The heat treatment atmosphere must protect the material from oxidation. Often carbon or nitrogen can be added to the component by mixing methane, CO, or ammonia into the processing atmosphere. Some special treatments, including steam, are applicable to PM materials. Rust formation on ferrous components is avoided by heating in a dry atm at temperatures below approx. 370°C. But, as shown in Figure, it is possible to form a stable Fe₃O₄ at higher temperatures by adjusting the partial pressure of water to hydrogen. At that point, steam is introduced and the T is increased to approx. 520°C to promote surface oxidation reaction:

$$3\text{Fe}(s) + 4\text{H}_2\text{O}(g) \rightarrow \text{Fe}_3\text{O}_4(s) + 4\text{H}_2(g)$$

![Graph showing the partial pressure ratio of H₂O to H₂ vs. temperature in °C.]
Joining: After fabrication, several components may need to be joined to form an assembly. The assembly might involve different materials that could not be combined in sintering. As identified in table, all of the usual joining processes are applicable to PM materials.

Bonding porous PM materials requires special care. Pores reduce thermal conductivity and can wick/suck molten metal away from the area being joined, so they must be cleaned.

Braze, diffusion, and adhesive bonds are all weaker than other joining techniques; electron beam and laser welding can cause distortion in porous components. These factors influence the selection of the actual joining process. At low porosity levels, below approx. 8%, no major difference exists between joining procedures for PM materials.

At porosities between 10% and 20%, fusion techniques are possible, but the joining conditions must minimize the amount of melt. At higher porosity levels, molten metal joining techniques should not be used because of distortion and residual stresses generated by the contracting weld.
Joining Processes for P/M Components and Materials

adhesive bonding - bonding between clean surfaces by the action of an acrylic or epoxy giving a low strength chemical bond

arc welding - consumable (MIG) or nonconsumable (GTA) arc is formed to melt material at the contact, the metal flows and bonds the objects prior to solidification

brazing - a low melting liquid is formed by heating the component, the liquid wicks into a gap of approximately 0.5 mm width and near surface pores to create a chemical and mechanical bond

diffusion bonding - contacting parts are heated to a high temperature under low loads such that atomic diffusion forms a metallurgical bond; also known as sinter bonding

electron beam welding - local melting of contacting materials by use of a high energy electron beam

friction welding - inertial energy from a moving or spinning object is converted into heat at a frictional contact to cause bonding

laser weld - local melting to form a bond between two contacting parts by use of high energy lasers

press fit - a mechanical bond formed by the localized plastic deformation at an interference zone between two close tolerance components with approximately 0.2% misfit

resistance welding - electrical current passes through the contact between simple shapes to cause heating and subsequent bonding
Surface Treatments: Several treatments can be applied to improve function or aesthetics. Examples of post-sintering surface treatments include deburring, coating, spraying, painting, polishing, cleaning, anodizing, plating, sealing, and laser glazing.

Deburring removes sharp edges, flash, burrs or other surface irregularites. It is performed by subjecting the component to tumbling or vibration with abrasive media, or surface abrasion such as sand blasting.

Coatings are used to improve wear life and provide corrosion resistance. Typical coatings for corrosion resistance are based on Cr, Ni, Cu, Zn, As, or Cd.

Impregnation is a widely employed technique for sealing surface connected pores. It is used to fill pores with oil for self-lubrication, or to fill the pores with polymers to improve corrosion resistance and machining. After impregnation, the material is impermeable. The contact angle controls the infiltration process. If $\theta \rightarrow 0$, impregnating fluid will spread to eventually fill all the pores. Large pores have less resistance to filling, so they will fill most rapidly.
An important means of improving fatigue life of a PM component is through shot peening. Surface compressive forces are generated by bombarding the component with small diameter shot. The shot leaves small indentations that create a cold worked layer on the surface.
Compact Characterization

The characteristics of PM compacts can be divided into 4 groups. The microstructural characteristics like the grain size and dispersion of phases, pore size, shape and interconnectivity; mechanical properties such as strength, ductility, toughness; surface properties include catalytic, filtration and corrosion behaviors.

Microstructural Features: Polished cross-sections of a powder compact provide information on the grain and pore structure. Pore size and shape can be quantified by the intercepts lengths measured on a magnified microstructure. The easiest measure of grain size is obtained by counting the number of grain boundaries intercepted by a test line on a magnified picture. The mean grain intercept size is the line length divided by the magnification and number of intercepts.

Scanning electron microscopy (SEM) is useful in visualizing the 3-D nature of pores. The level of porosity can be calculated from the relative amount of pore space.
Pore Characteristics:

Porosity: gives the fraction of the total volume which is void. For simple geometries, porosity is measured by determining the weight and dimensions and comparing the density to the theoretical value.

The Archimedes technique of water immersion is useful for measuring density if the pores can be sealed to prevent water penetration during the analysis. Various sealants, including silicone oil, are available for that.

The Archimedes technique for obtaining density for a porous material requires preventing water penetration of pores. The sample is weighed dry ($W_1$), after oil impregnation ($W_2$), and immersed in water ($W_3$). Usually a wire is used to suspend the sample in the water and its weight $W_w$ must be measured in water too. Then the density $\rho$ can be calculated from the weight determinations:

$$\rho = \frac{W_1 - W_w}{[W_2 - (W_3 - W_w)]}$$

where $\rho_w$ is the density of water ($\text{g/cm}^3$) which is temperature dependent:

$$\rho_w = 1.0017 - 0.0002315 T$$

$T$ being water $T$ in °C.
Pore Shape: It is highly variable, SEM allows examination of the pore structure. Optical microscopy is the first way to determine pore shape from a random structure. Intrusion of plastic into the pores with subsequent etching is another means to view shape. The figure shows cross-sections of the pore shapes classified in modeling porous materials. In general, cylindrical pore shape is used because it is easiest to deal with mathematically.

Open pore structures are most useful for self-lubricating bearings, filters.

Pore shape is a difficult parameter to quantify with a single measure.
Pore Size: Porosity is an incomplete measure of the pore structure. Many different pore sizes, shapes, and levels of connectivity are possible at any given porosity. In the extreme case, consider that 20% porosity in a structure can be achieved by just one large hole and several million small pores. Therefore, it is necessary to seek greater detail concerning the pore structure.

Mercury porosimeter provides an approach for estimating the pore size distribution for materials containing open pore networks. The technique is good for pores as small as 1 nm. Pressure is used to drive mercury into the pore structure from the outside surface. Since mercury is not wetting most materials, the amount of mercury entering the material vs. the applied pressure allows calculation of the pore size distribution. This calculation requires assumption of a pore shape model (usually cylindrical).
Open vs. Closed Porosity: Only the open pores contribute to the flow-related properties like filtration and permeability. The total amount of porosity is important in dealing with mechanical properties. Mercury porosimetry measures only the open pore structure. Optical metallography cannot distinguish between open and closed porosity. Helium pycnometry can give a measure of the closed porosity. Other pore structure analysis techniques, like gas adsorption and gas permeability, are applicable only to open pores.

Mechanical Properties

The mechanical properties of PM materials are degraded by the presence of pores. Table provides an example of the property degradation by listing some properties vs. porosity for a sintered and heat-treated 0.5% C steel.

<table>
<thead>
<tr>
<th>Porosity Effects on Mechanical Properties of a Heat Treated Fe-0.5C</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/M Steel</td>
</tr>
<tr>
<td>porosity, %</td>
</tr>
<tr>
<td>yield strength, MPa</td>
</tr>
<tr>
<td>tensile strength, MPa</td>
</tr>
<tr>
<td>elongation, %</td>
</tr>
<tr>
<td>hardness, HRB</td>
</tr>
<tr>
<td>impact energy, J</td>
</tr>
</tbody>
</table>
Testing: Several standard tests for mechanical properties may be applied to PM materials. The radial crush strength is a basis for analyzing the properties of sintered products such as cylindrical bearings. The test is shown in figure with the expected fracture condition. The failure load of the crushed cylinder is measured, and the radial crush strength $\sigma_R$ is calculated as:

$$\sigma_R = \frac{F_b (D - T)}{LT^2}$$

where $L$ is the sample length, $D$ is the outer diameter, $T$ is the wall thickness, and $F_b$ is the breaking load.

The transverse rupture strength is the most common measure of the strength of low ductility PM materials, especially the green strength. The transverse rupture strength $\sigma_T$ is calculated from the specimen geometry and failure load as:

$$\sigma_T = \frac{3F_b L}{2WT^2}$$

where $F_b$ is again breaking load, $T$ is thickness, $W$ is width, and $L$ is the distance between the lower load supports.
There is a flat tensile bar design used for die compaction in Fig. The projected cross-sectional area is 6.65 cm², with a 25 mm gauge length. The thickness of the bar is generally held to 5 to 6 mm and tensile strength is calculated using the maximum load divided by the cross-sectional area. The tensile geometry allows measurement of the strength and yield behavior, as well as elasticity and elongation.

Ductility variations with Porosity. Porosity degrades ductility, and there is additional sensitivity to pore shape and placement.

The negative effects of pores are due to strain concentrations, uneven cross-section, poor workhardening, and their role as crack initiation sites. For sintered PU materials, the ductility can be approximated as:

\[ \tau = \frac{(1 - \varepsilon)\frac{1}{2}}{(1 + c \varepsilon^2)\frac{1}{2}} \]

where \( \tau \) is the relative ductility, \( c \) is an empirical constant, and \( \varepsilon \) is the porosity.

The relative ductility is the ductility of the porous material divided by the ductility of equivalently processed wrought material.
Surface Properties

Surface Activity: The high surface area of a small pore structure is beneficial for applications such as catalysis, fuel cells, filters which require high surface areas and large porosities (from 50 to 90%).

Corrosion Resistance: The lower corrosion resistance results from 3 factors:

i) the presence of pores which give a higher total surface area per unit volume,

ii) the long term anneals associated with sintering, and

iii) the interstitial pickup from the sintering atmosphere.

A good example is; the preservation of corrosion resistance requires a uniform chromium distribution without the formation of compounds. In a nitrogen, oxygen, or carbon containing atmosphere, the chromium in a stainless steel becomes preferentially compounded. As a consequence, the chromium is depleted from regions near grain boundaries, resulting in localized corrosive attack. A high sintered density eliminates surface area over which attack can occur.
Best corrosion resistance is associated with well-sintered and densified materials. Selected chemical additions can be made to the powder or sintered compact to improve corrosion resistance. Infiltrating the pore structure with organic substances after sintering also can reduce corrosion problems.

**Filtration Properties:** Two types of filtration behavior are associated with porous metals fabricated from metal powders. Figure shows both cake formation (surface) and internal trapping (depth) mechanisms in a schematic form. Cake formation leads to self-filtration as the pores in the cake limit the material and fluid passing through the filter. In that sense, the porous metal is a support for the self-filting cake. Cake filtration is associated with high contamination concentrations in the fluid, low flow rates, and low concentrations of very fine debris/waste.
The internal trapping (depth) mode is associated with low concentrations of contaminants in the feed fluid and high flow rates. For cake filtration, the surface pore size determines the operational characteristics. Trapping at internal pore sites depends on a curved pore shape.

The ideal filter will remove all of the contaminants and resist flow reductions as a consequence of the filtration process.

The powder metallurgy filters are most effective in low viscosity fluids like gases. In liquid filtration, streamline flow through the pores can carry debris to large depths and even through the filter.
Examples of PM Applications

Structural components, controlled porosity applications, electrical applications, magnetic applications, thermal applications, friction applications, high temperature app, corrosion resistance app, high hardness app, high density app, wear resistance app, low density app, composites.

Find out and read these subjects. You should be able to give at least 1 example for each of these applications.