17.1 Introduction

- This chapter describes the powder metallurgy (P/M) process, in which metal powders are compacted into desired and often complex shapes and sintered (heated without melting) to form a solid piece.

- This process first was used by the Egyptians in about 3000 B.C. to iron tools. One of its first modern uses was in the early 1900s to make the tungsten filaments for incandescent light bulbs.

- A wide range of parts and components are made by powder-metallurgy techniques (See Fig 17.1): (a) balls for ball-point pens, (b) automotive components (which constitute about 70% of the P/M market), (c) tool steels, tungsten carbide, and cerments as tool and die materials, (d) graphite brushes impregnated with copper for electric motors, (e) magnetic materials, (f) metal filters and oil-impregnated bearings with controlled porosity, (g) metal foams, (h) surgical implants, and (i) several others for aerospace, nuclear, and industrial application.

- P/M has become competitive with processes (such as casting, forging, and machining), particularly for relatively complex parts made of high strength and hard alloys.

- The most commonly used metals in P/M are iron, copper, aluminum, tin, nickel, titanium, and the refractory metals.

- Powder sources are generally bulk metals and alloys, salts, and other compounds.

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Figure 17.1 (a) Examples of typical parts made by powder-metallurgy processes. (b) Upper trip lever for a commercial sprinkler made by P/M. This part is made of an unleaded brass alloy; it replaces a die-cast part with a 60% savings. (c) Main-bearing metal-powder caps for 3.8 and 3.1 liter General Motors automotive engines

- The powder-metallurgy process consists of the following operations, in sequence (see Fig. 17.2):
  1. Powder production
  2. Blending
  3. Compaction
  4. Sintering
  5. Finishing operation
17.2 Production of Metal Powders

17.2.1 Methods of Powder Production

- There are several methods of producing metal powders, and most of them can be produced by more than one method.
- The microstructure, bulk and surface properties, chemical purity, porosity, shape, and size distribution of the particles depend on the method used (see Figs. 17.3 & 17.4).
- Such characteristics significantly affect the flow and permeability during compaction and in subsequent sintering operations.
- Particle sizes produced range from 0.1 to 1000 \(\mu m\).
A. Atomization.

- Atomization produces a liquid-metal stream by injection molten metal through a small orifice.
- The stream is broken by jets of inert gas or air → gas atomization (Fig. 17.5a), or water → water atomization (Fig. 17.5b).
- The size and shape of the particles formed depends on the temperature of the molten metal, rate of flow, nozzle size, and jet characteristics.
- Use of water results in slurry of metal powder and liquid at the bottom of the atomization chamber. Although the powders must be dried before they can be used, the water allows for rapid cooling of the particles and higher production rates.
- Gas atomization usually results in more spherical particles (See Fig. 17.3c).
- In centrifugal atomization, the molten-metal stream drops onto a rapid rotating disk or cup, so that centrifugal forces break up the molten-metal stream and generate particles (Fig. 17.5c).
- In another centrifugal atomization, a consumable electrode is rotated rapidly (about 15,000 rev/min) in a helium-filled chamber (Fig. 17.5d). The centrifugal force breaks up the molten tip of the electrode into metal particles.
B. Reduction.

- The reduction of metal oxides (i.e., removal of oxygen) uses gases, such as hydrogen and carbon monoxide, as reducing agents.
- Very fine metallic oxides are reduced to the metallic state.
- Powders produced are spongy and porous and have uniformly sized spherical or angular shapes.

C. Electrolytic deposition.

- Utilizes either aqueous solution or fused salts.
- The powders produced are among the purest available.

D. Carbonyls.

- Metal carbonyls, such as iron carbonyl [Fe(CO)5] and nickel carbonyl [Ni(CO)4], are formed by letting iron or nickel react with carbon monoxide.
- The reaction products are then decomposed to iron and nickel, and they turn into small, dense, uniformly spherical particles of high purity.

E. Comminution.

- Mechanical comminution (pulverization) involves crushing (Fig. 17.6), milling in a ball mill, or grinding of brittle or less ductile metals into small particles.
- A ball mill (Fig. 17.6b) is a machine with a rotating hollow cylinder partly filled with steel or white cast-iron balls.
- For brittle materials, the powder particles produced have angular shapes.
- For ductile materials, particles are flaky and not suitable for P/M applications.

![Figure 17.6](image)

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

F. Mechanical alloying.

- Powders of two or more metals are mixed in a ball mill (see fig. 17.7).
- Under the impact of hard balls, the powders fracture and bond together by diffusion, forming alloy powders.
- The dispersed phase can result in strengthening of the particles or can impart special electrical or magnetic properties of the powder.
Figure 17.7 Mechanical alloying of nickel particles with dispersed smaller particles. As nickel particles are flattened between the two balls, the second smaller phase is impresses into the nickel surface and eventually is dispersed throughout the particle due to successive flattening, fracture, and welding events.

G. Miscellaneous methods. Other less commonly used methods for making powders are:
- Precipitation from a chemical solution.
- Production of fine metal chips by machining.
- Vapor condensation.

17.2.2 Particle size, shape, and distribution
- **Particle size** is usually measured by screening – by passing the metal powder through sieves of various mesh sizes.
  - **Screen analysis** is achieved by using a *vertical stack* of screens with the mesh size becoming fine as the powder flows downward through the screens. The larger the mesh size, the smaller is the opening in the screen. For example, a mesh size of 30 has an opening of 600 µm, size of 100 has 150 µm, and size 400 has 38 µm.
  - In addition to screen (sieve) analysis, several other methods are available for particle-size analysis:
    1. **Sedimentation**, which involves measuring the rate at which particles settle in a fluid.
    2. **Microscopic analysis**, which may include the use of transmission and scanning electron microscopy.
    3. **Light scattering** from a laser that illuminates a sample consisting of particles suspended in a liquid medium. The particles cause the light to be scattered, and a detector then digitizes the signals and computes the particle-size distribution.
    4. **Optical** (such as particles blocking beam of light), which is then sensed by photocell.
    5. **Suspending particles** in a liquid and then detecting particle size and distribution by electrical sensors.

- **Particle shape**
  - Particle shape is usually described in terms of **aspect ratio**.
  - Aspect ratio is the ratio of the largest dimension to the smallest dimension of the particle.
  - The ratio ranges from unity (spherical particles) to about 10 for flake-like or needle-like particles.

- **Shape factor (SF)**
  - **Shape factor** (shape index) is a measure of the ratio of the surface area of the particle to its volume – normalized by reference to a spherical particle of equivalent volume.
  - Thus, the shape factor for a flake is higher than that for a sphere.
Size distribution
- It is an important consideration because it affects the processing characteristics of the powder.
- The distribution of a particle is given in terms of frequency-distribution plot (section 36.7).
  The maximum is called the mode size.

Other properties of metal powders that have an effect on their behavior in processing them are:
- a) Flow properties when filled into dies.
- b) Compressibility when being compacted.
- c) Density, as defined in various terms such as theoretical density, apparent density, and the density when the powder is shaken or tapped in the die cavity.

17.2.3 Blending Metal Powders
- Blending (mixing) powders (second step in P/M) is carried out with the following in mind:
  - The ideal mix is one in which all the particles of each material (and of each size and morphology) are distributed uniformly.
  - Proper mixing is essential to ensure uniformity of mechanical properties throughout the part.
  - When a single metal is used, the powders may vary significantly in size and shape, hence they must be blended to obtain uniformity from part to part.
  - Powders of different metals can be mixed to impart special physical and mechanical properties to the P/M product.
  - Note that the mixture of metals can be produced by alloying the metal before producing a powder, or else blends can be produced (make powder alloy).
  - Lubricants can be mixed with the powders to improve their flow characteristics. They reduce friction between metal particles, improve flow of the powder metals into the die, and improve die life. Lubricants are typically stearic acids or zinc stearate in a proportion from 0.25% to 5% by weight.
  - Other additives – binders are used to develop sufficient green strength, and additives also can be used to facilitate sintering.
- Powder mixing must be under controlled conditions. Deterioration is caused by excessive mixing, which may alter the shape of the particles and work-harden them and, thus, make the subsequent compaction operation more difficult.
- Powders can be mixed in air, in inert atmosphere (to avoid oxidization), or in liquids (which act as lubricants and make the mix more uniform).
- Several types of blending equipment are available (Fig. 17.8).
Figure 17.8 (a) through (d) Some common bowl geometries for mixing or blending powders. (e) A mixer suitable for blending metal powders. Since metal powders are abrasive, mixers rely on the rotation or tumbling of enclosed geometries as opposed to using aggressive agitators.

- **Hazards**: because of their high surface area-to-volume ratio, metal powders can be explosive, particularly aluminum, magnesium, titanium, zirconium, and thorium. So precautions must include:
  a) grounding equipment,
  b) preventing sparks (by using non-sparking tools) and avoiding friction as a source of heat, and
  c) avoiding dust clouds, open flames, and chemical reactions.

### 17.3 Compaction of Metal Powders

- In this step blended powders are pressed into various shapes in dies.
- Purposes of compaction are to obtain the required shape, density, and particle-to-particle contact and to make part sufficiently strong for further processes.
- Figure 17.9 shows a sequence of steps. The powder (feedstock) is feed into the die by a feed shoe; the upper punch descends into the die (single or double punches). The lower punch raises the part out of the dies (see video).
- The presses used are actuated either hydraulically or mechanically.
- The process is carried out at room temperature, although it can be done at elevated temperature.

![Figure 17.9](image)

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.
The pressed powder is known as **green compact**. It has low strength, very fragile (like chalk) and can crumble very easily; this situation is **worsened** by **poor pressing practice**.

To obtain higher green strengths, the powder must be fed properly into the die cavity, and **proper pressures** must be developed throughout the part.

The density of the green compact depends on the pressure applied (see Fig. 17.10a). As the compacting pressure **increased**, the compact density approaches that of the metal in its bulk form.

Size distribution of the particles is an important factor in density.

- If all of the particles are of the **same size**, there always will be some porosity when they are packed together (theoretically a porosity of at least 24% by volume).
- **Introducing small particles** into the powder mix will fill the spaces between the larger powder particles and, thus, result in a higher density of the compact (see section 6.2).

The higher the density of the green compacted part, the higher its strength and elastic modulus (Fig. 17.10b). There is higher amount of solid metal in the same volume, and hence the greater its strength.

Figure 17.10  (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. (b) Effect of density on tensile strength, elongation, and electrical conductivity of copper powder.
Because of friction between (a) the metal particles in the powder and (b) the punch surfaces and the die walls, the density within the part can vary considerably. This variation can be minimized by proper punch and die design and by control of friction.

For example, it may be necessary to use multiple punches with separate movements, in order to ensure that the density is more uniform throughout the part (see Fig. 17.11).

However, density variation in components such as gears, cams, bushings, and structural parts may be desirable. So, densities can be increased in critical locations where high strength and where resistance are important and reduced where they are not.

![Density variation in compacting metal powders in various dies](image)

Figure 17.11 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 when compared with (c). (e) Pressure contours in compacted copper powder in a single-action press.

### 17.3.1 Equipment

**Pressure required for pressing** metal powders ranges from 70 MPa (for aluminum) to 800 MPa (for high-density iron parts) – see Table 17.1.

The compacting pressure required depends on the characteristics and shape of the particles, on the method of blending, and on the lubricants.

**Press capabilities** are on the order of 1.8 to 2.7 MN (200 to 300 tons), although presses with higher much higher capabilities are used for special applications. Most applications require less than 100 tons.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>70-275</td>
</tr>
<tr>
<td>Brass</td>
<td>400-700</td>
</tr>
<tr>
<td>Bronze</td>
<td>200-275</td>
</tr>
<tr>
<td>Iron</td>
<td>350-800</td>
</tr>
<tr>
<td>Tantalum</td>
<td>70-140</td>
</tr>
<tr>
<td>Tungsten</td>
<td>70-140</td>
</tr>
<tr>
<td>Other materials</td>
<td></td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>110-140</td>
</tr>
<tr>
<td>Carbon</td>
<td>140-165</td>
</tr>
<tr>
<td>Cemented carbides</td>
<td>140-400</td>
</tr>
<tr>
<td>Ferrites</td>
<td>110-165</td>
</tr>
</tbody>
</table>
For small tonnage, *mechanical presses* are used. *Hydraulic presses* (Fig. 17.12) with capacities as high as 45 MN (5000 tons) can be use for large parts.

Press selection depends on part size and its configuration, density requirements, and production rate.

However, the higher the pressing speed, the greater the tendency for the press to trap air in the die cavity, thus, preventing proper compaction.

Figure 17.12 A 7.3-mn (825-ton) mechanical press for compacting metal powder.
17.3.2 Isostatic Pressing

- Green compact may be subjected to *hydrostatic pressure* in order to achieve more uniform compaction and, hence density:
- **Cold isostatic pressing (CIP)**
  - Metal powder is placed in a *flexible rubber mold* typically made of neoprene rubber, urethane, polyvinyl chloride, or another elastomer (See Fig 17.13).
  - The assembly then is pressurized hydrostatically in a chamber, usually using water.
  - Most common pressure is 400 MPa, although pressures up to 1000 MPa may be used.
  - The ranges for *CIP* and other compaction methods in terms of size and complexity of a part are shown in Fig. 17.14.

![Schematic diagram of cold isostatic pressing](image1.png)

Figure 17.13 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.

![Capabilities graph](image2.png)

Figure 17.14 Capabilities, with respect to part size and shape complexity, available from various P/M operations. P/F means powder forging.
Hot isostatic pressing (HIP)

- The container is generally made of high-melting-point steel, and the pressurizing medium is high-temperature inert gas or vitreous (glasslike fluid) (see Fig. 17.15).
- Common pressure is \(100 \text{ MPa}\), (although it can be three times as high) and at a temperature of \(1200^\circ \text{C}\).
- HIP produces compacts having almost 100% density, good metallurgical bonding of the particles and good mechanical properties.
- Known for making high quality parts.
- HIP is used mainly in making superalloy components for the aircraft and aerospace industries and in military, medical, and chemical applications.
- It is used to close porosity; and as a final densification step for tungsten carbide cutting tool and P/M tool steels.

![Figure 17.15 Schematic illustration of hot isostatic pressing. The pressure and temperature variation versus time are shown in the diagram.](image)

The main advantages of isostatic pressing are:

- Because the pressure is uniform from all directions and no die-wall friction, fully dense compacts are produced with uniform grain structure and density (isotopic properties), irrespective of part shape.
- Parts with high length-to-diameter ratios have been produced with very uniform density, strength, toughness, and good surface detail.
- HIP is capable of handling much larger parts than those in other compacting processes.

The limitations of HIP are as follows:

- Wider dimensional tolerance than those obtained in other compacting process.
- Higher equipment cost and production time than are required by other processes.
- Applicability only to relatively small production quantities, typically less than 10,00 parts per year.

See Example 17.1 Hot isostatic pressing of a valve lifter.
17.3.3 Miscellaneous Compacting and Shaping Processes

- **Powder-Injection Molding (PIM)**
  - Also called metal-injection molding (MIM).
  - In this process very fine metal powders (<10 μm = 0.01 mm) are blended with 25 - 45% polymer or wax-base binder.
  - The mixture then undergoes a process similar to die casting (see section 11.3.5, also 19.3); it is *injected into the mold at a temperature of 135° to 200° C.*
  - The molded green parts are placed in a *low temperature oven* to burn off the plastic (debinding), or using solvent extraction to remove the binder.
  - The parts are then *sintered* in a furnace at a temperature *as high as 1375°.*
  - Metals *suitable* for powder-injection molding are those that melt at temperatures *above 1000° C*; such as carbon and stainless steels, tool steels, copper, bronze, and titanium.
  - Typical parts are components for watches, small-caliber gun barrels, scope rings for rifles, door hinges, impellers, and surgical knives.
  - Major advantages of PIM over conventional compaction are:
    - Complex shapes with wall thickness as small as 5 mm can be molded.
    - Mechanical properties are as nearly equal to those of wrought products.
    - Dimensional tolerances are good.
    - High production rates using multicavity dies.
    - Compete well with small investment-cast parts, small forging, and complex machined parts.
  - The major limitations of PIM are the high cost and limited availability of fine metal powders.

- **Rolling**
  - Also called *roll compaction.*
  - In this process, metal powder is *fed into the roll gap* in a two-high rolling mill (Fig. 17.17) and is compacted into a continuous strip at speeds *up to 0.5 m/s.*
  - The rolling process can be carried out at room or at elevated temperature.
  - Sheet metal for electrical and electronic components and for coins can be produced by this process.

Figure 17.17 Schematic illustration of powder rolling.
- **Extrusion**
  - Powder is encased in a metal container and hot extruded.
  - After sintering, performed P/M parts may be reheated and forged in a closed die to their final shape.
  - Superalloy powders, for example, are hot extruded for enhanced properties.

- **Pressureless compaction**
  - Die is filled with metal powder by gravity, and the powder is sintered directly in the die.
  - Because of the resulting low density, pressureless compaction is used principally for porous metal parts, such as filters.

- **Spray Deposition**
  - Spray deposition is a shape-generation process (see Fig. 17.18).
  - Basic components are (a) an atomizer, (b) a spray chamber with inert atmosphere, and (c) a mold for producing preforms.
  - Although there are variations, the best known is the Osprey process shown in Fig. 17.18. After the metal is atomized, it is deposited onto a cooled perform mold, usually made of copper or ceramic, where it solidifies.
  - The metal particles bond together, developing a density that normally is above 99% of the solid-metal density.
  - Spray-deposited forms may be subjected to additional shaping and consolidation processes, such as forging, rolling, and extrusion.
  - The grain size is fine, and the mechanical properties are comparable to those for wrought products made of the same alloy.

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![Diagram of Spray Deposition (Osprey Process)](image)

Figure 17.18 Spray deposition (Osprey Process) in which molten metal is sprayed over a rotating mandrel to produce seamless tubing and pipe.

- **Ceramic Molds**
  - Ceramic molds for shaping metal powders are made by the technique used in investment casting.
  - After the mold is made, it is filled with metal powder and placed in a steel container.
  - The space between the mold and the container is filled with particular material.
  - The container then is evacuated, sealed, and subjected to hot isostatic pressing.
  - Titanium-alloy compressor rotors for missile engines have been made by this process.
17.3.4 Punch and Die Materials

- The selection of such materials depends on the abrasiveness of the powder metal and the number of parts to be produced.
- Most common die materials are air- or oil-hardening tool steels (such as D2 or D3), with a hardness range 60 to 64 HRC (Table 5.7).
- Because of their higher hardness and wear resistance, tungsten-carbide dies are used for more severe applications. Punches generally are made of similar materials.
- Close control (of die and punch dimensions) is essential for proper compaction and die life.
- Too large a clearance between the punch and the die will allow the metal powder to enter the gap, where it will severely interfere with operation and cause eccentric parts.
- Clearance are generally less than 25 μm (= 0.025 mm).
- Die and punch surfaces must be lapped or polished (in the direction of tool movements in the die) for improved die life and overall performance.

17.4 Sintering

- Sintering is the process where green compacts are heated in a controlled-atmosphere furnace to a temperature below the melting point but sufficiently high to allow bonding (fusion) of the individual particles.
- The green compact is brittle, and its strength (green strength) is low.
- The nature and strength of bond between the particles and, hence, that of the sintered compact, depends on the complex mechanisms of diffusion, plastic flow, evaporation of volatile materials in the compact, re-crystallization, grain growth, and pore shrinkage.
- The principal variables in sintering are temperature, time, and furnace atmosphere.
- Sintering temperatures are generally within 70% to 90% of the melting point of the metal or alloy.
- Sintering times ranges from about 10 minutes for iron and copper alloys to as much as 8 hours for tungsten and tantalum. See Table 17.2.

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

- Continuous-sintering furnaces (used for most production) have three chambers:
  1. **Burn-off chamber** for volatilizing the lubricants in the green compact in order to improve bond strength and prevent cracking.
  2. **High-temperature** chamber for sintering.
  3. **Cooling chamber**.
To obtain optimum properties, proper control of the furnace atmosphere is successful sintering, for example: an oxygen-free atmosphere is essential to control the carburization and decarburization of iron and iron-based compacts and to prevent oxidation of powders.

A vacuum generally is used for sintering refractory-metal alloys and stainless steels.

Gases most commonly used for sintering are hydrogen, dissociated or burned ammonia, partially combusted hydrogen gases, and nitrogen.

Sintering mechanisms are complex and depend on the composition of the metal particles as well as the processing parameters.

The sintering mechanisms are diffusion, vapor-phase transport, and liquid-phase sintering:

- As temperature increases, two adjacent particles begin to form a bond by diffusion mechanism (solid-state bonding, Fig. 17.19a); as a result of this, the strength, density, ductility, and thermal and electrical conductivities of the compact increase. However, the compact shrinks. Hence, allowances should be made for shrinkage as are done for casting.

- The second sintering mechanism is vapor-phase transport (Fig. 17.19b). Because the material is heated very close to its melting temperature, metal atoms will release to the vapor phase from the particles. At convergent geometries (interface of two particles), the melting temperature is locally higher, and the vapor phase resolidifies. Thus, the interface grows and strengthens while each particle shrinks as a whole.

- If two adjacent particles are different materials, alloying can take place at the interface of the two particles. If one of the particles has a lower melting point than the other, the particle will melt and (because of surface tension) surround the particle that has not melted. This mechanism is known as liquid-phase sintering. As an example, is cobalt in tungsten-carbide tools and dies.

![Figure 17.19 Schematic illustration of two mechanisms for sintering metal powders: (a) solid-state material transport; and (b) vapor-phase material transport.](image-url)

- $R =$ particle radius,
- $r =$ neck radius,
- $p =$ neck-profile radius.
Mechanical properties.

- Depending on temperature, time, and processing history, different structures and porosities can be obtained in a sintered compact, and hence affecting its properties.
- Porosity cannot be eliminated completely because (a) voids remain after compaction and (b) gases evolve during sintering. Porosity may consist either of a network interconnected pores or of closed pores.
- Generally, if the density of the material is less than 80% of its theoretical density, the pores are interconnected.

Table 17.3 shows typical mechanical properties for several sintered P/M alloys.

<table>
<thead>
<tr>
<th>TABLE 17.3</th>
<th>Mechanical Properties of Selected P/M Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designation</td>
<td>MPIF type</td>
</tr>
<tr>
<td>Ferrous</td>
<td></td>
</tr>
<tr>
<td>FC-0208</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>FN-0405</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>601 AB, pressed bar</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Brass</td>
<td>CZP-0220</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti-6Al-4V</td>
</tr>
<tr>
<td>Superalloys</td>
<td>Hastelloy 19</td>
</tr>
</tbody>
</table>

MPIF: Metal Powder Industries Federation. AS = sintered, HT = hot, HIP = hot isostatic pressed.

Tables 17.4 gives the differences in mechanical properties of wrought versus P/M metals.

<table>
<thead>
<tr>
<th>TABLE 17.4</th>
<th>Comparison of Mechanical Properties of Some Wrought and Equivalent P/M Metals (as Sintered)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>Condition</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2014-T6</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6061-T6</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper, OFHC</td>
<td>W, annealed</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Brass, 260</td>
<td>W, annealed</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel, 1025</td>
<td>W, hot rolled</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless steel, 303</td>
<td>W, annealed</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: The density and strength of P/M materials greatly increase with further processing, such as forging, isostatic pressing, and heat treatments.
Table 17.5 shows the effects of various manufacturing processes on mechanical properties of a titanium alloy.

<table>
<thead>
<tr>
<th>TABLE 17.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Property Comparisons for Ti-6Al-4V Titanium Alloy</strong></td>
</tr>
<tr>
<td>Process*</td>
</tr>
<tr>
<td>Cast</td>
</tr>
<tr>
<td>Cast and forged</td>
</tr>
<tr>
<td>Blended elemental (P+S)</td>
</tr>
<tr>
<td>Blended elemental (HIP)</td>
</tr>
<tr>
<td>Prealloyed (HIP)</td>
</tr>
</tbody>
</table>

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

Source: Courtesy of R. M. German.

See Example 17.2 Shrinkage in sintering.

### 17.5 Secondary and Finishing Operations

- To **further improve the properties** of sintered P/M products, additional operations may be carried out after sintering:
  1. Coining and sizing: compaction operations using high pressure presses to improve the strength and surface finish by **further densification**.
  2. Sintered alloy-powder compacts may subsequently be **cold or hot forged** to the desired final shapes and sometimes by impact forging.
  3. Powder-metal parts may be subjected to other finishing operations such as:
     - **Machining**: for producing various geometric features by milling, drilling, and tapping (to produce threaded holes).
     - **Grinding**: for improved dimensional accuracy and surface finish.
     - **Plating**: for improved appearance and resistance to wear and corrosion.
     - **Heat treating**: for improved hardness and strength.

- The inherent porosity of P/M components can be utilized by **impregnating** them with fluid. **Bearings and bushings** that are lubricated internally with up to 30% oil by volume are made by immersing the sintered bearing in heated oil. These bearing have a continuous supply of lubricant (due to capillary action) during their service lives (also referred to as permanently lubricated).

- **Infiltration** is a process whereby s **slug** of a lower melting point **metal** is placed in contact the sintered part. The assembly then is heated to a temperature sufficiently high to melt the slug. The molten metal infiltrates the pores by capillary action and produces a **relatively pore-free part** having good density and strength. The most common application is the infiltration of iron-based compacts by copper. The advantages of infiltration are that the hardness and tensile strength of the part are improved and the pores are filled, thus preventing moisture penetration (which could cause corrosion).

See Example 17.3 Powder metallurgy gears for a garden tractor.
See Example 17.4 Production of tungsten carbide for tools and dies.
17.6 Design Considerations

Because of the unique properties of metal powders, their flow characteristics in the die, and the brittleness of the green compacts, there are certain design principles that should be followed (see Figures 17.20 - 17.22):

1. The shape of the compact must be kept as simple and uniform as possible. Sharp edges in contour, thin sections, variations of thickness, and high length-to-diameter ratios should be avoided.

2. Provision must be made for ejection of the green compact without damaging the compact. Thus holes or recesses should be parallel to the axis of the punch travel. Chamfers should be used to avoid damage of edges during ejection.

3. P/M parts should be made with the widest acceptable tolerances to maximize tool life.

4. Part walls should not be less than 1.5 mm thick; thinner walls can be achieved on small parts; walls with length-to-thickness ratios above 8:1 are difficult to press.

5. Steps in parts can be produced if they are simple and their size doesn’t exceed 15% of the overall part length.

6. Letters can be pressed if oriented perpendicular to the pressing direction and can be raised or recessed. Raised letters are more susceptible to damage in the green stage and prevent stacking.

7. Flanges or overhangs can be produced by a step in the die.

8. A true radius cannot be pressed; instead use a chamfer.

9. Dimensional tolerances are on the order of ±0.05 to 0.1 mm. Tolerances improve significantly with additional operations such as sizing, machining and grinding.

Figure 17.20 Die geometry and design features for powder-metal compaction.
Figure 17.21  Examples of P/M parts showing 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 machining operations.

Figure 17.22  (a) Design features for use with unsupported flanges.  (b) Design features for use with grooves.
The process capabilities of P/M may be summarized as follows:

- Can be used to make parts from high-melting-point refractory metals and parts which are difficult or uneconomical to produce by other methods.
- High production rates are possible on relatively complex parts using automated equipment and requiring little labor.
- Offers good dimensional control and in many instances eliminates machining and finishing operations, hence; reduces scrap and waste and saves energy.
- Availability of a wide range of compositions make it possible to obtain special mechanical and physical properties, such as stiffness, vibration damping, hardness, density, toughness, and specific electrical and magnetic properties.
- Some newer highly alloyed superalloys can be manufactured into parts only by P/M processing.
- Offers the capability of impregnation and infiltration for specific applications.

Limitations to P/M are:

- High cost of metal powder, particularly those for powder-injection molding, as compared to that of raw materials to be cast or wrought.
- High cost of tooling and equipment for small production runs.
- Limitations on part size.
- Mechanical properties such as strength and ductility are generally lower than those obtained by forging. However, properties of full-density P/M parts made by HIP or by additional forging operations can be as high as those made by other processes.

Because P/M is net or near-net shape, it increasingly has become competitive with casting, forging, and machining. However, the initial cost of powder, punches, dies, and equipment for processing means that production volume must be sufficiently high to cover these expenditures. The process is generally economical for quantities over 10,000 pieces; but there are exceptions.
Labor costs are not as high as in other processes, primarily because of the individual operations (powder blending, compaction, and sintering) are highly automated.

The near-net-shape capabilities of P/M significantly reduces or eliminates scrap. For example, weight comparisons of aircraft components produced by forging and by P/M processes are shown in Table 17.6.

Note that the P/M parts are subjected to further machining processes, thus the final parts weigh less than those made by either of the two processes alone.

Table 17.6 Forged and P/M Titanium Parts and Potential Cost Saving

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