POROUS P/M TECHNOLOGY

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By Mark Eisenmann
Metallurgical Engineer

The technology of fabricating lower density, porous Powdered Metal (P/M) materials is rapidly advancing to fulfill a wide variety of new applications. A rigid, permeable structure can be created utilizing P/M technology by forming a network of sintered powder particles and interconnected pore channels. Using similar manufacturing equipment and technology as structural P/M components, porous P/M materials are normally sintered to densities between 25-85% of theoretical mean density (TMD). Structural P/M components are typically 85%-99.9% of TMD. These unique engineered materials provide specialized products for applications such as filtration, fluid flow control, self lubricating bearings, spargers and battery electrodes.

Porous P/M materials are specified when special characteristics are required such as good mechanical properties, rigidity, corrosion resistance, uniform porosity and controlled permeability. For example, porous bronze, stainless steel or nickel alloys are often selected for service in elevated temperature and pressure environments. Porous materials such as papers, synthetic fibers and plastics are commonly selected for service in less severe conditions due to their lower cost [1]. However, in applications where disposal costs are significant due to the nature of the service environment, renewable porous P/M materials offer excellent cleanability for economical reuse. Other porous metal materials made from sintered fibers, foam, perforated sheet and screen may be selected as alternatives to porous P/M materials depending on the application[2]. Metal fiber / screen composites, screen / powder composites and fiber / powder composites are also sintered to form porous media [3,4,5]. Porous ceramics are utilized in applications which require higher temperature service or more extreme corrosion resistance than porous metals. However, porous ceramics are limited in their application due to substantially lower mechanical properties than metals and due to fabrication difficulties when joining to metal hardware [6].

Porous P/M materials accounted for about 2% of the overall powder metallurgy market based on market share by application. Approximately 70% of the overall P/M market is comprised of structural components for the automotive industry [7]. Porous P/M materials are also estimated to account for less than 2% of the overall filtration and fluid control markets which are currently dominated by lower cost, disposable porous media. Despite the small market size currently served by porous P/M materials, this material science is an emerging technology driven by increased environmental concerns, by improved product quality demands and by more complex processing of industrial products. The unique materials, characteristics, fabrication methods and applications of porous P/M technology are summarized in this article.

Materials Selection

Materials can be selected from a wide variety of powdered metal materials depending on the combination of application requirements and economics. The porosity is determined by the powder particle shape, by the powder size distribution, by the powder surface texture and by other powder characteristics which are dependent on the material processing method. Since the powder characteristics are one of the major factors in determining the porous material properties of the finished component, reproducible powder characteristics and manufacturing methods are critical to production of a consistent product.

The four most common porous P/M materials are bronze, stainless steel, nickel and nickel based alloys. Other materials such as titanium, aluminum, copper, platinum, gold, silver, iron, iron aluminide (Fe_3Al), niobium, tantalum and zirconium are fabricated into porous materials from powder [8]. The size distribution of the particles can be a direct result of the powder manufacturing process or can be altered by sieving or air classification techniques. The characteristics, sintering conditions and commercial availability of a powder will determine whether the desired material can be manufactured into a porous structure.

Bronze powders consisting of 89-90% copper, 10-11% tin and 0.1-0.5% phosphorous are the most common material for porous bronze P/M components such as filters and self-lubricating bearings. Small amounts of phosphorous can be added to improve mechanical strength [9]. Bearings can be produced from pre-blended elemental powder mixes or prealloyed powders. These '89/11' or '90/10' bronze powders are available from three main processes. Gas or air atomization of pre-alloyed bronze yields fine, spherical particles which can be processed to low densities by gravity sintering as shown in Figure 1. Spherical bronze particles can also be obtained by tin coating of gas atomized copper powder. Rounded particles are made from cutting tin coated copper wire with a composition of 93-97% copper and 3-7% tin [10] as shown in Figure 2. Bronze powder particle sizes range from 10 to 850 micrometers in diameter depending on the powder type.

Stainless steel and nickel based alloys are often specified for increased service life when more corrosion resistance, temperature resistance or strength is required. Due to economic considerations, the most common stainless steel materials chosen are the extra low carbon, austenitic grade, type 316L or from the non-standard, 2-3% silicon modified grade, known as '316B'. The additional silicon serves as a sintering aid by lowering the sintering temperature and controlling the porosity and mechanical properties. Other austenitic, 300 series grades, such as 304L and 347, along with the ferritic grades such as 430, are used in a few specialized applications where the required corrosion resistance or mechanical properties are superior to 316L SS. Nickel based alloys such as Hastelloy ® C22, Inconel ® 600, Monel ® 400, and Hastelloy ® X are utilized for extreme corrosion or thermal resistance.

Stainless steel and nickel base alloy powders are produced by water or gas atomization (refer to sections on production of stainless steel and high alloy powders and production of nickel based powders in this volume). Water atomization produces powders with rounded, irregular shapes that can be processed by compaction and sintering as shown in Figures 3 and 4. These particles interlock when compacted to form a part with sufficient green strength for handling. The water atomization process yields a wide variation in particle size distribution which must be separated into much narrower size ranges for subsequent processing into porous components. As the powder size decreases, the particle shape becomes more rounded and higher compaction forces are required to produce components with adequate green strength. Some nickel based alloys such as Hastelloy ® C22, tend to atomize into more rounded particles than similar size distributions of 316L SS and thus require increased compaction force to obtain similar green strength. Material characteristics such as hardness can also influence the compressibility of the powder. Water atomization typically produces particle sizes which range from as fine as 100 nanometers to as coarse as 1000 micrometers. The particles less than 10 micrometers in diameter are normally more spherical in shape and tend to have limited cold compaction green strength unless combined with an additive.

Stainless steel and nickel alloy powders are also produced by the gas atomization process which typically yields particles with spherical shapes. This powder cannot be readily compacted without additives. Components can be fabricated by vibratory filling of molds and gravity sintering. The mechanical properties of gravity sintered, spherical powders are normally much lower than other fabrication methods which use compaction. Therefore, gravity sintering is only used in special applications which require higher porosity or unique shapes. In addition, irregular shaped powders, and powders with binders, can be processed using gravity sintering to obtain low density products.

Carbonyl or water atomized nickel powders are rapidly growing in acceptance for use as porous P/M products. The thermal decomposition of nickel carbonyl produces very fine (0.5 - 10 micrometer) particles attached in a filamentary chain type structure. Very narrow particle size distributions are possible using this process which can result in extremely uniform pore size materials after processing as shown in Figure 5. Although these powders do not flow well, components with higher porosity and fine pore sizes are made using very low compaction pressures less than 6.9 MPa (1000 psi) [11]. For nickel components with larger pore sizes, water atomized, irregular shaped particles with diameters greater than 20 micrometers are normally selected instead of carbonyl nickel since the latter process produces more rounded particles as the particle size increases [12] .

The atomization process can be varied to produce particles with other shapes designed to optimize porosity and permeability. Potato-shaped powders consist of elongated, rounded particles with smooth surfaces. Coarser grades of potato-shaped powders can be compacted directly to form shaped parts while finer grades are normally combined with a binder to achieve adequate green strength. Other processes have compacted and sintered mixtures of irregular shaped particles with up to 25% spherical particles. The smoother surface and packing characteristics of potato-shaped powders and spherical powders can result in significant permeability increases, especially in the coarser filter grades [13].

The characteristics of the four most commonly used porous metal powder materials are briefly summarized to illustrate the different powder particle characteristics available to create porous structures. Characteristics of powder metal materials are more completely described in previous sections of this handbook and other references [14,15].

Processing Methods

After the material is selected, the P/M processing method is critical for determining the final mechanical properties and porous characteristics of the porous component. Selection of the fabrication method is dependent on the powder characteristics and the type of porosity required by the application. The preparation of the powders, the use of additives, the compaction methods and the sintering conditions must be carefully controlled to produce uniform and repeatable porous characteristics. Secondary operations are normally required to enhance metallurgical properties and to allow easier adaptation to the intended application.

Powder Preparation begins with the separation of the powder particles in the desired size distribution. Depending on the amount of secondary processing, commercial powders are available with either wide or narrow particle size distributions. For example, a wide particle size distribution such as ‘minus 150 micrometers’ (-100 mesh screen) can be generated depending on the powder manufacturing process. However, secondary sieving or screening can classify a much narrower particle size distribution such as between 75 and 150 micrometers (-100 / +200 mesh). Screening must be carefully monitored since there are significant variations in the screen openings or since the screen openings are blocked with fine particles. Therefore, significant amounts of particles which fall outside of the desired particle size range are not removed by screening. The porous part manufacturers process the commercially available powders into even narrower size distributions by removing oversize and undersize particles or by adding another screen to produce a tighter cut such as between 106 and 150 micrometers (-100 / +140 mesh). Vibratory or ultrasonic screening methods are normally used for particles greater than 20 micrometers (600 mesh screen) and other separation methods such as air classification are used for particles less than 20 micrometers. Porous P/M components manufactured from narrow particle size distributions have excellent reproducibility and uniformity of the final porosity.

Once the desired particle size distribution is obtained, the powder must be properly blended prior to use in order to avoid segregation and to maximize uniformity. The apparent and tap densities of the powder cuts are normally measured to meet tight specifications since these characteristics will control further processing steps such as powder flow and die filling. Excessive blending can change the powder characteristics by generating additional fine powder particles or by changing the particle surface. Additives such as lubricants, pore formers or binders are precisely mixed with the powder if required by the processing method [16,17]. Significant amounts of powder with controlled particle size distributions are used as loose pack beds for applications such as polymer filtration. However, most applications require further processing to develop a more rigid porous structure. The powder cleanliness and chemical analysis must also be carefully monitored to maintain the chemistry requirements of the material and to avoid contamination with other materials being processed. Since these materials are often used in aggressive environments, contamination from iron, carbon, aluminum, sulfur and other elements could cause significant reduction in mechanical properties or corrosion resistance. Dedicated powder processing equipment and manufacturing facilities are the best defense against contamination. Other trace impurities such as oxygen, alumina, silica and nitrogen levels from the powder manufacturing process can also effect the final mechanical properties.

Compaction Methods and sintering are normally required to produce porous materials from stainless steel, nickel based alloys and nickel materials in order to achieve the best combination of mechanical strength, metallurgical properties and porosity. Lower density, higher permeability parts from these alloys can also result from using a gravity sintering process without compaction of the powder when the application does not require higher strength levels of compacted and sintered parts. Die compaction, isostatic pressing, and roll compaction increase the green strength of the part by cold welding of the particle to particle contact areas due to plastic deformation. As compaction force is increased, the density and green strength of the porous part increases which results in finer porosity and lower permeability than methods which do not use compaction prior to sintering. However, when compared to compacted structural P/M parts, the lower density and green strength limit the shape complexity of a porous component. For porous materials, uniform density is critical to the function of the parts since the largest porosity and greatest permeability will be in the lowest density region. Density variations of more than +/- 2.5% within the same component will cause significant difference in performance.

Die Compaction and sintering are the most common methods of improving mechanical properties for porous parts with length to diameter ratios of less than 5:1. Discs, cups, bushings and other shapes can be readily compacted by filling the powder into dies and using hydraulic or mechanical P/M presses. Typically, porous materials are manufactured to achieve the lowest density part in order to maximize porosity and permeability. Minimum green handling strength can be obtained by using lower compaction forces in the range of 700 - 2100 kg/cm^2 (5 - 15 tons/in^2). By comparison, higher density structural P/M components require compaction pressures of 4200 - 8400 kg/cm^2 (30 - 60 tons/in^2) [18]. Porous parts with 20 -50% green densities usually have minimal green strength which require careful handling and often have to be manually picked off the press and placed in a sintering tray. Higher green density parts in the 50 -80% range have sufficient green strength to allow the press feed shoe to eject the part off the die table and into a container. For low density parts made from coarse powders, press rates can be less than 5 parts per minute and part handling is critical to final yield rates. With proper sintering, die compaction can hold dimensional tolerances within +/- 1%.

Die compaction with lower tooling forces can be accomplished with die wall lubrication or adding less than 0.5% lubricant to the powder. In the case of coarser water atomized stainless steel powders, only 0.1 - 0.3% lubricant addition to the powder is generally used. Since smaller particle sizes of this same material are generally more rounded and have better particle packing (smaller pores), slightly higher pressing forces and lubricant additions are required for adequate green strength. Waxes and stearates are commonly added to the powder to reduce die wall friction and tool wear. However, since increasing the lubricant percentage also reduces green strength, minimizing lubricant additions is often a better alternative than obtaining maximum tool life service. Tooling must be kept in a highly polished condition with tight tolerances to avoid smearing of the part surface during ejection. If smearing or galling of the part surface occurs, significant reductions in the final surface porosity size and in the overall part permeability occur. Improper monitoring of lubricant additions and tooling conditions can lead to problems with the uniformity and the reproducibility of the porosity.

Isostatic Compaction is a common method of compaction for producing components such as tubes which have a length to diameter ratio greater than 3:1. Isostatic compaction can produce more uniform density porous components when compared to die compaction [19]. The wet bag Cold Isostatic Pressing (CIP) process uses a hydraulic fluid to apply pressure to the tooling which is sealed after powder filling. As the hydraulic fluid is gradually pressurized, the soft polyurethane outer liner compresses the powder against the metal core rod to obtain sufficient green strength. This 'outside-in' pressing process results in a green part with smooth inner surface and a rougher outer surface. If the pressing direction is reversed by using an expandable polyurethane inner bladder to compress the powder against a metal outer sleeve, a tube with a smooth outer surface can be obtained. Other near net shapes such as cones, funnels and tubes with splines can be manufactured using the CIP process [20]. For example, a 1" OD x ¾" ID x 3" long tube would have uniform density along the entire length whereas a similar sized, die compacted bushing would have high density ends and a lower density center. Hot Isostatic Pressing (HIP) combines the advantages of CIP and sintering into one process and is utilized in applications where complex shapes are needed or when a material has low green strength for handling.

Roll Compaction of porous nickel sheet materials have been commonly used in the production of battery materials [21,22]. Nickel and other powders are rolled to a thickness ranging from 0.13 to 3.8 mm (0.005 - 0.150") and widths up to 1 meter (39.37") depending on the green strength and requirements of the application. Controlling the powder feed is critical to the process to obtain the best uniformity of the final product. Attempting to roll sheet with larger cross-sectional thickness can lead to delamination or low density center regions which cause poor mechanical properties. Thin cross sections or powders with low green strength limit the handling of the porous sheet prior to sintering. The rolled sheet can be directly fed into a sintering furnace to minimize handling problems in certain high volume applications. Roll compaction is used to produce an economical, uniform density material with good mechanical properties and tight dimensional tolerances (+/- 2% on thickness). Width and length tolerances are determined by secondary machining, cutting or shearing operations. Shapes or patterns can often be designed into the rolls or parts can be stamped from the finished porous sheet.

Other Forming Methods used to manufacture porous metal components include centrifugal slurry casting [23,24], blow molding [25], metal injection molding [25], extrusion [26], and gravity filling of shaped molds. Sheet materials can also be made using other processes such as a liquid laydown method which uses a powder and binder slurry [27]. Complicated shapes and lower density components are formed by using additives or pore formers such as water and/or thermoplastic binders that allow sufficient handling strength. Removal of the additives prior to sintering is normally accomplished in the preheat zone of the furnace or in a separate controlled bake out process. Metal spraying [28] can create a controlled porous structure with or without additives by spraying molten metal onto a base material to combine compaction and sintering into one process.

Sintering of porous metal is a critical balance between maximizing material properties and maximizing the open porosity and permeability. However, since permeability and material properties such as strength and ductility are generally inversely related, the desired balance of these characteristics normally occurs in a very small processing window [29,30]. Sintering requires the proper compromise of temperature, time at temperature and atmosphere to arrive at the desired porosity characteristics. Porous components which are not adequately sintered exhibit poor mechanical properties due to lower density and to insufficient interparticle neck growth. Porous components which are exposed to excessive sintering conditions will result in lower permeability and higher densities than desired. The preheat and cooling portions of the sintering cycle must also be closely controlled to achieve the proper metallurgical properties. Controlling the preheat conditions ensures adequate burn off of additives and lubricants as well as minimizing the distortion of the parts. The cooling conditions must be designed to provide maximum corrosion resistance and to avoid oxidation.

Sintering Temperature must be selected by considering the material, the powder shape and the powder particle size distribution. Sintering is normally accomplished at 70 - 90% of the material melting temperature. Finer powder particles require a lower sintering temperature since the surface energy driving force to initiate bond growth is much higher than for a coarser particle. Sintering at too high a temperature will also cause the formation of very large pores and non uniform porosity just prior to melting. Controlling the furnace temperature within +/- 1% of the optimum sintering temperature will achieve the best porosity uniformity and reproducible properties. Furnace design, furnace loading and furnace hot zone uniformity are critical to the production of porous metal components. Even slight lot to lot variations due to differences in the powder shape or the powder particle size distribution can often require adjustment of the sintering temperature to maintain the balance of properties and permeability.

Sintering Time must be monitored to allow for a minimum exposure time at the desired sintering temperature. Sintering for a least 30 - 60 minutes at the maximum sintering temperature is recommended for most materials for sufficient bond formation and growth. Inadequate sintering time can lead to large variations in part shrinkage and final density causing porosity and permeability variations. The sintering time at temperature must allow for the temperature of the furnace load to stabilize at the desired temperature especially when batch size and furnace recovery can widely vary. Furnace profiles and recovery rates for various load sizes for each furnace must be considered when determining appropriate sintering time. Shrinkage and density measurements can be used to control sintering time and temperature if the furnace atmosphere is consistent. Excessive sintering will unnecessarily reduce permeability due to pore size reduction and pore closure without significantly improving mechanical properties.

Sintering Atmosphere selection is critical for determining the metallurgical properties of the porous metal product. Since porous materials have much higher surface area than a similar size structural part, the atmosphere has more contact with surfaces throughout the part rather than just near the surface. Porous parts also contain relatively large amounts of trapped air in the pores which must be removed by purging or good atmosphere circulation in the furnace. Often, higher flow rates of an atmosphere or longer vacuum pump down times are required to displace the air prior to sintering. The sintering cycle can be subdivided into three main processes; preheating, sintering and cooling. Each process of the sintering cycle has unique atmosphere requirements which provides the optimum properties of the porous metal product just as with structural P/M components [31,32]. The preheating cycle must remove any lubricants or binders from the green compact and normally requires an oxidizing atmosphere. A separate furnace is often used to burn off these additives in order to avoid contamination of the sintering furnace. Preheating in the same furnace with a reducing atmosphere is often sufficient to remove low levels of additives since the open porous network allows more complete removal of the thermal decomposition products than with a structural part. Specifically, mechanical strength and corrosion resistance properties are highly dependent on the interaction with the sintering atmosphere. Porous materials are commonly sintered in reducing atmospheres such as nitrogen-hydrogen mixtures, 100% hydrogen and dissociated ammonia or in vacuum. Inert atmospheres such as dry argon can be used to sinter some of the specialty porous materials such as aluminum, refractory metals and precious metals. Reactive materials such as titanium and zirconium require good vacuum sintering with a high purity, inert backfill gas. Nitrogen containing atmospheres can have a nitriding effect on some materials such as porous stainless steels. Series 300 stainless steels can benefit from increased tensile strength with slightly lower ductility in a reactive nitrogen sintering atmosphere such as dissociated ammonia. However, reduced corrosion resistance may result unless the cooling rate is carefully controlled to minimize the formation of chromium nitrides [33]. A hydrogen atmosphere with a low dew point or vacuum sintering with a hydrogen backfill during cooling will produce the best combination corrosion resistance and mechanical properties for porous stainless steels. The cooling process cycle usually requires a reducing or oxygen free, inert gas atmosphere for best metallurgical properties. By preventing heavy oxidation or nitriding during cooling, a protective passive surface layer will form and good mechanical properties will result. Carbon containing atmospheres are not normally utilized in processing porous materials since higher carbon levels are usually detrimental to corrosion resistance.

Gravity Sintering refers to one of the simplest methods of sintering to improve the mechanical properties of a porous component. Diffusion or liquid phase bonds form between the particles when loose (noncompacted) powders are heated to a temperature near the solidus temperature [34]. Localized melting of the particle surfaces form necks between the powder particle contact surfaces and the amount of shrinkage during sintering controls the characteristics of the interconnected porosity. As an example, spherical porous bronze powders are poured and vibrated into a graphite or an oxidized stainless steel mold without compaction. The bronze or tin coated copper powder is then sintered at 800 - 1000 ^{O}C (1472 - 1832 ^{O}F) for 20 minutes in a reducing atmosphere to form a liquid phase between the particles [9]. Upon cooling, a strong metallurgical bond is formed at the contact points between the powder particles. Discs, cups, bushings or other simple shapes can be produced using this method. Typically, parts have a 1^{O} draft angle to facilitate part release from the mold and have dimensional tolerances of +/- 3%.

Secondary Operations are widely used to modify the part shape, the porosity and the surface characteristics of a porous part. Porous parts can often be formed to net shapes for use without secondary operations. However, the lower green strength and density of porous parts can limit the complexity of the green part and subsequent handling prior to sintering. The part shape complexity can be enhanced by sizing, machining and forming. Secondary sizing processes can improve the roundness, flatness and other dimensional tolerances which cannot be held during sintering. Porous P/M materials must not be over stressed during sizing since cracking or closure of the pores will occur. Sizing operations will increase the density of the part and reduce the surface porosity in the tool contact areas.

Secondary machining operations are used to produce features such as threads or tighter dimensional tolerances which cannot be readily controlled during compaction. Conventional machining of porous materials will close off the majority of the surface porosity due to metal smearing. Machining can be utilized to blind off the porosity and fluid flow in selected areas depending on the application. Controlled chemical etching of a machined surface can restore the surface porosity and still retain the tighter dimensional tolerances produced by machining. Care must be taken to avoid contamination of the porous material during machining or chemical reactivating. Machining methods without coolants and special cleaning processes are often used to remove the contamination after processing. Other machining methods such as electrical discharge machining (EDM) are also used to avoid closing off the surface porosity. However, removal of any machining fluids again requires special cleaning methods. Conventional machining, EDM and laser methods are used to cut porous parts from larger parts or sheets.

Forming of porous materials by cold working using dies or calendering rolls is used to change the part shape. Flat sheet can be formed into tubes and seam welded. Cold working during forming will increase the density, hardness and tensile strength of the porous material, with a corresponding decrease in ductility. Forming is also utilized to make special shapes and assemblies. Light sizing and swaging operations alter the surface layer to produce parts with tighter dimensional tolerances than as pressed components. The surface porosity is flattened during forming and the permeability and the surface pore size are decreased. However, porous P/M materials are difficult to straighten or flatten due to their elastic properties which result in significant 'spring back' behavior just prior to crack initiation.

Joining methods such as brazing, welding, gluing, sinterbonding and mechanical interlocking are used to create porous metal assemblies. The conditions for joining lower density materials to other porous materials or to solid materials are very different from joining solid materials. For example, brazing materials and processing conditions must be selected to avoid wicking of the braze material away from the joint area. Often a braze material is selected to form a higher melting point eutectic upon alloying with the porous base material in order to solidify the braze material in the joint area.

Welding of porous materials to other porous materials or to solid materials becomes much more complex than welding solid materials. The addition of filler metal, the reduction of weld heat input and the use of special welding gases are required to overcome welding problems associated with higher porosity and gases trapped in the pores. Good weld joint design will allow proper heat distribution to prevent leaks and large holes. Weld purge gases and material cleanliness are important to avoid contamination and to provide good corrosion resistance. Tungsten inert gas, electron beam and laser welding processes are used to obtain full penetration weld joints with relatively narrow heat affected zones. Post weld heat treatment processes such as annealing or stress relieving are recommended for good metallurgical properties.

Heat treatment or thermal cycles in reducing atmospheres can also be used for sinterbonding porous parts by processing at 10 - 65 ^{O}C (50 - 150 ^{O}F) below the sintering temperature in order to maintain the porosity and permeability. Sinterbonding is a thermal processing method used to form a metallurgical diffusion bond between two parts such as between a porous part and assembly hardware. The hardware is generally the same material as the porous component and allows the sinterbonded assembly to be more easily adapted to the application than if only a porous part was used. The diffusion bonds formed are significantly lower than welded or brazed joints since the sinterbonds are only formed at the local contact points. However, the sinterbonds are significantly stronger than just an interference fit alone and can ensure that the porous component will not be easily removed. Sinterbonding can be accomplished during a sintering cycle if proper allowances for shrinkage are considered. The sintered porous part must have adequate strength to allow for a press fit assembly without developing cracks. The press fit interference for parts less than 25.4 mm (1") OD is between 0.025 - 0.1 mm (0.001 - 0.004"). The hardware surface should have at least a 0.4 micrometer (16 microinch) surface finish so that the assembly interface does not have any gaps which may form openings larger than the pores in the porous metal component. The assemblies are normally checked for joint integrity after sinterbonding.

Thermal processing can also be utilized for removal of oxidation, burn off of certain contaminants introduced by secondary operations, and for passivation of the metal surfaces. Oxidation color from the heat affected zone of welds or from the heat of a cutting operation must often be removed by heat treatment in a reducing atmosphere for corrosion resistance or aesthetic reasons. Organic contaminates which are captured in the pores from prior processing steps or improper handling can be vaporized and removed from the pores by thermal processing. Heat treatment in a reducing atmosphere can also restore a uniform oxide layer upon cooling which forms a passive surface on the porous metal in order to increase corrosion resistance.

Porous sintered metals can be coated with a material such as silicone to alter the surface characteristics. Silicone treatment of the pores changes the hydrophilic nature of the surfaces to a hydrophobic surface which still maintains some permeability. Metal oxide coatings have been successfully formed on the porous surfaces to increase corrosion resistance or to decrease the pore size by applying a thin layer of submicron particles of a metal oxide such as silica, titanium dioxide or alumina [35,36]. These fine metal oxide particles can be bonded to a coarser porous metal substrate to produce a dual porosity structure with good permeability and excellent corrosion resistance.

Porous Material Characteristics

Design engineering information is readily available for many of the porous material characteristics such as density, pore size and distribution, bubble point, permeability and mechanical properties [8,10,17]. However, many of the unique characteristics of porous P/M materials such as elevated service temperature and corrosion resistance properties in specialized environments require additional design engineering considerations. The density, pore size, pore size distribution and permeability will determine the overall performance of a porous material in an application. The interrelationship of these four characteristics often allows the design engineer to specify only one or two of these factors. For example, testing has shown that the permeability of a porous part can be accurately predicted if the density and the initial powder particle characteristics are known for a particular processing method [37]. The initial powder particle size controls the pore size and distribution when sintered to a specified density. The permeability is related to the pore size and pore distribution. Other porous material characteristics can be estimated from wrought (or full density P/M) products since higher density products have more extensive test data available in the literature. Limited availability of design engineering data for porous materials often results in the need for actual testing in the intended application prior to use.

Material Density is an important characteristic for predicting mechanical properties and permeability. As the density decreases (and porosity increases), the mechanical properties are reduced and the permeability is increased. Porosity consists of interconnected channels and isolated pores. Isolated pores that are either closed or dead end channels do not contribute to the overall permeability and the percentage of isolated pores must be considered if density comparisons are used to specify a component. Nearly all of the porosity in a component with an overall density less than 75% of theoretical mean density (TMD) is interconnected to the surface pores and is usable for filtration and for fluid flow paths [38]. As the overall density increases from 75% to 92% of TMD, the percentage of isolated pores increases rapidly and the functional interconnected porosity is depleted. Density measurement methods for porous materials are described by International Organization for Standardization (ISO) Document 2738 [39] which uses the Archimedes principle. The porosity must be fully sealed prior to immersion in water using this method. Overall density can be estimated by weighing and volume calculation for simple part geometry. Density can also be measured by optical analysis of carefully prepared surfaces. The cutting, polishing and etching techniques during metallographic preparation must be monitored to avoid smearing or excessive removal of the surface porosity. Density uniformity throughout a porous product must be considered when measuring overall density since the forming process may introduce large variations. For example, a coaxial pressed cup could have a density variations of more than 5-10% when comparing the lower density side walls versus the higher density end cap.

Pore characteristics such as size, shape and distribution can be determined using many different measurement techniques. A comparison of the various pore characterization methods reveals that while the test method is usually consistent to show relative differences between various porous material grades, the test methods do not always agree. [40]. Since it is normally possible to correlate the various test methods, technical information regarding pore characteristics must be carefully compared to determine if the pore characteristics are equivalent.

One of the most common pore size characterization methods is a ‘bubble point’ test which measures the pressure required to release the first bubble from the surface of a porous material submerged in a liquid and pressurized from one side as shown in Figure 6. The liquid selected for this testing must have good wetting characteristics with relatively low viscosity and surface tension such as isopropanol. Several standard test methods such as ASTM E 128 [41] and ISO 4003 [42] have been developed to measure the pressure at which the first bubbles form and break away from one area. The maximum interconnected pore diameter can be estimated by using Poiseuille’s law for capillaries and an additional pore shape correction factor for noncylindrical pores;

$$d = 4\,K\,R\cos B/\,P$$

where d = pore diameter, K = shape correction factor, R = surface tension of the wetting liquid, B = contact angle of liquid and porous material, and P = pressure at first bubble point [43]. The shape correction factor, K , is largely dependent on the shape of the pores and the porous material. The shape correction factor can vary from about 0.2 for more spherical pores (e.g., bronze) to 0.4 for more irregular shaped pores (e.g., 316L SS). Therefore, the bubble point test is not a highly accurate measurement of pore size, but serves only as a reproducible, non-destructive test for ranking porous material grades by the largest pore size. The maximum pore size of the porous media calculated from the bubble point test is not a direct indication of filtration performance, but the results can be correlated to more complex filter retention testing. The filter industry often refers to the diameter of the largest pore determined by the bubble point method as a ‘micron rating’.

This terminology should not be confused with the diameter of a particle retained by a filter or the absolute filtration rating. The bubble point test is not a good indicator of the gas or liquid filtration rating since filtration is dependent on many other variables such as the uniformity and distribution of the pores, the media thickness, and the type of solids being filtered. The bubble point method is also an excellent integrity test of a material which has been subjected to secondary operations such as welding or forming in order to determine if any larger pores were created.

Mercury porosimetry and a mean flow pore size distribution measurement technique developed by Wenman and Miller use the Washburn Equation to calculate the pore diameter as the pressure is gradually increased [44,45]. Mercury porosimetry calculates the interconnected pore size and pore distribution of material by measuring the pressure required to force mercury into the pores and the volume of mercury in the pores. The other method determines the pore size distribution using a fluid which fully pre-wets the porous sample and then measures the pressure differential as the air flow is gradually increased. As the pressure increases, the fluid is forced from the larger pores first and the air flow permeability begins to increase until the sample is dried. A comparison of the wet and dry permeability curves allows the calculation of the pore size and distribution. ASTM F 316 [46] details the test method for determining the maximum pore size by bubble point testing and the pore size distribution by mean flow pore testing. The capillary action of the porosity is dependent on pore size and is an important property for applications which require fluid wicking and storage.

Permeability is a measure of the resistance to flow through a porous material and is one of the most important characteristics for design engineers specifying porous materials. The fluid flow through a porous material is normally expressed as a volumetric flow rate at a specified pressure differential for a given surface area (e.g., standard liters per minute per square centimeter at dP = 1000 kg/cm^2 of nitrogen). The nature of the fluid flow can be characterized as diffusional, laminar or turbulent depending on flow velocity. For very low flow rates, diffusional flow is the predominant mechanism and is not dependent on the fluid viscosity since the mean free path of the molecular collisions is larger than the pores. Laminar or viscous flow occurs at higher flow rates than diffusional flow but the flow rate must be below the ‘critical’ velocity. Turbulent flow occurs at higher flow rates above the critical velocity and at higher pressure differentials. Other types of flow mechanisms termed slip and inertial flow occur in the transition regions between diffusion, viscous and turbulent flow as shown in Figure 7 [47]. For example, inertial flow mechanisms must be considered to account for the energy losses and increased flow resistance of the gas at higher flow rates as it changes direction in the tortuous pore network flow path. For laminar viscous flow of non-compressible liquids, the volumetric flow rate, Q, can be predicted by Darcy’s Law:

$$Q = dP\ A\ C_V / t\ V$$

where dP is the differential pressure, A is the surface area, C_V is the coefficient of viscous permeability, t is the material thickness, and V is the dynamic viscosity of the fluid. In the case of compressible gases, Darcy’s law is modified to allow for the gas volume change with pressure as shown below;

$$Q = A\ C_V\ (P_1^2 - P_2^2) / 2\ P_2\ t\ V$$

where P_1 = the upstream pressure and P_2 = the downstream pressure [48]. For higher pressures and gas velocities, the flow rate through a porous material can be predicted by a modified version of Darcy’s law which includes correction factors for inertial and slip flow [48]. Although the permeability can often be accurately modeled, the complex gas flow physics of the porous structures limits the accuracy of the theoretical calculation of fluid flow, especially in the extreme low and high flow regions. As the specific gravity of a gas increases due to an increase in pressure or a decrease in temperature, the permeability decreases. As the viscosity of a gas increases due to an increase in pressure or temperature, the permeability also decreases. Pressure increases result in only a slight increase in the gas viscosity, but significantly increase the gas density. Temperature increases result in an increase in the gas viscosity and a reduction in the gas density. When comparing different porous materials, the accuracy of theoretical calculations is often reduced due to the interactions of these variables along with the various flow mechanisms operating in the micro-channels of the porous structure.

As shown above, the flow rate is also dependent on the surface area and the thickness of a porous structure. As surface area is increased, the differential pressure required to produce the same flow rate is decreased. Also, as the thickness of a material is decreased, the pressure differential is reduced to obtain the same flow rate. When comparing two porous materials, higher permeability indicates that a lower pressure differential was required to produce the same flow. Therefore, less surface area of a material with a higher permeability is required to produce the same fluid flow rate as a porous material with lower permeability. The economics become more favorable as the porous material surface area is reduced to meet the desired flow rate. The pressure differential and permeability are important design characteristics for determining overall flow rates for applications such as filter systems.

Permeability Testing is one of the best methods to specify the characteristics of a porous material. Compressible gas flow is dependent on many variables such as the specific gravity, viscosity, temperature and pressure conditions of the gas being measured. A typical gas permeability test schematic is shown in Figure 8. The flow path position of the volumetric flow measuring device is critical in order to avoid inaccurate measurements if an excessive back pressure or vacuum is created. Many references have investigated gas flow dynamics and have proposed models for predicting flow rates as conditions are varied [30,48,49,50]. The flow rate is measured by controlling the pressure differential and correcting the measured flow to standard temperature and pressure conditions using the ideal gas law to correct for gas volume changes. The atmospheric temperature and pressure must be measured in order to correct the measured gas flow rate back to standard temperature (21.1 ^{O}C, 70 ^{O}F or 294.1 ^{O}K) and pressure (29.92 inches of mercury or 760 mm Hg). Accurate flow rate comparisons can then be made between porous parts tested with non-standard conditions. A general formula which accounts for volume changes and corrects the measured gas flow rate back to standard conditions is given below:

$$Q_s = Q_m (P_m / P_s) (T_s / T_m)$$

where Q_s = the standard flow rate, Q_m = the measured flow rate, P_m = the measured pressure in mm of Hg, P_s = the standard pressure, T_m = the measured temperature, and T_s = the standard temperature. Corrections to standard conditions are significant since a small pressure change of 25.4 mm (1") of Hg or a small temperature change of 2 ^{O}C can result in about a 1% difference in the flow rate.

Additional correction factors can further improve the accuracy of permeability testing by accounting for changes in the gas viscosity and for the interactions of the gas with the pore structure as temperature and pressure are varied. As temperature increases, the gas viscosity increases and the gas density decreases which in turn increases the measured gas flow rate relative to standard conditions. Also, as the gas contracts to enter or expands to exit the pore structure, energy losses occur to reduce the flow [49]. When measuring the flow of one gas and calculating the flow rate equivalent of a different gas, the flow rate is adjusted for differences in gas viscosity or specific gravity. Gas flow conversions are important when testing of the actual gas is not practical due to safety or handling reasons. For example, the flow rate of nitrogen is often measured and used to estimate the actual flow rate of a toxic or corrosive gas at the same temperature and pressure conditions.

The volumetric flow rate can also be calculated by dividing the mass flow rate by the fluid density. The mass flow rate of gases can be measured with an accuracy of about +/- 2% by devices which correlate the gas flow rate to the cooling rate of the gas as it flows past a hot wire. These devices are based on calculating the gas flow rate by measuring the amount of energy required to keep the wire at a reference temperature and knowing the thermal conductivity of the gas. Mass flow rates do not need to be corrected back to standard conditions. Volumetric flow rates which are corrected back to standard conditions can achieve an accuracy of better than +/- 1% by collecting the fluid in a known volume as a function of time. Volumetric flow rate devices such as positive displacement piston meters are highly accurate primary standards. Mass flow rate devices are slightly less accurate and are secondary standard devices.

Liquid permeability is also sensitive to variations in temperature, pressure, viscosity and density. Noncompressible liquids flowing through porous materials are highly dependent on the viscosity and the ability of the fluid to wet the pore structure. Liquid flow rates are often difficult to reproduce if the fluid does not have consistent wetting properties. For example, isopropyl alcohol is preferred for liquid flow testing of porous metal materials whereas water does not wet well. Water can also have large differences in the mineral content depending on the source and these quality differences can make flow rate comparisons difficult, especially for tighter porous structures. The permeability of gases and liquids through a rigid porous material can be determined by specialized testing as described by ISO 4022 [51] and ASTM E 128 [41].

Mechanical Properties such as ductility, tensile strength, shear strength, collapse strength, burst strength, and fatigue life of porous materials are highly dependent on the porosity and the processing method [52,53]. Table 1 illustrates typical values for tensile strength, elongation and shear strength of 90% copper / 10% tin bronze discs and 316L stainless steel sheet as a function of density and filter grade as rated by the bubble point method [8,10,54]. Mechanical properties increase significantly as the pore size and the percentage of porosity decreases [54,55,56,57]. Alternatively, permeability decreases as the pore size and the percentage of porosity decreases. Therefore, an optimum balance of mechanical properties and permeability must be achieved to meet the application. Processing methods and materials can be normally selected to create a porous P/M material which will meet the minimum mechanical properties and provide the maximum permeability. In some more severe applications involving high pressure differentials, corrosive environments and/or high temperature service, mechanical properties are maximized at the expense of permeability in order to maximize service life. Enhanced mechanical properties will also extend the number of cleaning and reuse cycles in some applications.

Other material properties such as thermal conductivity, thermal expansion, fatigue, electrical conductivity and magnetic properties are also highly dependent on porosity and generally decrease as porosity increases [58,59]. For example, thermal expansion can be directly related to the porosity by the equation [58]:

$$C_t = C_o D_f^{1/3}$$

where C_t is the effective thermal expansion of the porous material, C_o is the bulk thermal expansion of the wrought material and D_f is the fractional density. Other theoretical relationships have been proposed to cover the mechanical properties over a broad range of porous materials and porosity levels, but actual testing is recommended to determine the properties since slight variations in porosity and processing methods can produce significant changes [60,61].

Elevated Temperature and Corrosion Properties are often important criteria for selection of porous P/M materials versus other porous materials such as plastics and papers. The maximum service temperatures for several P/M materials are listed in Table 2. The application environment is also critical to obtaining maximum service life since the atmosphere may be oxidizing, reducing, or inert in nature. Mechanical properties at an elevated temperature may be significantly reduced by accelerated corrosion reactions in atmospheres that contain ammonia, carbon, chlorine, fluorine, hydrogen, moisture, sulfur or other reactive materials. For example, catastrophic oxidation of 316L SS can occur at a lower temperature than expected due to the formation of low melting point eutectic such as vanadium pentaoxide if vanadium is used as a reaction catalyst. The presence of lead and molybdenum can also result in catastrophic oxidation [62]. The corrosion resistance of 316L SS is also reduced in ammonia service at 540 ^{O}C (1004 ^{O}F) due to the formation of a brittle nitride layer and in the presence of sulfur due the formation of iron and nickel sulfides. Temperature fluctuations and localized hot spots can cause accelerated oxidation due to spalling or cracking of the passive layer.

Corrosion resistance of porous P/M materials is a very complex subject due to the large number of variables which change the material behavior [63]. Material variables include composition, porosity characteristics (density, pore size, pore distribution, pore surface condition), and the effect of interstitial elements (carbon, nitrogen, oxygen). Processing variables include delube conditions, sintering conditions (time, temperature, atmosphere composition, dewpoint, and cooling rate) and secondary operations (cold work, machining, welding and heat treatment [64]. Environmental variables include fluid composition, velocity, aeration, temperature, process cycle and exposure conditions. Corrosion failure of porous materials is normally due to localized attack of the sinterbonds due to intergranular corrosion, crevice corrosion, stress corrosion cracking, and pitting mechanisms [65,66]. There is limited design engineering data which predicts the corrosion rates of porous materials in various environments. In general, porous materials have significantly higher corrosion rates due to their larger surface area than the comparable wrought material. In order to predict the service life of porous materials without actual testing, corrosion handbooks [67] for solid materials offer a reference point. As general rule, avoid selecting a porous material for an environment which does rate the corrosion resistance of the solid material as excellent. Even a very low corrosion rate for a solid material at the specified conditions can often still be too high for a porous material which obtains its mechanical properties from the very small bonds at the particle contact points. The corrosion resistance of a solid is often rated using a low fluid velocity in contact with the surface layer. Increased fluid velocity in the pore structure and aeration of the fluid may decrease the corrosion resistance of a porous material if the passive layer on each powder particle is disturbed. Also, pitting and crevice corrosion mechanisms can occur in porous materials which have dead end pore channels. Pitting corrosion can also occur if a corrosive liquid remains in the pores to create a localized concentration cell. Inadequate cleaning or prolonged storage without drying after removal from service can cause pitting failure.

There are many methods to enhance the corrosion resistance of porous materials. Proper alloy selection will result in the best protection against corrosion although the economic considerations of the more expensive alloys may be prohibitive. One advantage of the P/M process is that special alloys or custom blends can be made. For example, more nickel, chromium and manganese can be added to improve corrosion resistance of a 300 series stainless steel rather than being limited to standard alloys. Bronze filters can be plated with nickel or tin to improve corrosion resistance. While it is difficult to predict actual service life in a particular application, common corrosion tests can give some indication of corrosion reactions. Evaluating corrosion resistance using standard immersion (weight loss) testing and salt spray tests can often predict the behavior of porous materials [68]. One of the best indicators of corrosion resistance uses porous tensile bar samples suspended in the actual solution. While the fluid flow velocity effects are not considered in this test, mechanical testing and optical analysis can detect the effects of corrosion. Electrochemical testing can also be used to indicate the potential of a sample to exhibit passive behavior in a solution [65,68]. For stainless steels, indicator tests to determine the presence of unalloyed iron or carbide precipitation at grain boundaries will determine proper processing. Sensitization of 316L SS due to slow cooling in nitrogen containing atmospheres during sintering or carbide precipitation during welding can lead to intergranular corrosion [69]. Welding should be followed by an annealing or stress relieving heat treatment to increase corrosion resistance and mechanical properties. Proper handling to minimizing contamination and corrosion initiation sites (e.g., fingerprints, scratches, dents, foreign material) can also improve corrosion resistance.

Filtration Properties are dependent on the porous material characteristics, the surface area available for filtration and the process conditions of the application. Filtration and separation are intricate technologies which can be classified into six general areas; gas-solid, liquid-solid, gas-liquid, gas-gas, solid-solid, and liquid-liquid separation. Porous P/M parts are normally utilized for solid particles separation from a process stream, but have significantly different filtration properties in gas or liquid service [70]. The filter efficiency or filter rating in a gas stream will be higher than for liquids. There are additional gas-liquid separations possible with porous P/M parts such as bronze filters which separate water from air due to surface tension differences. Filters are specified and compared by their desired performance characteristics which include high permeability, low pressure drop, retention efficiency of specified particle sizes, particle loading capacity and resistance to blinding. The desire to have high permeability must be balanced with the minimum mechanical properties required for filtration. As the porosity is reduced, the density of a filter increases resulting in higher strength and lower permeability. Predicting filter performance in an application is difficult since there are many process variables such as the nature of the particles (size, shape, compressibility, composition), particle concentration, fluid flow rate, viscosity, vibration, service temperature and pressure.

Surface and depth type filter mechanisms perform the separation of solids from a process stream with porous P/M media. Surface filtration is characterized by the formation of a layer of particles (cake filtration) on the upstream surface of porous media due to sieving, direct interception and bridging of the particles. As the filter cake forms, the layer of particles begins to filter the process stream and the porous media acts more as a support. Wire mesh screens are examples of surface type filters which are generally used to retain coarser particles (> 140 micrometers). Finer filtration retention can be accomplished with screens, but the higher pressures required to drive the fluid often pushes the finer particles into the screen openings to cause blinding. Thin layers of fiber metal bonded to the surface of a screen can provide even finer levels of filtration with improved permeability [71]. Surface filters can be easily cleaned by reversing the flow direction if properly sized. Depth filtration is a more complex form of filtration than surface filtration since it is characterized by the retention of particles within the interconnected pore structure. Particles are retained by a variety of mechanisms including direct interception, inertial impaction, diffusion, adsorption, electrostatic attraction and gravitational settling [72]. In gas-solid separation, depth filtration depends primarily on capturing particles by interception, diffusion, electrostatic deposition and impaction mechanisms [73]. These mechanisms are less important in liquid-solid separation since the electrostatic repulsion and the hydrodynamic fluid flow forces allow certain particle sizes to navigate the pore channels and to not be captured. Hydrophobic and electrostatic adsorption can also be important in liquid filters depending on the nature of the electrical charge interactions of the filter media, the contaminants and the liquid. Sieving mechanisms also occur in depth filters depending on the size and distribution of the contaminants.

For filtration requirements less than 140 micrometers, porous P/M materials offer a combination of surface and depth filtration. Porous P/M materials are fabricated in relatively thin cross sections as low as 0.12 mm (0.005 in) for use as surface filters. Typically, thicker wall cross sections are fabricated to obtain a strong, rigid media which can withstand the higher operating pressures associated with depth type filters. The permeability decreases and the corresponding pressure drop increase across the filter as the thickness of the media is increased. Filtration ratings can be determined from standardized testing under tightly controlled conditions in order to compare various filter grades and materials. Standardized filter efficiency tests using monosized glass beads, test dusts or polydisperse salt particles are utilized to more accurately determine filter ratings [57,74,75,76]. Other common industrial tests such as the Beta Rating Test use a known contaminant in a multipass filter challenge method [77]. Filter challenge testing will eliminate some of the confusion when filters are described by 'absolute', 'nominal' or 'mean' filter ratings based on a correlation of the pore size determined by the bubble point test. These descriptions can only offer a reference point for the actual filter efficiency at a given particle size since a '10 micron' rated filter may retain any where from 50% to 99.9999999% of 10 micrometer particles depending on the application and test method. In addition, this filter rating does not indicate the filtration efficiency of the most penetrating particle [73]. Particles which are smaller or larger than 10 micrometer may be more difficult to retain depending on the test conditions and filter media. Testing the filter in the application is recommended to determine the actual performance and efficiency by measuring the downstream contaminants.

Cleaning and subsequent reuse of porous P/M materials is a major advantage over disposable media which generally have low strength, limited temperature capability and corrosion resistance and cannot be practically cleaned. The economic justification to utilize porous metals often depends on extending the service life with numerous cleaning cycles. Regeneration of porous metal media with blocked porosity can be accomplished with a variety of cleaning techniques and solutions depending on the nature of the foulant. Cleaning methods include thermal removal, ultrasonic immersion, reverse flow methods, high velocity water jets, and chemical processing with soaking and rinsing baths. Cleaning solutions can range from mild detergents to harsher caustic solutions or diluted acids depending on the type of blockage. The cleaning solution and technique must be selected to avoid damage or corrosion of the base metal. Combinations of methods and solutions can be selected for optimal cleaning. Some of the reverse flow, gas and liquid blowback methods can be performed in situ while other methods such as furnace cleaning, salt baths and ultrasonic baths require removal of the porous part. Cleaning service organizations determine the best method to clean the part without damage based on testing and experience. After cleaning the part, the cleaning solutions must be thoroughly flushed and dried. Visual inspection, bubble point testing and permeability testing are performed to determine the effectiveness of the cleaning method to return the porous part to the original manufacturers specifications. Measuring the weight before and after cleaning can also be used to evaluate cleaning performance as long as corrosion is not an issue. Gathering data on each serialized part prior to service will provide a baseline for measuring cleaning effectiveness. Mechanical cleaning methods such as wire brushing, scraping, sand blasting or glass bead blasting must be avoided to prevent pore smearing and further entrapment of the contaminants. The porous part cannot always be fully cleaned without damaging the base material, but the part can be sufficiently cleaned to be returned to service.

Applications

A summary of the major applications of porous P/M materials are listed below. Filtration, flow control, battery electrodes and self lubricating bearings are the largest commercial applications. Many specialized applications have been developed to take advantage of the unique characteristics of porous materials as shown in Table 3.

Filtration and separation technology applications [2,8,76,78,79] are the largest market for porous P/M materials. Many industrial applications require the fine filtration capability, superior mechanical properties and corrosion resistance of porous metals, especially at higher temperature and pressures. Particle retention, media uniformity, absence of particle shedding and cleanability are critical to the filter system operation. Porous metals can also be used to support finer filter membranes or used as filter septum that are coated with ion exchange resins.

Laminar flow control devices utilizing porous P/M flow restrictors [2,8,79,80,81] are more accurate and reliable than other volumetric flow limiting products such as orifices and micrometering valves that operate at higher fluid velocities. Orifice technology normally relies on controlling gas flow in the turbulent flow regime by requiring that the inlet pressure is at least double the outlet pressure. Porous P/M materials are more resistant to contamination and plugging since there are hundreds of small flow paths available instead of a single orifice. Flow restrictors are used to provide a constant flow for a given set of conditions (pressure, temperature and fluid) and are mechanically strong devices that do not have mechanical or electrical components that can wear or require calibration.

A few applications of porous P/M materials rely on the extremely high internal surface area and porosity available[2,22,82]. For example, the conductivity of the electrodes for alkaline batteries and for fuel cells can be significantly increased by large contact area with the reaction fluid. Biomedical implants use the large surface area to allow tissue growth into the porous structure to allow good joint attachment.

Reservoirs and capillary attraction devices are other major application areas [2,8,80,82]. Self lubricating bearings that store lubricants in the pores and protect the surface from wear are one of the oldest commercial applications of porous P/M materials. Heat removal devices for microelectronics packaging and for cooling devices used in satellites are some of the newest application areas.

Sound, pressure and vibration dampening components are also common industrial applications [2,79,80,81]. Porosity acts as an acoustical impedance and will dampen certain sound frequencies while others pass through. A pressure surge in a fluid delivery line will also be dampened by reducing the fluid velocity as it passes through the small interconnected channels. Many pressure gages have porous metal pressure snubbers to dampen the vibration or pressure change rate and to provide smoother operation of the indicating needle.

Boundary layer control devices such as air floatation bars and vacuum hold down plates are highly specialized applications [2,8,80,81,83]. A boundary layer of air for non contact turning of thin films, tapes or webs can be formed on the outside diameter of a fine porosity tube when the inside cavity is pressurized.

Gas-liquid contacting applications [83,84]. Flowing gas through a fine grade, porous P/M material with high surface area produces small bubbles which result in high efficiency transfer contact of the gas to the liquid. Finer pore size materials are used to prevent the liquid from penetrating back into the pores at lower internal pressures. Conventional drilled pipe spargers produce larger bubbles that do not dissolve and react as well as the finer bubbles generated by porous metals.

Overall, the application of porous P/M technology is rapidly emerging as cost effective, renewable, industrial resource that offers diverse solutions to engineering challenges.

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Table 1: Typical Mechanical Properties of Bronze and 316L Stainless Steel Filters

Material	**Filter Grade[1] Micrometers**	**Density Percent**	**Min. UTS MPa (ksi) [2]**	**Elong.[3] Percent**	**Shear Strength MPa (ksi)**
Bronze	---	100 [4]	xxx	xxx	xxx
Bronze	10	75	48 (7)	8	150 (21.8)
Bronze	20	68	41 (6)	6	120 (17.4)
Bronze	40	62	35 (5)	4	100 (14.5)
Bronze	90	57	28 (4)	3	75 (10.9)
Bronze	150	54	21 (3)	2	40 (5.8)
Bronze	250	52	14 (2)	2	30 (4.3)
316L SS [5]	---	100 [3]	482 (70)	30	xxx
316L SS	0.2	80	180 (26)	6	350 (50.7)
316L SS	0.5	75	159 (23)	6	330 (47.8)
316L SS	2	65	117 (17)	5	290 (42.0)
316L SS	5	62	90 (13)	5	250 (36.2)
316L SS	10	60	69 (10)	4	150 (21.7)
316L SS	20	55	48 (7)	3	100 (14.5)
316L SS	40	50	31 (4.5)	2	80 (11.6)
316L SS	100	40	27 (3.9)	2	70 (10.1)

Note 1: Filter grades in micrometers as estimated by bubble point test method.

Note 2: UTS = Minimum values for Ultimate Tensile Strength are shown

Note 3: Minimum Elongation Percentage

Note 4: The theoretical mean density for wrought bronze is 8.8 g/cm^3 and for 316L SS is 8.0 g/cm^3.

Note 5: Cold finished and annealed bar stock per ASTM A276

Table 2: Elevated Temperature Service for Selected Porous Filter Materials.

	Maximum Temperature	Maximum Temperature
Material	Oxidizing Atmosphere	Reducing Atmosphere
Bronze	150 ^{O}C (304 ^{O}F)	400 ^{O}C (750 ^{O}F)
316L SS	400 ^{O}C (750 ^{O}F)	538 ^{O}C (1000 ^{O}F)
Inconel ® 600	593 ^{O}C (1100 ^{O}F)	815 ^{O}C (1500 ^{O}F)
Hastelloy ® X	788 ^{O}C (1450 ^{O}F)	927 ^{O}C (1700 ^{O}F)

Table 3: Major Application Areas of Porous P/M Materials

Filtration / Separation Technology

Polymer Processing	Chemical Processing	Petrochemical
Caustic / Sizing Recovery	Catalyst Recovery	FCC catalysts
Nylon & Polyester Fibers	Process Gases and Liquids	Slurry Oils
Gel Shearing	Fluid Bed Reactor Products	Flue Gases

Power Generation	Mineral Processing	Pharmaceutical
Condensate Water Polishing	Coal, Silica, Metal Oxides	Process Steam
Fossil Fuel Waste Streams	Calciner & Incinerator Off Gas	Oxygen Filters
Radioactive Material Refining	Catalyst Manufacturing	Autoclave Vent Filters

Semiconductor	Fluid Power	Chemicals
Particle Removal Process Gas	Protect Hydraulic Valves	Acids, Solvents & Inks
Bulk Gas Delivery Systems	Pneumatic Equipment	Adhesives and Greases
Purifier Media Retainers	Water Removal in Air Lines	Precipitates, Salts & Carbon

Analysis Instruments	Food and Beverage	Other Filter Areas
Gas / Liquid Chromatography	Removal of Yeast from Beer	Oil Burners
Gas Sampling	Juice/ Sugar Clarification	Aircraft and Marine Fuel
Sensor Protection	Cooking Oil, Corn Syrup	Paper and Pulp

Flow Control Devices and Flow Restrictors

Flow Restrictors	Calibrated leaks	Flow Rate Timing devices
Vents and Breathers	Gas and liquid metering	Fuses, Vacuum Delay Valves

Surface Area Devices

Batteries	Fuel cells	Ionizers
Electrodes	Biomedical implant/prostheses	Cathode dispensers

Reservoirs and Capillary Attraction

Self lubricating bearings	Die wall lubrication	Heat sinks
Heat exchangers	Liquid wicks- evaporation	Applicators
Transpiration Cooling	Printer ink reservoirs	Atomizers

Dampening

Sound Attenuation	Telephone Transmitters	Pressure Snubbers
Exhaust Silencers / Mufflers	Flame Arrestors / Quenching	Vibration Reduction
Hearing Aids	Pressure Equalization	Microphone Frequency

Boundary Layer Control

Air Bearings	Turning Bars for Film/Webs	Polymer Fiber Cooling
Floatation Devices	Fluidizer Plates for fluid beds	Friction Reduction
Material Handling / Transport	Vacuum Plates	Mold Release

Gas - Liquid Contacting

Aerators	Spargers	Bubblers
Agitation of Liquids	Chlorine & Oxygen Bleaching	Enhances Chemical Reactions
Oxygenation for Fish Farming	Oxygen & Volatile Stripping	Hydrogenation
Bioremediation	Water / Oil Separation	Fermentation
Steam Injectors/Heat Transfer	pH Control	Carbonators

Figure 1: Gas atomized, prealloyed bronze powder particles with a size range of 63 to 100 micrometers that are gravity sintered to **xx**% dense in order to yield a 40 micrometer filter grade (200X magnification)

Figure 2: Tin coated, rounded, cut copper wire particles with a size range of 250 to 425 micrometers that are gravity sintered to **xx55**% dense in order to yield a **xx** micrometer filter grade (100X magnification)

Figure 3: Water atomized, 316L stainless steel powder particles with a size range of 300 to 600 micrometers that are compacted and sintered to 45 % dense in order to yield a 40 micrometer filter grade (200X magnification)

Figure 4: Water atomized, 316L stainless steel powder particles with a size range of 45 micrometers and less that are compacted and sintered to 75% dense in order to yield a 0.5 micrometer filter grade (750X magnification)

Figure 5: Carbonyl nickel powder particles with a size range of 2 to 4 micrometers that are compacted and sintered to 35 % dense in order to yield a 0.1 micrometer filter grade (2000X magnification)

Figure 6: Schematic layout of bubble point testing apparatus

Figure 7: Flow mechanisms

Figure 8: Schematic layout of gas permeability testing apparatus