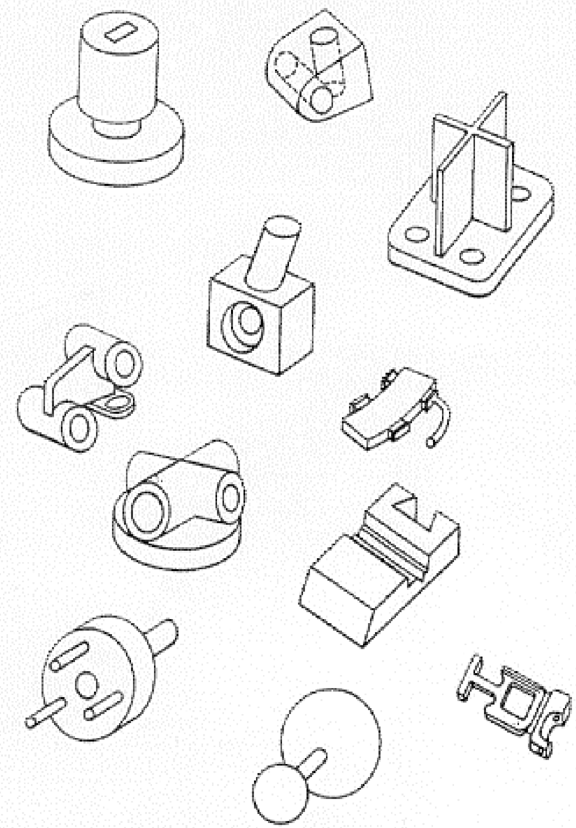


Figure 6. Examples of possible geometries for MIM parts (27).

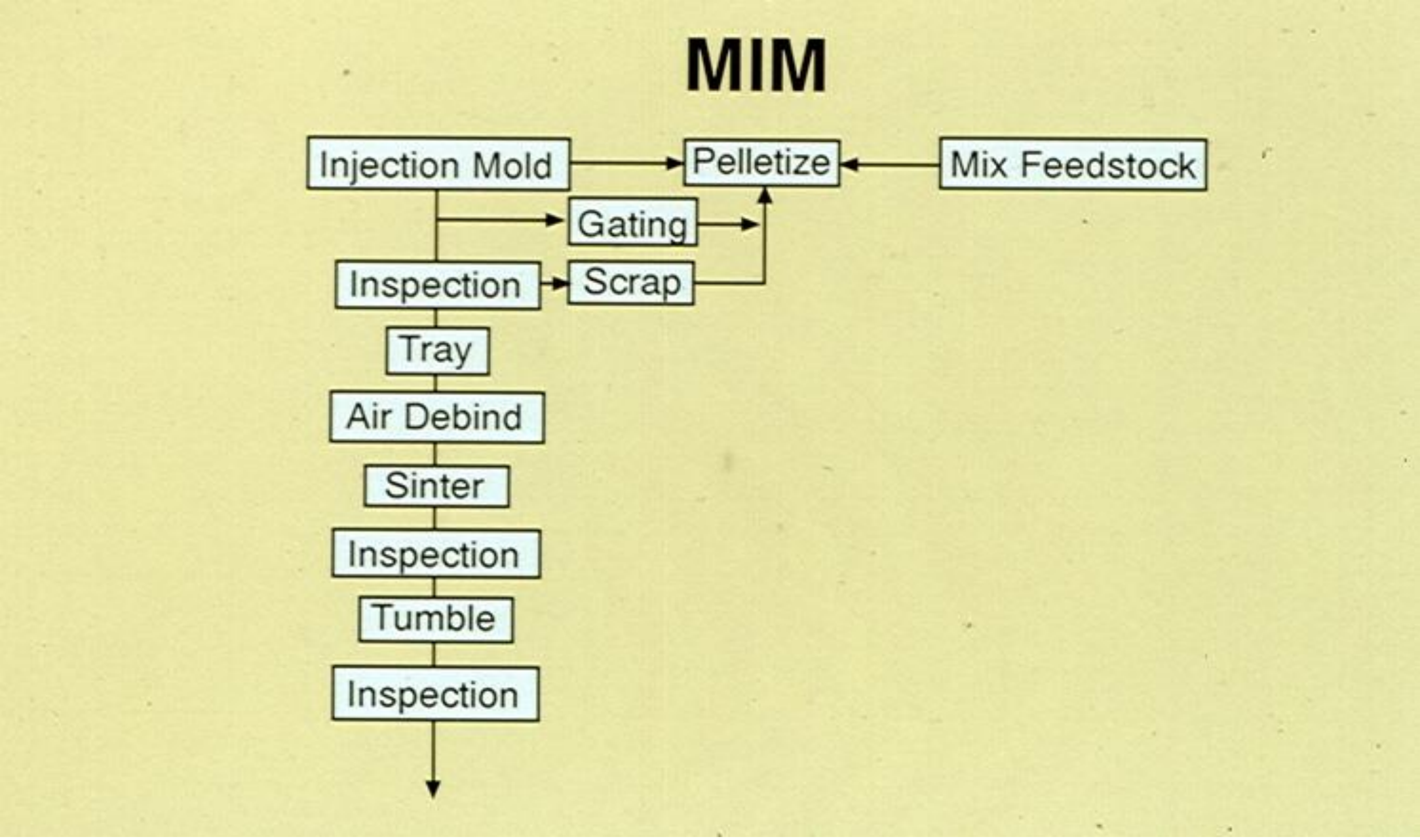

LIBERTY

Applications, General Case Studies: Connecting Rod

Applications, General Case Studies: Orthodontia Brackets

MIM vs. Discrete machining and Investment casting:

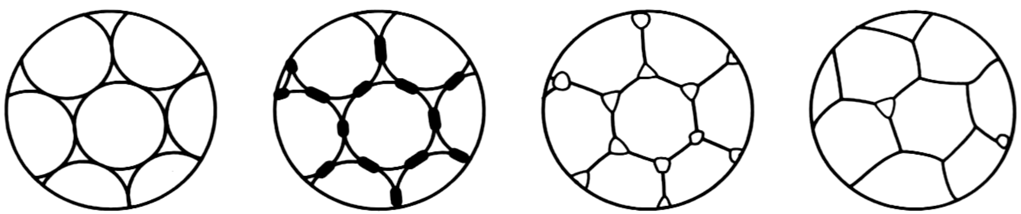
- Elimination of all machining operations
- Better material utilization (no chips, sprues, etc)
- Able to produce smaller parts than investment cast
- Able to produce more complex geometries than machining
- Massive reduction in labor
- Complete payback in about 2 years

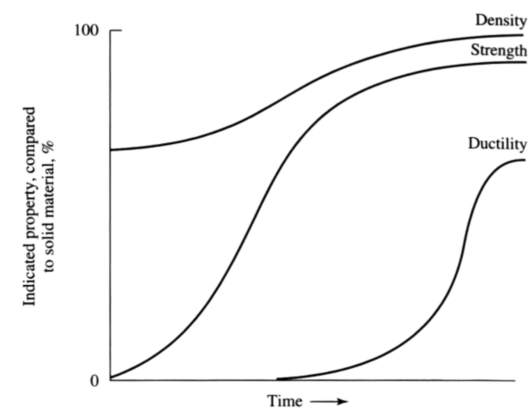

MIM
Injection Mold
Pelletize
Mix Feedstock
Gating
Inspection
Scrap
Tray
Air Debind
Sinter
Inspection
Tumble
Inspection

Applications, General Case Studies: Orthodontia Brackets

Sintering

- **Parts are heated to 0.7~0.9 *Tm*.**
- **Transforms compacted mechanical bonds to much stronger metallic bonds.**





- **Shrinkage always occurs:**

$$Vol\_shrinkage = \frac{V_{sintered}}{V_{green}} = \frac{\rho_{green}}{\rho_{sintered}}$$

$$Linear\_shrinkage = \left(\frac{\rho_{green}}{\rho_{sintered}}\right)^{1/3}$$

Sintering

- The process whereby compressed metal powder is heated in a controlled atmosphere furnace to a temperature below its melting point, but high enough to allow bonding of the particles.
- Sintered density depends on its “green density” and sintering conditions (temperature, time and furnace atmosphere).
- Sintering temperatures are generally within 70 to 90% of the melting point of the metal or alloy.
- Times range from 10 minutes for iron and copper to 8 hours for tungsten and tantalum

- 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).

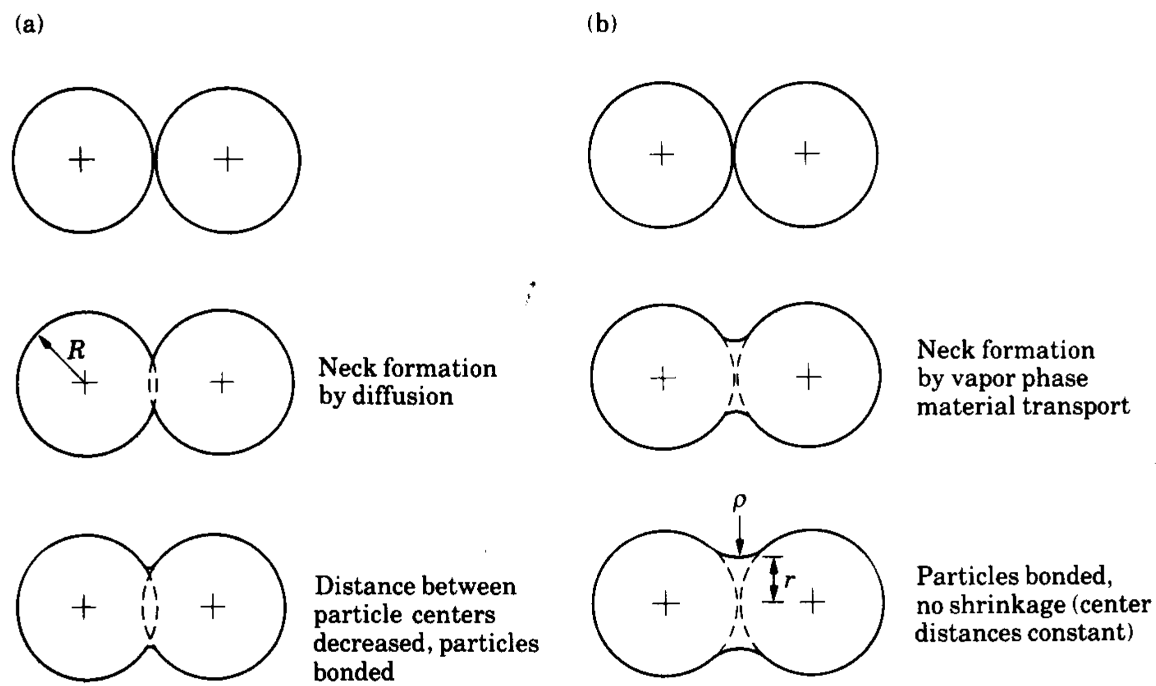


FIGURE 11.13 Schematic illustration of two mechanisms for sintering metal powders: (a) solid-state material transport; and (b) liquid-phase material transport. R = particle radius, r = neck radius, and ρ = neck profile radius.

Finishing

- The porosity of a fully sintered part is still significant (4-15%).
- Density is often kept intentionally low to preserve interconnected porosity for bearings, filters, acoustic barriers, and battery electrodes.

- However, to improve properties, finishing processes are needed:
  - Cold restriking, resintering, and heat treatment.
  - Impregnation of heated oil.
  - Infiltration with metal (e.g., Cu for ferrous parts).
  - Machining to tighter tolerance.

Design Considerations

- Shape of compact must be kept as simple and uniform as possible. Sharp changes in contour, thin sections, etc. should be avoided.
- Provisions must be made for ejection of the green compact from the die without damaging the compact.
- Parts should be produced with the widest tolerances.