CHAPTER 17
Powder Metal Processing and Equipment
Refer to Fig.17-10a. What should be the volume of loose ..... 

A course copper powder is compacted in a mechanical press at a pressure of 20 tons/in² ....
Using the internet, locate suppliers of metal powders and compare the cost of the powder with the cost of ingots for three different materials.
Powder Metallurgy (PM)

- **PM**: Metal parts are made by compacting fine metal powders in suitable dies and **sintering** (heating without melting).
- **Typical products**: from tiny balls for ball-point pens, to gears, cams, and bushings, to cutting tools, to porous products (filters and oil-impregnated bearings).
- **Most commonly used metals in P/M**: iron, Cu, Al, tin, Ni, Ti, and refractory metals.
- For parts made of brass, bronze, steels, and stainless steels, pre-alloyed powders are used, where each powder particle itself is an alloy.
Powder Metallurgy (PM) - Typical Parts
Powder Metallurgy
Sequence of Operations

PM process basically consists of the following operations in sequence:

1. Powder production
2. Blending
3. Compaction
4. Sintering
5. Finishing operations
Production of Metal Powders

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

- Atomization
- Reduction
- Electrolytic deposition
- Carbonyls
- Commination
- Mechanical alloying

Metal powders ➔ Blending ➔ Cold compaction ➔ Sintering ➔ Secondary and finishing operations

Additives: lubricants

Pressing
- Isostatic pressing
- Rolling
- Extrusion
- Injection molding

Atmosphere
- Vacuum

Hot compaction
- Isostatic pressing

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Production of Metal Powders

- Particle sizes: 0.1 µm - 1000 µm.
- Powder production method affects (F17.3):
  - The shape
  - Size distribution
  - Porosity
  - Chemical purity
  - Bulk and surface characteristics of the particles

- These characteristics are important, because they significantly affect the flow and permeability during compaction and in subsequent sintering operations.
Production of Metal Powders

Particle Shapes in Metal Powders

One-dimensional

- Acicular (chemical decomposition)
- Irregular rodlike (chemical decomposition, mechanical comminution)

Two-dimensional

- Flake (mechanical comminution)
- Dendritic (electrolytic)

Three-dimensional

- Spherical (atomization, carbonyl (Fe), precipitation from a liquid)
- Rounded (atomization, chemical decomposition)
- Angular (mechanical disintegration, carbonyl (Ni))
- Irregular (atomization, chemical decomposition)
- Porous (reduction of oxides)

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Production of Metal Powders

Particle Shapes in Metal Powders - 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
Methods of Powder Production

- **Atomization**: a liquid-metal stream is produced by injecting molten metal through a small orifice. The stream is broken up by jets of inert gas, air, or water.
- Size of particles formed depends on:
  1. temperature of metal.
  2. rate of flow.
  3. nozzle size.
  4. jet characteristics.

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Methods of Powder Production

- **Reduction**: reduction of metal oxides (removal of oxygen) using gases such as H₂ and CO, as reducing agents.
  - very fine metallic oxides are reduced to the metallic state.
  - Spongy and porous powders
  - uniformly sized spherical or angular shapes.
- **Electrolytic deposition**: utilizes either aqueous solutions or fused salts. Powders produced are among the purest available.
- **Carbonyls**: Metal carbonyls, such as iron carbonyl (FeCO) and nicked carbonyl (Ni(CO) ), are formed by letting iron or nickel react with CO.
  - The reaction products are then decomposed to iron and nickel, and they turn into small, dense, uniformly spherical particles of high purity.
Methods of Powder Production

Mechanical Comminution

- Involves crushing (Fig. 17.6), milling in a ball mill, or grinding brittle or less ductile metals into small particles.
- **A ball mill** is a machine (Fig. 17.6b) with a rotating hollow cylinder partly filled with steel or white cast iron balls.
  - With brittle materials, the powder particles produced have angular shapes.
  - With ductile metals, they are flaky, and they are not particularly suitable for powder metallurgy applications.
Methods of Powder Production

Mechanical alloying:

- powders of two or more pure metals are mixed in a ball mill.
- Under the impact of the hard balls, the powders fracture and join together by diffusion, forming alloy powders.
Particle Size, Distribution, and Shape

Particle Size Analysis

- **Screening**: The larger the mesh size, the smaller is the opening in the screen mesh. For example, size of 30 has an opening of 600μm, size 100 has 150μm, and size 400 has 38μm.
- **Sedimentation**: measuring rate at which particles settle in a fluid.
- **Microscopic analysis**: use of transmission and scanning electron microscopy.
- **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, a detector then digitizes the signals and computes the particle size distribution.
- **Optical means**: such as particles blocking a beam of light that is then sensed by a photocell.
- **Suspending particles** in a liquid and then detecting particle size and distribution by electrical sensors.
- **The distribution of particle size** is given in terms of a frequency distribution plot. The maximum is called the mode size.
Particle Size, Distribution, and Shape

Particle Shape

- **Particle shape** has a major influence on processing characteristics.
- The shape is usually described in terms of aspect ratio or shape factor.
  - **Aspect ratio** is the ratio of the largest dimension to the smallest dimension of the particle.
  - **Shape factor (SF)**: 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.
Blending Metal Powders

Blending is carried out for the following purposes:

1. Powders made by various processes have different sizes and shapes, so they must be mixed to obtain uniformity.

2. Powders of different metals and other materials can be mixed in order to impart special physical and mechanical properties and characteristics to the PM product.

3. Lubricants can be mixed with powders to improve their flow characteristics.
   - reducing friction between metal particles
   - improving flow of powder metals into the dies
   - lengthening die life
   - Lubricants typically are stearic acid or zinc stearate, in a proportion of from 0.25% to 5% by weight.
Blending Metal Powders

- Powder mixing must be carried out under controlled conditions, to avoid contamination or deterioration.
- **Deterioration** is caused by excessive mixing, which may alter the shape of particles and work harden them and thus make the subsequent compacting operation more difficult.
- Powders can be mixed in air, in inert atmospheres, or in liquids, which act as lubricants and make the mix more uniform.
- **Hazards:** Because of their high surface area-to-volume ratio, metal powders are explosive, particularly Al, Mg, Ti, Zr, and thorium.
Blending Metal Powders

Figure 17.7: Some common equipment geometries for mixing or blending powders:

a) Cylindrical
b) rotating cube
c) double cone
d) twin shell
Compaction of Metal Powders

**Purposes of compaction:**
1. obtain required shape, and density,
2. particle-to-particle contact
3. make part sufficiently strong for further processing

**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
Compaction of Metal Powders

- **Green compact**: The pressed powder.
- Density of green compact depends on:
  1. applied pressure.
  2. size distribution of the particles. If all the particles are of the same size, there will always be some porosity when they are packed together.

- The higher the density,
  1. the higher the strength and elastic modulus of part (F17.9b).
  2. the higher the amount of solid metal in the same volume, and hence the greater its resistance to external forces.

- Because of friction between metal particles in the powder and friction between the punches and the die walls, the density within the part can vary considerably.
Compaction of Metal Powders

(a) Density (g/cm³) vs. Compactaing pressure (tons/in²)
- Copper powder, coarse 8.49 g/cm³
- Copper powder, fine 1.44
- Iron powder, coarse 2.75
- Iron powder, fine 1.40

(b) Sintered density (g/cm³) vs. Tensile strength (MPa)
- Tensile strength
- Conductivity
- Elongation
- Electrical conductivity (% IACS)
Compaction of Metal Powders

- Density variation can be minimized by:
  1. proper punch and die design
  2. control of friction.
- For example, use multiple punches, with separate movements, to ensure that the density is more nearly uniform throughout the part (F17.10).
Compaction of Metal Powders

Equipment

• **Pressing Pressure**: from 70MPa for AL to 800MPa for high-density iron parts.

• The compacting pressure **depends** on:
  1. Characteristics and shape of particles
  2. Method of blending
  3. Lubricant

• **Selection** of press depends on:
  1. part size and configuration
  2. density requirements
  3. production rate

• The **higher** the pressing speed, the **greater** the tendency for the press to trap air in the die cavity and prevent proper compaction.
Compaction of Metal Powders
Cold Isostatic Pressing- F17.12

1. metal powder is placed in a flexible rubber mold made of neoprene rubber, urethane, polyvinyl chloride.
2. The assembly is then pressurized hydrostatically in a chamber, by water.
   - Most common pressure: 400MPa.
Compaction of Metal Powders

Hot Isostatic Pressing - F17.14

1. The container is usually made of a high-melting-point sheet metal, and the pressurizing medium is inert gas or a vitreous (glasslike) fluid.

2. Common conditions for HIP are 100 MPa at 1100 °C.

3. Main advantage of HIP: ability to produce compacts having almost 100% density, good metallurgical bonding of particles, & good mechanical properties.

(a) Fill can  
(b) Vacuum bakeout  
(c) Hot isostatic press  
(d) Remove can
Compaction of Metal Powders

Isostatic Pressing

- Main advantages of Isostatic pressing:
  1. Because of uniformity of pressure from all directions and the absence of die wall friction, it produces fully-dense compacts of practically uniform grain structure and density (hence, isotropic properties), irrespective of shape.
  2. Parts with high length-to-diameter ratios have been produced with very uniform density, strength, and toughness and good surface detail.
  3. Handling much larger parts than are other compacting processes.

- Limitations of Isostatic pressing:
  1. Wider dim tolerances than are caused by other compacting processes.
  2. Greater cost and time than are required by other processes.
  3. Applicability only to relatively small production quantities (<10,000).
Compaction of Metal Powders
Metal Injection Molding (MIM)

- **In MIM:**
  1. Very fine metal powder (<10 μm) are blended with either a polymer or a wax based binder.
  2. The mixture then undergoes a process similar to die casting.
  3. The molded greens are placed in a low-temperature oven, to burn off the plastic -or else the binder is removed by solvent extraction.
  4. Then they are sintered in a furnace.
- **Metals suitable for MIM:** carbon and stainless steels, tool steels, Cu, bronze, and Ti.
- **Typical parts:** components for watches, small-caliber gun barrels, heat sinks, automobiles, and surgical knives.
- **Major advantages** of MIM over conventional compaction:
  1. Complex shapes, having wall thicknesses as small as 5mm, can be molded and then easily removed from the dies.
  2. Mechanical properties are nearly equal to those of wrought products.
  3. Good Dimensional tolerances.
  4. High production rates can be achieved using of multi-cavity dies.
Compaction of Metal Powders – Other Processes

**Rolling:** Powder is fed to the roll gap in 2-high rolling mill, and is compacted into a continuous strip at speeds of up to 0.5 m/s.

- Rolling process carried out at room or at elevated temperature.
- Common parts: Sheet metal for electrical and electronic components and for coins.

**Extrusion:** powder is incased in a metal container and extruded.

- After sintering, preformed PM parts may be reheated and then forged in a closed die to their final shape.

**Pressureless compaction:** The die is filled with metal powder by gravity, and the powder is sintered directly in the die.

- Because of resulting low density, pressureless compaction is used principally for porous parts such as filters.
Ceramic molds:
1. Ceramic molds are made by the technique used in investment casting.
2. 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 particulate material.
3. The container is then evacuated, sealed, and subjected to hot isostatic pressing. Titanium-alloy compressor rotors have been made by this process.

Punch and Die Materials:
Selection of punch & die materials for PM depends on:
1. Abrasiveness of the powder metal.
2. Number of parts.

Most common die materials: air-or oil-hardening tool steels, such as D2 or D3, with a hardness range of 60-64 HRC (T5.7). Tungsten-carbide dies are used for more severe applications.

Diametral clearances are generally less than 25 μm.
Sintering

- **Sintering**: 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 nature and strength of the bond between the particles, and, hence, that of the sintered compact, depend on:
  1. The mechanisms of diffusion
  2. Plastic flow
  3. Evaporation of volatile materials in the compact
  4. Re-crystallization
  5. Grain growth
  6. Pore shrinkage
- **Principal variables in sintering:**
  1. Temperature
  2. Time
  3. Furnace atmosphere
- **Sintering temperatures (Table 17.3)**: 70% to 90% of melting point.
Sintering

- Continuous sintering-furnaces have 3 chambers:
  1. A burn-off chamber for volatilizing the lubricants in the green compact, in order to improve bond strength and prevent cracking.
  2. A high-temperature chamber for sintering
  3. A cooling chamber
- An oxygen-free atmosphere is essential to:
  1. Control carbonization and decarburization of iron and iron-based compacts.
- A vacuum is generally used for sintering refractory metal alloys and stainless steels.
- Gases most commonly used for sintering a variety of other metals are:
  - Hydrogen
  - Dissociated or burned ammonia
  - Partially combusted hydrocarbon gases
  - Nitrogen
Sintering - Mechanisms

- **Diffusion Mechanism:** As temperature increases, two adjacent particles begin to form a bond by a diffusion mechanism (solid state bonding). As a result, strength, density, ductility, and thermal & electrical conductivities of the compact increase.

- **Vapor-Phase Transport Mechanism:** Because the material is heated to very close to its melting temperature, metal atoms will release to the vapor phase from the particles. At the interface of two particles, the melting temperature is locally higher, and the vapor phase re-solidifies. Thus, the interface grows and strengthens, while each particle shrinks as a whole.

- **Liquid-Phase Sintering:** If two adjacent particles are of different metals, alloying can take place at the interface of the two particles. One of the particles may have a lower melting point than the other, in that case, one particle may melt and, because of surface tension, surround the particle that has not melted.
Sintering - Mechanisms

(a) Neck formation by diffusion

(b) Neck formation by vapor phase material transport

Distance between particle centers decreased, particles bonded

Particles bonded, no shrinkage (center distances constant)
Sintering – Mechanical Properties

• Porosities may consist either of a network of interconnected pores or of closed holes.
• Generally, if density of material is less than 80% of its theoretical density, pores are interconnected.
• The effects of various processes on the mechanical properties of a titanium alloy are shown in Table 17-5. Note that HIP titanium has properties that are similar to those for cast and forged titanium.
• Example: shrinkage in sintering:
Secondary and Finishing Operations

- **Coining and sizing**: compaction operations performed under high pressure in presses, to:
  1. impart dim accuracy to the sintered part.
  2. improve its strength and surface finish by further densification.

- **Use of preformed and sintered alloy powder compacts**, which are subsequently cold or hot forged to the desired final shapes, some times by impact forging. These products have:
  1. good surface finish.
  2. good dimensional tolerances.
  3. uniform and fine grain size.

- **Impregnating**: A typical application is to impregnate the sintered part with oil, usually by immersing the part in heated oil. Bearings and bushings that are internally lubricated, with up to 30% oil by volume, are made by this method.
Secondary and Finishing Operations

- **Infiltration, a process whereby:**
  1. A slug of a lower-melting-point metal is placed against the sintered part.
  2. The assembly is then heated to a temperature sufficient to melt the slug.
  3. The molten metal infiltrates the pores, by capillary action, to produce a relatively pore-free part having good density and strength.

- The most common application: infiltration of iron-base compacts by Cu.

- Infiltration may also be **used with lead:** Because of low shear strength of lead, the infiltrated part develops lower frictional characteristics than the one not infiltrated. Some bearing materials are formed in this way.

- **Advantages of infiltration:** improved hardness and tensile strength, and that the pores are filled.

- **Heat treating,** for improved hardness and strength;

- **Machining:** producing various geometric features by milling, drilling, & tap.

- **Grinding:** for improved dimensional accuracy and surface finish;

- **Plating:** for improved appearance & resistance to wear & corrosion.
Design Considerations for PM

• The shape of the compact must be as simple and uniform as possible.
• Avoid sharp changes in contour, thin sections, variations in thickness, and high length-to-diameter ratios.
• Provision must be made for ejecting the green compact from the die without damaging the compact; for example, holes or recesses should be parallel to the axis of punch travel.
• Implement the widest dimensional tolerances that are consistent with their intended applications, in order to increase tool and die life and to reduce production costs.
• Dimensional tolerances of sintered P/M: ±0.05-0.1mm.
Design Considerations for PM

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.
Process Capabilities

**Advantages:**
1. PM is a technique for making parts from high-melting-point refractory metals, parts which may be difficult or uneconomical to produce by other methods.
2. High production rates on relatively complex parts, by use of automated equipment requiring little labor.
3. Good dimensional control and, in many cases, elimination of machining & finishing operations, thus reducing scrap, waste and saving energy.
4. The availability of a wide range of compositions makes it possible to obtain special mechanical and physical properties.
5. Capability for impregnation and infiltration for special applications.

**limitations:**
1. The high cost of metal powder.
2. The high cost of tooling and equipment for small production runs.
3. Limitations on part size and on shape complexity.
4. Resulting mechanical properties, such as strength and ductility, are generally lower than those obtained by forging.
Economics of Powder Metallurgy

- Produce parts at or near net shape, thus eliminating many secondary operations and scrap.
- The high initial cost of punches, dies, and equipment for P/M processing means that production volume must be sufficiently high to warrant this cost.
- The process is generally economical for quantities over 10,000 pieces.