Powder Metallurgy & Particulate Materials

- Parts are produced from metallic powders.
- PM production sequence involves the following (1) powder production, (2) Adding lubricants, (3) blending, (4) hot or cold compaction, (5) cold compacts – green compacts are sintered at a prescribed temperature – below the melting temperature - and time, and (6) secondary or finishing operation.
- PM process wastes very little material – about 97% of the starting powder is converted into the product.
- Specified degree of porosity can be attained in a PM part to produce porous metal parts. Example: oil-impregnated bearings.
- Certain parts are difficult to produce by other methods Example: diamond bearings core drills, tungsten filament for incandescent lamps bulbs.
- Metallic powders are expensive.
- Tooling and equipment costs are high.
- Powders need of special handling and storage.
- Variations in density throughout a part.
- Only certain geometries are possible
- Normally used for large tonnage production.
PM Process Sequence

Atomization
Reduction
Electrolytic deposition
Carbonyls
Comminution
Mechanical alloying

Metal powders

Blending

Additives
Lubricants

Cold compaction

Pressing
Isostatic pressing
Rolling
Extrusion
Injection molding

Sintering

Atmosphere
Vacuum

Secondary and finishing operations

Coining
Forging
Machining
Heat treating
Impregnation
Infiltration
Plating
Engineering Powders – Particle Shape

The geometric features of the engineering powders are:

• Chemistry and purity
• Particle size and distribution
• Particle shape and internal structure
• Surface area

Particle Shape and Internal Structure:
Several possible particle shapes can be produced. The shapes and internal structure of the particles depend on the production method. The particle shape to use depend on the requirements of the end-product.
Atomization

(a) Ladle
Molten metal
Tundish
Atomizing gas spray
Atomizing chamber
Metal particles

(b) Tundish
High-pressure water manifold
Atomization tank
Water atomization
Dewatering

(c) Ladle
Molten metal
Tundish
Liquid metal
Metal particles
Spinning disk

(d) Inert gas
Vacuum
Rotating consumable electrode
Spindle
Nonrotating tungsten electrode
Collection port
Atomization

A liquid metal stream is broken up into small droplets by jets of inert gas or air or water (forcibly cooled). Most of the commercial powder are produced by atomization. The temperature of the molten metal, the rate of flow, the nozzle and jet characteristics all have an effect on the size and shape of the particles.
A steam of liquid metal is made to collide with a rotating disk, using the centrifugal forces to break up the stream and generate particles (centrifugal atomization).

**Comminution**

Involves the breaking up of large solid particles by mechanical means, such as crushing in a ball mill, or grinding.

(a) Roll crushing.
(b) Ball milling – a rotating drum partially filled of harder balls.
(c) Hammer milling
**Mechanical Alloying:**

A ball milling machine is filled up with a mixture two or more different powders. Under the impact of the hard balls (usually at high RPM and under protective atmosphere), the powders fracture and bond together (cold welding) by diffusion.

![Diagram](image)

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.
Other Methods of Making Powders

**Chemical Reduction:** Oxide particles are reduced in gases such as hydrogen and carbon monoxide at high temperatures.

**Electrolytic Deposition:** By using aqueous solutions and/or fused salts of the required metal in an electrolytic processes, metallic particles are precipitated from solution.

**Carbonyls:** Metal carbonyls are decomposed into their respective metal. Usually used to produced very small particles of Co, Fe or Ni with a tight particle size distribution.

**Condensation:** Particles can form by the condensation from its metal vapors.

Iron powders produced by decomposition of iron pentacarbonyl (photo courtesy of GAF Chemical Corp); particle sizes range from about 0.25 - 3.0 microns (10 to 125 μ-in).
Rapidly Solidified Powders (microcrystalline, pseudocrystalline or amorphous)

When the cooling rate of the atomized liquid is increased, ultra-fine particles can form with little or no crystallinity (amorphous powders).

Amorphous materials can have properties different from their crystalline counterparts, such as increased strength, improved magnetization behavior, improved corrosion resistance, etc. Example: Amorphous metal transformer cores lose about 60 to 70% less energy in magnetization than conventional silicon steels.
Powder Testing and Evaluation
Evaluation of the particles for their suitability for further processing should be carried out.

Methods for Determining the Particle Size and Distribution:

**Optical Microscopy (range 0.2-100microns)**

Measurements on the microscopic image of the particles is carried out by an eye-piece fitted with a micrometer or by an automated image analyzer system.

**Sieving (range 40 to 9500microns)**

Standard sized sieves are available to cover a wide range of sizes. These sieves are designed to sit in a stack so that material falls through smaller and smaller meshes until it reaches a mesh which is too fine for it to pass through. The stack of sieves is mechanically shaken to promote the passage of the solids. The fraction of the material between pairs of sieve sizes is determined by weighing the residue on each sieve. The result achieved will depend on the duration of the agitation and the manner of the agitation.
• Screens (square screens) of different mesh sizes is the most common method to determine the particle size.

• The number of openings per linear inch is referred to as the Mesh Count. That is, a 200 mesh means 200 openings per linear inch. Higher mesh counts mean smaller particle sizes.
Sieving

- A micron is $1/25,000^{th}$ of an in.

<table>
<thead>
<tr>
<th>Sieve Mesh No.</th>
<th>Inches</th>
<th>Microns</th>
<th>Typical Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.056</td>
<td>1400</td>
<td>Beach sand</td>
</tr>
<tr>
<td>28</td>
<td>0.028</td>
<td>590</td>
<td>Fine sand</td>
</tr>
<tr>
<td>60</td>
<td>0.0098</td>
<td>250</td>
<td>Fine sand</td>
</tr>
<tr>
<td>100</td>
<td>0.0059</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>0.0030</td>
<td>75</td>
<td>Portland cement</td>
</tr>
<tr>
<td>325</td>
<td>0.0017</td>
<td>43</td>
<td>Silt</td>
</tr>
<tr>
<td>400</td>
<td>0.0015</td>
<td>38</td>
<td>Plant Pollen</td>
</tr>
<tr>
<td>(1200)*</td>
<td>0.0005</td>
<td>12</td>
<td>Red Blood Cell</td>
</tr>
<tr>
<td>(2400)*</td>
<td>0.0002</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>(4800)*</td>
<td>0.0001</td>
<td>2</td>
<td>Cigarette smoke</td>
</tr>
</tbody>
</table>

Mesh numbers in parentheses are too small to exist as actual screen sizes. They are estimates included for reference.
Aperture Size and Open Area

A screen mesh contains open spaces (holes) and material (wire). Open Area is the total area of the holes divided by the total area of the cloth. Open Area describes how much of the mesh is open space. With aperture size (L) and wire thickness (D), Open Area can be calculated as follows:

\[
\text{open area} = 100 \times \frac{L^2}{(L + D)^2}
\]

### Open Area in % as a function of mesh size

<table>
<thead>
<tr>
<th>Mesh number</th>
<th>Opening Size (µm)</th>
<th>Thickness of wire (µm)</th>
<th>Open Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4,700</td>
<td>1,200</td>
<td>63%</td>
</tr>
<tr>
<td>60</td>
<td>250</td>
<td>160</td>
<td>37%</td>
</tr>
<tr>
<td>100</td>
<td>150</td>
<td>110</td>
<td>33%</td>
</tr>
<tr>
<td>200</td>
<td>75</td>
<td>57</td>
<td>30%</td>
</tr>
</tbody>
</table>

(a) A plot of the weight of particles as a function of particle size. The most populous size is termed the mode. In this case, it is between 75µm and 90µm. (b) Cumulative particle-size distribution as a function of weight. Source: Reprinted with permission from Randall M. German, *Powder Metallurgy Science*, Princeton, NJ: Metal Powder Industries Federation, 1984.
Specific Surface Area of Particles

Surface area/unit mass = **specific surface area**

Calculate from size distribution and shape factor

Size is expressed as a "typical" dimension, $D_p$

Volume of the particle can be expressed as:

$$V_p = pD_p^3$$  \hspace{1cm} (1)

$$A_p = 6qD_p^2$$  \hspace{1cm} (2)

where  $V_p$ is the volume of the particle,

$A_p$ is the area of the particle surface,

$D_p$ is the typical dimension of the particle

$p, q$ are factors that connect the particle geometries. (subscript $p$ and factor $p$)

Ratio of surface area to volume is:

$$A_p/V_p = 6 (q/p) D_p = 6\lambda / D_p$$  \hspace{1cm} (3)

and so

$$A_p = 6q V_p / pD_p = 6 \lambda (V_p / D_p)$$  \hspace{1cm} (4)

For a mass $m$ of particles of density $\rho$, the number of particles equals $m / \rho V_p$ each of area $A_p$.

So total area:

$$A_t = (m / \rho V_p)\lambda (V_p / D_p) = 6 \lambda m / \rho D_p$$  \hspace{1cm} (5)

where $A_t$ is the total surface area of the mass of particles.

Equation (5) can be combined with the results of a sieve analysis to estimate the total surface area of a powder.
Example: Surface Area of Salt Crystals Estimate the surface areas of these two fractions on a 5Kg sample

- 38% of a rock salt sample passes through a 7 mesh screen and it is retained on a 9 mesh screen
- 5% passed 80 mesh and it was retained on a 115 mesh screen

Salt density = 1050 kg·m⁻³ and Shape Factor (λ) is 1.75

Apertures of Tyler sieves

<table>
<thead>
<tr>
<th>Passes</th>
<th>Retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 mesh</td>
<td>9 mesh</td>
</tr>
<tr>
<td>2.830 mm</td>
<td>2.000 mm</td>
</tr>
<tr>
<td>80 mesh</td>
<td>115 mesh</td>
</tr>
<tr>
<td>0.177 mm</td>
<td>0.125 mm</td>
</tr>
</tbody>
</table>

Mean size(1): -7 + 9 mesh = 2.415 mm = 2.415 x 10⁻³ m
Mean size(2): -80 + 115 mesh = 0.151 mm = 0.151 x 10⁻³ m

So, from Eqn. (5):

\[
A_1 = \frac{(6 \times 1.75 \times 0.38 \times 5)}{(1050 \times 2.410 \times 10^{-3})} = 7.88 \text{ m}^2
\]
\[
A_2 = \frac{(6 \times 1.75 \times 0.05 \times 5)}{(1050 \times 0.151 \times 10^{-3})} = 16.60 \text{ m}^2
\]
**Example:** Determine the shape factor for (1) a spherical particle, (2) a cubic particle and (3) a cylindrical particle with a length to diameter ratio of 2.

\[ k = \frac{A}{V} D_{eq} \]

K= shape factor

Deq = the diameter of the sphere that has the same volume as the particle or object being considered.

A = Area

V = Volume

\[
k = \frac{\pi D^2}{\left(\frac{\pi D^3}{6}\right)} D = 6 \quad \text{sphere}
\]

\[
D_{eq} = \left(\frac{6V}{\pi}\right)^\frac{1}{3} = \left(\frac{6L^3}{\pi}\right)^\frac{1}{3} = 1.24L \quad k = \frac{6L^2}{L^3} 1.24L = 7.44 \quad \text{cube}
\]

\[
A = \frac{2\pi D^2}{4} + \pi DL = 2.5\pi D^2
\]

\[
V = \frac{\pi D^2 L}{4} = \frac{\pi D^3}{2} \quad \Rightarrow \quad D_{eq} = \left(\frac{6V}{\pi}\right)^\frac{1}{3} = \left(\frac{6\left[\frac{\pi D^3}{2}\right]}{\pi}\right)^\frac{1}{3} = 1.442D
\]

\[
k = \left[\frac{2.5\pi D^2}{\left(\frac{\pi D^3}{2}\right)}\right] 1.442D = 7.21 \quad \text{cylinder L/D ratio of 2}
\]
**Sedimentation (0.08-300microns)**

The terminal settling velocity of particles through a liquid medium in a gravitational centrifugal environment is measured using Andreasen apparatus.

![Diagram of sedimentation process]

**Particle Volume Measurement (0.5-300microns)**

The powder is suspended in an electrolyte solution and it is then made to flow through a short insulated capillary section between two electrodes and the resistance of the system is measured. When a particle passes through the capillary, a momentary peak in the resistance occurs and the amplitude of the peak is proportional to the particle size. Counting is done by a computer.

![Diagram of particle volume measurement]

Inter-particle Friction and Powder Flow

The ability of the powder to flow readily and pack tightly is affected by the friction between particles. The friction between particles is measured by the angle of repose (angle formed by a pile of powder as it is poured from a narrow funnel).

Smaller particle sizes generally show greater friction and steeper angles!

Little friction between spherical particles!

As shape deviates from spherical, friction between particles tends to increase

Spherical shapes have the lowest interpartical friction!

To facilitate flow during pressing, the interparticle friction can be reduced by the addition of lubricants.
Particle Density

**True Density:** Density of the solid material with no porosity or the density of the powder that has been melted into a solid (no porosity) mass.

**Bulk Density:** The mass of the powder divided by the volume of the powder that has just been poured (no compacted). The bulk density is lower than the true density due to the presence of porosity.

\[
Packing - Factor = \frac{Bulk - density}{True - density}
\]

\[
Void - volume = (Bulk - volume) - (True - volume)
\]

Typical values for loose powder have a packing factor that ranges from 0.5 to 0.7.

Packing can be increased by
- mixing powders of different sizes such that the smaller powders fit into the spaces between the larger powders.
- Vibrating the powders will cause them to accommodate more tightly.
- Pressure or compaction will greatly increase the packing factor by deformation of the particles and/or rearrangement.
Porosity

Porosity is defined as the ratio between the volume of the pores (empty spaces within the solid) to the bulk volume.

In principle:

\[ \text{Porosity} + \text{Packing} - \text{Factor} = 1 \]

\[ \text{Porosity}(\varepsilon) = \frac{(\text{Bulk - volume}) - (\text{True - volume})}{(\text{Bulk - volume})} \]

Example:

A sample of calcium oxide powder with a true density of 3.203 g.cm\(^{-3}\) and weighing 131.3 g was found to have a bulk volume of 82 cm\(^3\) when placed in a 100-ml graduated cylinder. Calculate the porosity?

\[ \text{True - volume} = \frac{131.3 \text{g}}{3.203 \text{g \cdot cm}^{-3}} = 41 \text{cm}^3 \]

\[ \text{Porosity}(\varepsilon) = \frac{82 - 41}{82} = 0.5 \text{ or } 50\% \]
Blending Powders

Blending must be carried out to homogenize the mixture of powders and additives (lubricants and binders). Example: mixture of industrial diamonds and tungsten particles must be homogenized for diamond bearing core drills.

Controlled blending conditions must be used in order to avoid contamination or deterioration.

Different bowl geometries are available for efficient mixing.

Some powder metals may be prompt to oxidation or explosion due to their high surface area to volume ratio.

Some bowls are especially constructed to avoid sparks.

Bowls can be grounded to avoid building of charges due to friction.
Compaction of Metal Powders

• The pressed powder is known as the **Green Compact**.
• Pressing the powder is necessary to obtain the required shape of the part, increase the density and increase the particle-to-particle contact points necessary for sintering.
• The density of the green compact and of the final P/M part depends strongly on the applied pressure.
• Pressures can range between 20000 and 100000psi.
• The green compact is still very porous with approximately 70% of the true density.
The higher is the density of the green compact, the higher is the strength and elastic modulus of the final P/M part. As the green compact pressure is increased, the porosity of the final P/M part decreases. To ensure a more uniform density across the green compact, multiple punches can be used.
The required pressure depends on the characteristics of the powder, i.e., shape, lubrication, blending method.

**TABLE 17.1**
Compacting Pressures for Various Powders

<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>

**TABLE 18-1**
Typical Compacting Pressures for Various Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Compaction Pressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous metals and filters</td>
<td>3–5</td>
</tr>
<tr>
<td>Refractory metals and carbides</td>
<td>5–15</td>
</tr>
<tr>
<td>Porous bearings</td>
<td>10–25</td>
</tr>
<tr>
<td>Machine parts (medium-density iron &amp; steel)</td>
<td>20–50</td>
</tr>
<tr>
<td>High-density copper and aluminum parts</td>
<td>18–20</td>
</tr>
<tr>
<td>High-density iron and steel parts</td>
<td>50–120</td>
</tr>
</tbody>
</table>
Effect of compacting pressure on green density (the density after compaction but before sintering). Separate curves are for several commercial powders.

**Stresses during Compaction**

Coordinate system and stresses acting on an element in compaction of powders. The pressure is assumed to be uniform across the cross-section.
Equilibrium of forces in the vertical direction.

\[
\left(\frac{\pi D^2}{4}\right) p_x - \left(\frac{\pi D^2}{4}\right) (p_x + \delta p_x) - (\pi D) \cdot (\mu \sigma_r) \delta x = 0
\]

\[
D \delta p_x + 4 (\mu \sigma_r) \delta x = 0
\]

The values of \( p_x \) and \( \sigma_r \) are unknown.

We define the factor \( k \) as a measure of the inter-particle friction during compaction.

\[
\sigma_r = k \cdot p_x \Rightarrow \delta p_x + \frac{4 \cdot \mu \cdot k \cdot p_x}{D} \delta x = 0
\]

\[
\frac{\delta p_x}{p_x} = \frac{4 \cdot \mu \cdot k}{D} \delta x
\]

\[
p_x = p_0 e^{-\frac{4 \cdot \mu \cdot k \cdot x}{D}}
\]

If there is no friction \( k=1 \) and the powder behaves like a fluid. Then \( \sigma_r = p_x \) (hydrostatic pressure).

Similar to the expression of upsetting.

Integrating from \( p_x = p_0 \) when \( x=0 \).

The local compacting pressure decreases as the length to diameter ratio and \( k \) increases.
**Example:**

Assume that a powder mix has a $k=0.5$ and a $\mu=0.3$. At what depth will the pressure in a straight cylindrical compact of 10mm diameter become (a) zero and (b) half of the pressure at the punch?

(a) zero

The distance $x$ will have to approach infinity.

(b) Half of the compacting pressure at $x=0$

$$0.5 \cdot p_O = p_O e^{\left(-\frac{4 \cdot 0.3 \cdot 0.5 \cdot x}{10}\right)} \Rightarrow 0.5 = e^{(-0.06x)} \Rightarrow x = 11.55\text{mm}$$
Classes of P/M Equipment

The equipment has been grouped in our classes according to the complexity of the P/M part.
Isostatic Pressing

Cold Isostatic Pressing (CIP)
- The powder is placed in a flexible rubber mold.
- The chamber is hydrostatically pressurized up to 150ksi.
- A more uniform compaction and density are achieved.
- Typical applications are automotive cylinder liners.

Hot Isostatic Pressing (HIP)
- Compaction and sintering are combined in a single step.
- Final P/M parts emerge at full density and with uniform and isotropic properties.
- The container is made of a high-melting point sheet metal.
- Usually uses inert gases as pressurizing medium
- Common conditions are 15ksi and 2000F
- Method is used for reactive or brittle materials (Be, Zr, Ti, U).
- It is used in the production of superalloy components for the aircraft and aerospace industries
- Also used to densify existing parts.
- It improves the strength, toughness, fatigue resistance and creep resistance of a P/M part.
- It is an expensive, long and not a high volume process.
Hot isostatic pressed carbide cap on a steel shaft.
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 R. M. German, *Powder Metallurgy Science*, Metal Powder Industries Federation, Princeton, NJ; 1984.

Capabilities, with respect to part size and shape complexity, available form various P/M operations. P/F means powder forging. Source: Courtesy of Metal Powder Industries Federation.
**Sintering**

Sintering is a heat treatment designed to cause diffusion between adjacent particles, leading to bonding and thereby increasing strength and hardness. The temperature for sintering ranges between 70 to 90% the melting point of the metal (in absolute scale). The driving force behind sintering is the reduction of surface energy. The green compact shrinks during sintering due to the elimination of the pores.
Sintering is a complex process and involves diffusion of solid atoms, recrystallization, grain growth, pore shrinkage, liquid phase sintering and evaporation of volatile materials.

### 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>
<tr>
<td>Process*</td>
<td>Density (%)</td>
<td>Yield strength (MPa)</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Cast</td>
<td>100</td>
<td>840</td>
</tr>
<tr>
<td>Cast and forged</td>
<td>100</td>
<td>875</td>
</tr>
<tr>
<td>Blended elemental (P+S)</td>
<td>98</td>
<td>786</td>
</tr>
<tr>
<td>Blended elemental (HIP)</td>
<td>99</td>
<td>805</td>
</tr>
<tr>
<td>Prealloyed (HIP)</td>
<td>100</td>
<td>880</td>
</tr>
</tbody>
</table>

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

Source: Courtesy of R. M. German.
Powder Metallurgy: Connecting Rods


Forged on left; P/M on right
## Powder Metallurgy

### Advantages
- Virtually unlimited choice of alloys, composites, and associated properties
- Refractory materials are popular by this process
- Controlled porosity for self lubrication or filtration uses
- Can be very economical at large run sizes (100,000 parts)
- Long term reliability through close control of dimensions and physical properties
- Wide latitude of shape and design
- Very good material utilization

### Disadvantages
- Limited in size capability due to large forces
- Specialty machines
- Need to control the environment – corrosion concern
- Will not typically produce part as strong as wrought product. (Can repress items to overcome that)
- Cost of die – typical to that of forging, except that design can be more – specialty
- Less well known process
Other Powder Techniques:

Powder Rolling:
Extrusion:

Canning of powder. Heating or evacuation of sealed container followed by forging or evacuation. Mechanical or chemical removal of container material.

For smooth powder flow and densification, streamlined designs are used.
Spray Deposition

It is a shape-generation process die

The basic components are (1) an atomizer, (2) a spray chamber with an inert atmosphere, and (3) a mold for producing preforms.
Impregnation & Infiltration

Porosity is an inherent characteristic of powder metallurgy processes. Special products can be created by filling the empty pores with oil (impregnation), polymers or metals (infiltration).

Impregnation

The pores of a P/M part is permeated with oil or other fluid such as a polymer. Example: oil-impregnated bearings, gears

Oil-impregnated Porous Bronze Bearings

www.ondrives.com
Infiltration

An operation in which the pores of the PM part are filled with a molten metal

• The melting point of the filler metal must be below that of the PM part
• Involves heating the filler metal in contact with the sintered component so capillary action draws the filler into the pores
• The resulting structure is relatively nonporous, and the infiltrated part has a more uniform density, as well as improved toughness and strength.
• Suitable for non-soluble systems such as W-Cu. Miscibility of one metal in the other causes increasing of viscosity of the infiltrated liquid, lowering of the capillary forces and hence short infiltration distances.
• Infiltration and liquid phase sintering are the only processes available when producing parts with high melting point materials for example W particles embedded in copper, or diamond bearing cutting tools.
Hi-Tech Applications of P/M

- Electrical Contacts
- Sliding Electrical Contacts
- Very Hard Magnets
- Very Soft Magnets
- Anti-friction products
- Friction products
- Filters
- Refractory Material Products
- Hard and Wear Resistant Tools
- Ferrous & Non-ferrous Structural parts etc.

Microstructure: ceramic particles in metal matrix

SiC particles in an Aluminum Matrix, 400X
Tungsten refractory metal, 200X
### TABLE 18-6 Comparison of Four Powder Processing Methods

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Conventional Press and Sinter</th>
<th>Metal Injection Molding (MIM)</th>
<th>Hot-Isostatic Pressing (HIP)</th>
<th>P/M Forging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of workpiece</td>
<td>Intermediate</td>
<td>Smallest</td>
<td>Largest</td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td>&lt;5 pounds</td>
<td>&lt;1/4 pounds</td>
<td>1–1000 pounds</td>
<td>&lt;5 pounds</td>
</tr>
<tr>
<td>Shape complexity</td>
<td>Good</td>
<td>Excellent</td>
<td>Very good</td>
<td>Good</td>
</tr>
<tr>
<td>Production rate</td>
<td>Excellent</td>
<td>Good</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>Production quantity</td>
<td>&gt;5000</td>
<td>&gt;5000</td>
<td>1–1000</td>
<td>&gt;10,000</td>
</tr>
<tr>
<td>Dimensional precision</td>
<td>Excellent</td>
<td>Good</td>
<td>Poor</td>
<td>Very good</td>
</tr>
<tr>
<td>Density</td>
<td>Fair</td>
<td>Very good</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td>80–90% of wrought</td>
<td>90–95% of wrought</td>
<td>Greater than wrought</td>
<td>Equal to wrought</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Intermediate</td>
<td>High</td>
<td>Somewhat low</td>
</tr>
<tr>
<td></td>
<td>$0.50–5.00/lb</td>
<td>$1.00–10.00/lb</td>
<td>&gt;$100.00/lb</td>
<td>$1.00–5.00/lb</td>
</tr>
</tbody>
</table>
Processing of Ceramics

Crushing or grinding the raw materials into very fine particles.

Mixing with additives (binder: to hold the particles together, lubricant: to reduce friction, wetting agent: to improve mixing process, plasticizer: to improve ease of forming mixture, agents: control of foaming and sintering, deflocculent: to create an uniform mixture by applying like charges to all particles, causing them to repel each other.

Shaping, drying, and firing the material.
Figure 17.1: Usual steps in traditional ceramics processing: (1) preparation of raw materials, (2) shaping, (3) drying, and (4) firing. Part (a) shows the workpart during the sequence, whereas (b) shows the condition of the powders.
**Crushing**
(a.k.a. comminution or milling)

Crushing is typically done in a ball mill, in either wet or dry conditions.

Wet milling is preferred because it strengthens particle bonds and limits dust.

For correct sizing, the crushed particles are passed through a sieve.
Mixing

Particles are then mixed with one of the additives listed and described on the previous slide.
Advanced Ceramics: Materials for Automobile Engines

Advantages:
- Operate at high temperatures – high efficiencies
- Low frictional losses
- Operate without a cooling system
- Lower weights than current engines

Disadvantages:
- Ceramic materials are brittle
- Difficult to remove internal voids (that weaken structures)
- Ceramic parts are difficult to form and machine

Potential candidate materials: Si₃N₄, SiC, & ZrO₂
Possible engine parts: engine block & piston coatings

Advanced Ceramics: Materials for Ceramic Armor

Components:
- Outer facing plates
- Backing sheet

Properties/Materials:
- Facing plates -- hard and brittle
  - fracture high-velocity projectile
  - Al₂O₃, B₄C, SiC, TiB₂
- Backing sheets -- soft and ductile
  - deform and absorb remaining energy
  - aluminum, synthetic fiber laminates
Ceramic Fabrication Methods (i)

Particulate Forming

Glass Forming

Cementation

Particulate Forming

Ceramic powders

Ball milling, blending, and spray drying—binders, surfactants, plasticizers, etc. added

Slip casting

Compaction (uniaxial or isostatic)

Tape casting

Extrusion

Injection molding

Drying

Optional Green ceramic machining

Degassing

Binder burnout and sintering using controlled atmosphere as needed

Secondary machining or other operations

Final sintered ceramic product

Hot pressing or hot isostatic pressing
**Slip Casting (Drain Casting)** - The crushed particles are first mixed with water, then they are poured into a mold. Pouring must be done properly to avoid air pockets.

When some of the water has been absorbed, the remainder of the mixture is poured out of the top of the mold.

The top of the part can then be trimmed.

**Advantages** - inexpensive components

**Disadvantages** - limited control of dimensions & low production rate

Sequence of operations in slip-casting a ceramic part. After the slip has been poured, the part is dried and fired in an oven to give it strength and hardness.
Solid casting

Slip poured into mold

Water absorbed

Finished piece
The starting mixture must have a plastic consistency, with 15% to 25% water.

**Plastic Forming**

Plastic Forming Methods:

- Hand modeling (manual method)
- Jiggering (mechanized method)
- Pressing
- Isostatic pressing
- Extrusion

**Jiggering**

Similar to potter's wheel methods, but hand throwing is replaced by mechanized techniques.
**Powder Pressing:** It is used for both clay and non-clay compositions.

- Powder (plus binder) compacted by pressure in a mold
  - Uniaxial compression - compacted in single direction
  - Isostatic (hydrostatic) compression - pressure applied by fluid - powder in rubber envelope
  - Hot pressing - pressure + heat (decreased porosity)

**Sintering** occurs during firing of a piece that has been powder pressed
- powder particles coalesce and reduction of pore size
Tape Casting

**Doctor-Blade Process** - Used to produce ceramic sheets thinner than 1.5mm.

Ceramic mixture is forced under a blade to create a film, which is then dried in a drying chamber (usually attached to the same machine).

Thin sheets of green ceramic cast as flexible tape

Used for integrated circuits and capacitors

*Slip* = suspended ceramic particles + organic liquid (contains binders, plasticizers)
**Extrusion** - Ceramic particles mixed into a solution with 20-30% water.

Then mixture is pushed through a small die opening by a “screw-type piece of equipment.”

**Advantages** - low cost, high production

**Disadvantages** - wall thickness limited
Forming and Shaping of Glass

Glass is one of three basic types of ceramics (traditional, modern and glasses). Glass is distinguished by its amorphous (noncrystalline) structure.

Structure: Network formers
Molecules that link up with each other to form long chains and networks. Hot glass cools, chains unable to organize into a pattern. Solidification has short-range order only.

Raw Materials: **Glass forming oxides**: usually the dominant constituent ($\text{SiO}_2$, $\text{B}_2\text{O}_3$, $\text{P}_2\text{O}_5$, etc.). **Fluxes**: reduce melting temperatures ($\text{Na}_2\text{O}$, PbO, K$_2$O, Li$_2$O, etc).

**Property modifiers**: added to tailor chemical durability, expansion, viscosity, etc. ($\text{CaO}$, Al$_2$O$_3$, etc.). **Colorants**: oxides with 3d, 4f electron structures; minor additives (<1 wt%). **Fining agents**: minor additives (<1 wt%) to help promote bubble removal (As-, Sb-oxides, KNO$_3$, NaNO$_3$, NaCl, fluorides, sulfates)
Shaping processes to fabricate these products can be grouped into three categories:

1. **Discrete processes** for piece ware (bottles, jars, plates, light bulbs)
2. **Continuous processes** for making flat glass (sheet and plate glass) and tubing (laboratory ware, fluorescent lights)
3. **Fiber-making processes** to produce fibers (for insulation and fiber optics)

### Piece Ware Shaping Processes

**Spinning** – similar to centrifugal casting of metals  
**Pressing** – for mass production of flat products such as dishes, bake ware, and TV tube faceplates  
**Press-and-blow** – for production of wide-mouth containers such as jars  
**Blow-and-blow** - for production of smaller-mouth containers such as beverage bottles and incandescent light bulbs  
**Casting** – for large items such as large astronomical lenses that must cool very slowly to avoid cracking.
Molten Glass - Gob
Shaping of Flat and Tubular Glass

Processes for producing flat glass such as sheet and plate glass:

**Rolling of Flat Plate**
Starting glass from melting furnace is squeezed through opposing rolls whose gap determines sheet thickness, followed by grinding and polishing for parallelism and smoothness.

**Float Process**
Molten glass flows onto the surface of a molten tin bath, where it spreads evenly across the surface, achieving a uniform thickness and smoothness - no grinding or polishing is needed.
Danner Process
Molten glass flows around a rotating hollow mandrel through which air is blown while the glass is drawn.
Forming of Glass Fibers

Glass fiber products can be divided into two categories, with different production methods for each:

1. Fibrous glass for thermal insulation, acoustical insulation, and air filtration, in which the fibers are in a random, wool-like condition. *Centrifugal spraying*
2. Long continuous filaments suitable for fiber reinforced plastics, yarns, fabrics, and fiber optics. *Drawing*