

# Chapter 18: Powder Metallurgy

## Introduction

- Powder metallurgy (粉末冶金) is the name given to the process by which fine powdered materials are **blended**, **pressed** into a desired shape, and then **heated** to bond surfaces
- Typically used when large amounts of small, intricate parts with high precision are required
- Little material waste and **unusual mixtures** can be utilized
- Used for parts in the automotive industry, household appliances, and recreational equipment (to name a few)

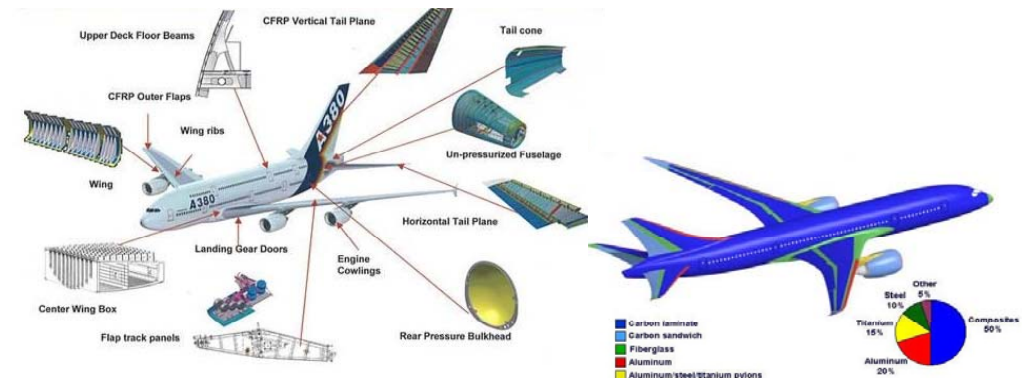
## Powder Metallurgy Products

- **Automotive** (Brake pads, Gear parts, Connecting rods, Planetary carriers, Sintered Engine Bearings)



## Powder Metallurgy Products

- **Aerospace** (Light weight Aluminum base structural materials, High temperature Composite materials)



(Source: <http://www.mechanicalengineeringblog.com/tag/powder-metallurgy/>)

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## Powder Metallurgy Products

- **Cutting tools** (Hard metals, Diamond containing materials)



(Source: <http://www.mechanicalengineeringblog.com/tag/powder-metallurgy/>)

## Powder Metallurgy Products

- **Medicine** (Dental implants, Surgical instruments)



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## Powder Metallurgy Products

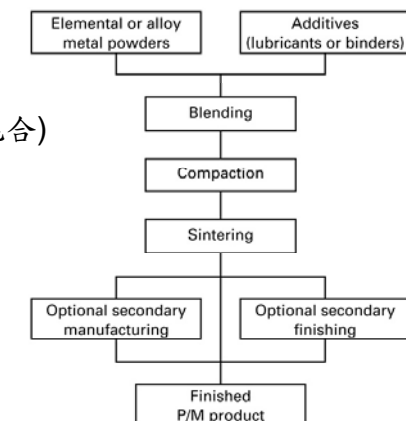
- **Abrasives** (Grinding and Polishing wheels and Discs);
- **Electrical, Electronic and Computer parts** (Permanent magnets, Electrical contacts).



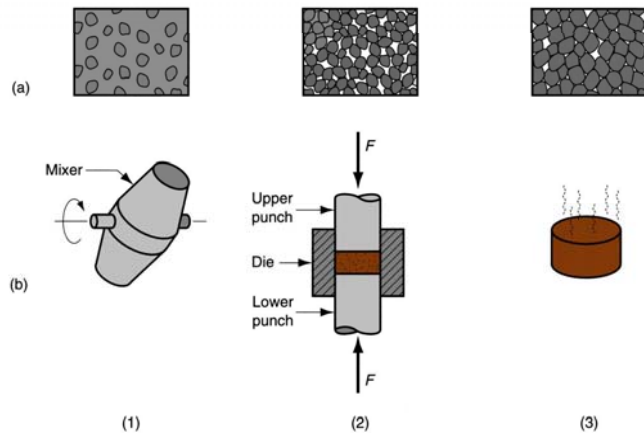
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## The Basic Process

- Four basic steps
  - 1. Powder manufacture
  - 2. Mixing or blending (混合)
  - 3. Compacting (加壓)
  - 4. Sintering (燒結)



**Figure 18-1** Simplified flow chart of the basic powder metallurgy process.



Conventional powder metallurgy production sequence: (1) blending, (2) compacting, and (3) sintering; (a) shows the condition of the particles while (b) shows the operation and/or workpart during the sequence.

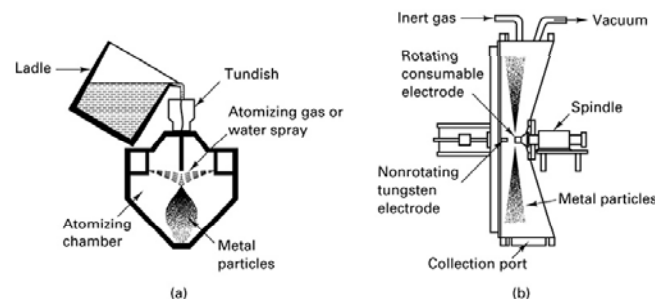
(Source: Groover)

## Powder Manufacture

- Properties of powder metallurgy products are highly dependent on the characteristics of starting powders
- Some important properties and characteristics
  - Chemistry and purity
  - Particle size
  - Size distribution
  - Particle shape
  - Surface texture
- Useful in producing prealloyed powders

## Powder Manufacture

- The majority of commercial powder is produced by some form of melt atomization
  - Atomization is a process where liquid metal is fragmented into small droplets that cool and solidify into particles



**Figure 18-2** Two methods for producing metal powders: (a) melt atomization and (b) atomization from a rotating consumable electrode.

## Rapidly Solidified Powder (Microcrystalline and Amorphous)

- If the cooling rate of an atomized liquid is increased, ultra-fine or microcrystalline sized grains can form
- Some metals can solidify without becoming crystalline (called amorphous materials)
- Amorphous materials can have high strength, improved corrosion resistance, and reduced energy to induce and reverse magnetization

## Powder Testing and Evaluation

- *Flow rate* measures the ease with which powder can be fed and distributed into a die
- *Apparent density* is the measure of a powder's ability to fill available space without external pressure
- *Compressibility* is the effectiveness of applied pressure in raising the density of the powder
- *Green strength* is used to describe the strength of the pressed powder after compacting

## Powder Mixing and Blending

- The majority of powders are mixed with other powders, *binders*, and *lubricants* to achieve the desired characteristics in the finished product
- Sufficient diffusion must occur during sintering to ensure a uniform chemistry and structure
- Unique composites can be produced

## Compacting

- Loose powder is compacted and densified into a shape, known as *green compact*
- Most compacting is done with mechanical presses and rigid tools
  - Hydraulic and pneumatic presses are also used

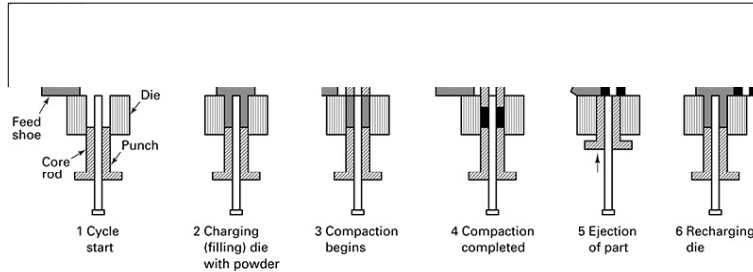
| Application                                 | Compaction Pressures  |          |
|---|-----------------------|----------|
|   | tons/in. <sup>2</sup> | Mpa      |
| Porous metals and filters                   | 3–5                   | 40–70    |
| Refractory metals and carbides              | 5–15                  | 70–200   |
| Porous bearings                             | 10–25                 | 146–350  |
| Machine parts (medium-density iron & steel) | 20–50                 | 275–690  |
| High-density copper and aluminum parts      | 18–20                 | 250–275  |
| High-density iron and steel parts           | 50–120                | 690–1650 |



**Figure 18-3** (Left) Typical press for the compacting of metal powders. A removable die set (right) allows the machine to be producing parts with one die set while another is being fitted to produce a second product. (Courtesy of Alfa Laval, Inc., Warminster, PA.)

# Compaction Sequence

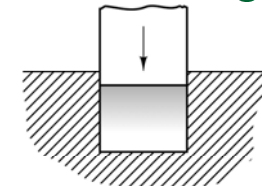
- Powders do not flow like liquid, they simply compress until an equal and opposing force is created



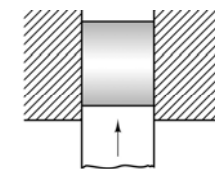
**Figure 18-4** Typical compaction sequence for a single-level part, showing the functions of the feed shoe, die core rod, and upper and lower punches. Loose powder is shaded; compacted powder is solid black.

# Additional Considerations During Compacting

- When the pressure is applied by only one punch, the maximum density occurs right below the punch surface and decreases away from the punch
- For complex shapes, multiple punches should be used

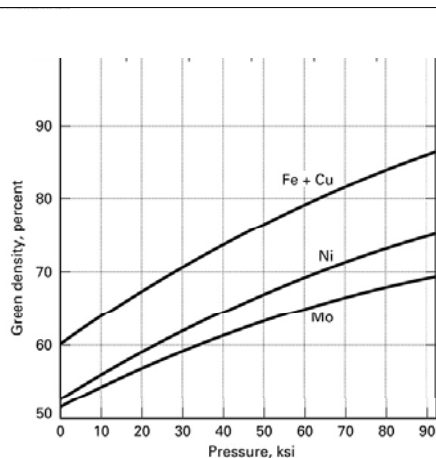


**Figure 18-5** Compaction with a single moving punch, showing the resultant nonuniform density (shaded), highest where particle movement is the greatest.

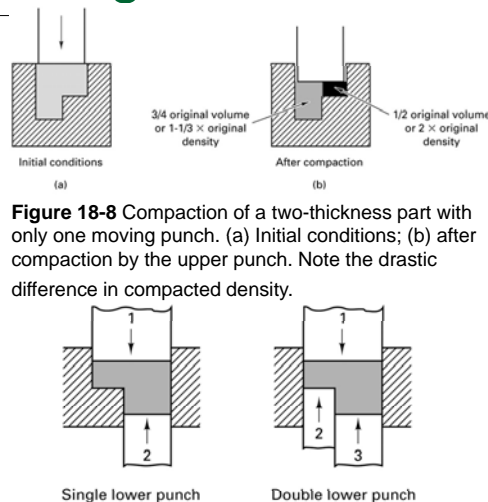


**Figure 18-6** Density distribution obtained with a double-acting press and two moving punches. Note the increased uniformity compared to Figure 18-5. Thicker parts can be effectively compacted.

# Effects of Compacting



**Figure 18-7** Effect of compacting pressure on green density (the density after compaction but before sintering). Separate curves are for several commercial powders.



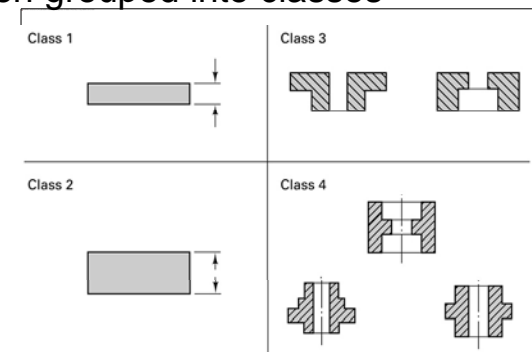
**Figure 18-8** Compaction of a two-thickness part with only one moving punch. (a) Initial conditions; (b) after compaction by the upper punch. Note the drastic difference in compacted density.

**Figure 18-9** Two methods of compacting a double-thickness part to near-uniform density. Both involve the controlled movement of two or more punches.

# Classes of Powder Metallurgy Equipment

- The complexity of the part dictates the complexity of equipment
- Equipment has been grouped into classes

**Figure 18-10** Sample geometries of the four basic classes of press-and-sinter powder metallurgy parts. Note the increased pressing complexity that would be required as class increases.





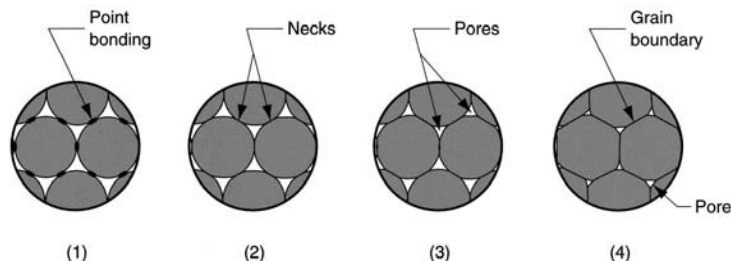
## Complex Compacting

- If an extremely complex shape is desired, the powder may be encapsulated in a **flexible mold**
  - Process is known as isostatic compaction
  - Done in a pressurized gas or liquid
- In warm compaction, the powder is heated prior to pressing
- The amount of lubricant can be increased in the powder to reduce friction
- Because particles tend to be abrasive, tool wear is a concern in powder forming

## Sintering

- In the sintering operation, the pressed-powder compacts are **heated** in a controlled atmosphere to **right below the melting point**
- Three stages of sintering
  - **Burn-off** (purge)- combusts any air and removes lubricants or binders that would interfere with good bonding
    - Porosity
  - **High-temperature**- desired solid-state diffusion and **bonding** occurs
    - About **80% of the melting point**
  - **Cooling period**- lowers the temperature of the products in a controlled atmosphere
- All three stages must be conducted in oxygen-free conditions

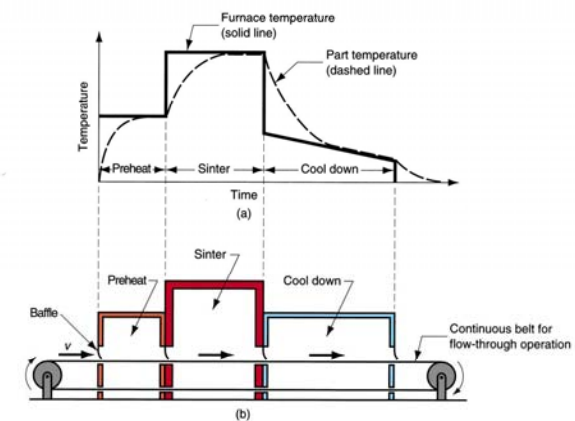
## Sintering Sequence



Sintering on a microscopic scale: (1) particle bonding is initiated at contact points; (2) contact points grow into "necks"; (3) the pores between particles are reduced in size; and (4) grain boundaries develop between particles in place of the necked regions.

(Source: Groover)

## Sintering Cycle and Furnace



(a) Typical heat treatment cycle in sintering; and (b) schematic cross section of a continuous sintering furnace.

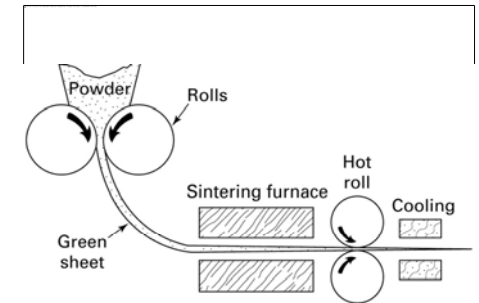
(Source: Groover)

## Hot-Isostatic Pressing

- Hot-isostatic pressing (HIP) combines **powder compaction** and **sintering** into a single operation
  - Gas-pressure squeezing at high temperatures
- Heated powders may need to be protected from harmful environments
- Products emerge at full density with uniform, isotropic properties
- Near-net shapes are possible

## Other Techniques to Produce High-Density P/M Products

- High-temperature metal deformation processes can be used to produce high density P/M parts
- Spray forming
  - Inert gases propel molten droplets onto a mold
  - The droplets are semisolid and flatten upon impact

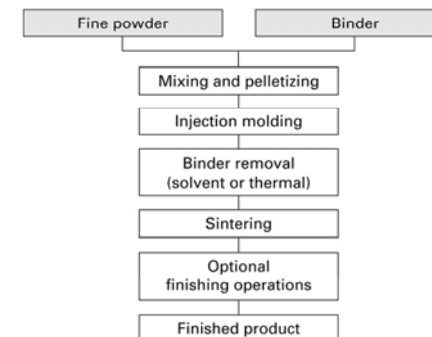


**Figure 18-11** One method of producing continuous sheet products from powdered feedstock.

## 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
  - Similar to the injection molding (射出成形)
- 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.)

## 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
- **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 <sup>a</sup> | Form and Composition   | Condition <sup>b</sup> | Percent of Theoretical Density | Tensile Strength    |     | Elongation in 2 in. (%) |
|-----------------------|------------------------|------------------------|--------------------------------|---------------------|-----|-------------------------|
|                       |                        |                        |                                | 10 <sup>3</sup> 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                      |
| Copper                | P/M 601 AB             | T6                     | 94                             | 36.5                | 252 | 2                       |
|                       | Wrought OFHC           | Annealed               | —                              | 34                  | 234 | 50                      |
|                       | P/M copper             | As sintered            | 89                             | 23                  | 159 | 8                       |
| Brass                 | Wrought 260            | Repressed              | 96                             | 35                  | 241 | 18                      |
|                       | P/M 70% Cu-30% Zn      | Annealed               | —                              | 44                  | 303 | 65                      |
|                       |                        | As sintered            | 89                             | 37                  | 255 | 26                      |

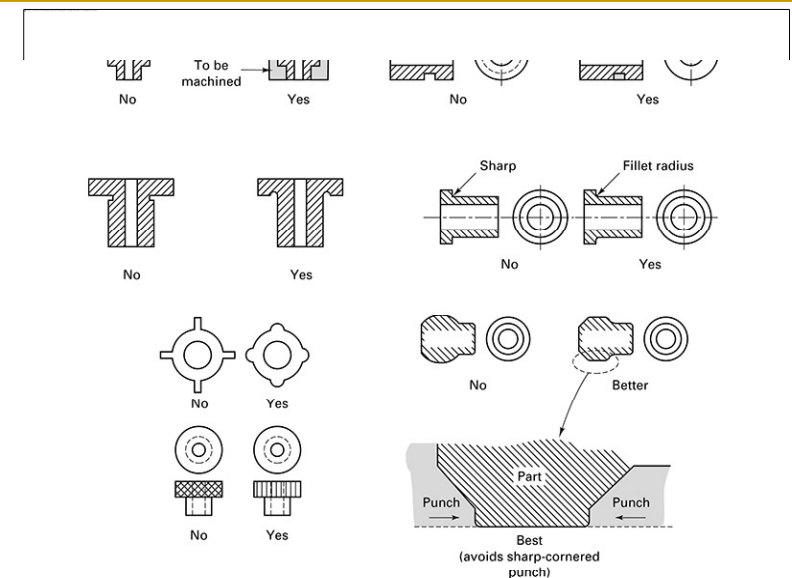
<sup>a</sup>Equivalent wrought metal shown for comparison. <sup>b</sup>HR, hot rolled; T6, age hardened.

# 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

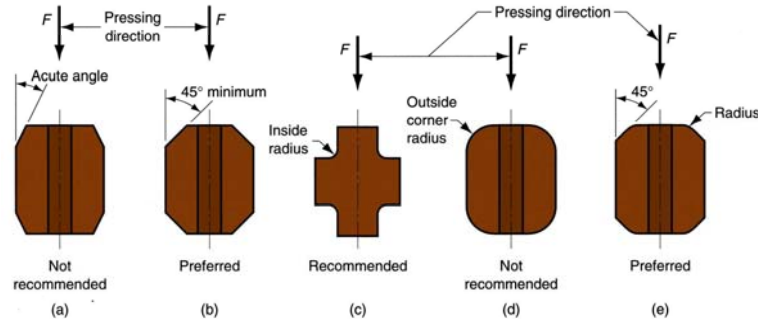
## Basic Rules for P/M Parts

- Consideration should be made for product tolerances
- Design should consider and compensate for dimensional changes that will occur after pressing or sintering



**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.

## Chamfers and Corner Radii



Chamfers and corner radii are accomplished but certain rules should be observed: (a) avoid acute angles; (b) larger angles preferred for punch rigidity; (c) inside radius is desirable; (d) avoid full outside corner radius because punch is fragile at edge; (e) problem solved by combining radius and chamfer.

(Source: Groover)

## Products Commonly Produced by Powder Metallurgy

- **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
- **Difficult to machine** or high melting points materials
- 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 an economic advantage

## Advantages and Disadvantages of Powder Metallurgy

- |  |   |
|--|---|
| <ul style="list-style-type: none"> <li>■ <b>Advantages</b> <ul style="list-style-type: none"> <li>□ Elimination or reduction of machining</li> <li>□ High production rates</li> <li>□ Complex shapes</li> <li>□ Wide variations in compositions</li> <li>□ Wide property variations                             <ul style="list-style-type: none"> <li>■ Ex. porosity</li> </ul> </li> <li>□ Scrap is eliminated or reduced</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>■ <b>Disadvantages</b> <ul style="list-style-type: none"> <li>□ Inferior strength properties</li> <li>□ High tooling costs</li> <li>□ High material cost</li> <li>□ <b>Size and shape limitations</b></li> <li>□ Dimensional changes during sintering</li> <li>□ <b>Density variations</b></li> <li>□ Health and safety hazards</li> </ul> </li> </ul> |
|--|---|

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<br><5 pounds     | Smallest<br><1/4 pounds         | Largest<br>1–1000 pounds     | Intermediate<br><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<br>±0.001 in./in.   | Good<br>±0.003 in./in.          | Poor<br>±0.020 in./in.       | Very good<br>±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<br>\$0.50–5.00/lb         | Intermediate<br>\$1.00–10.00/lb | High<br>>\$100.00/lb         | Somewhat low<br>\$1.00–5.00/lb |