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Chapter 7
Production Techniques of Metallic Foams in Lightweight Materials

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ABSTRACT

Lightweight materials were needed in many different areas, especially in order to reduce the required energy in areas such as automotive and aerospace industries. Metallic foams attract attention in light-weight material applications due to their unique properties. The pores in its structure provide advantages in many applications, both structural and functional by promising both ultra-lightweight construction, energy absorption, and damping insulation. Production techniques of metallic foams can generally be classified as liquid, solid, gas, and ionic state production according to the physical state of the metal at the beginning of the process. The production technique should be chosen according to the usage area and desired properties of the metallic foam and the suitability in terms of cost and sustainability of production. For this reason, the details of the production techniques should be known and the products that can be obtained and their properties should be understood. In this respect, this chapter emphasizes the production methods from past to present.

INTRODUCTION

Metal foams are a class of engineering materials developed for light-weight material applications (Dukhan, 2013). Metallic foam consists of a rigid frame and air-containing internal and external pores, which gives the material different characteristics. Due to the porous structure, metallic foams provide significant

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advantages in terms of vibration resistance, energy, and thermal absorption as well as lightness. Metal foam structures have attracted attention due to their high stiffness-to-weight and strength-to-weight ratios. Metallic foams are becoming an interesting and important field of research in recent times. It can be used in many structural and functional applications in many fields such as aviation, railway, building, and biomedical industries and especially in the automotive industry (Yilong et al., 2016; Claar et al., 2000; Andure et al., 2012; Qin et al., 2016; Bisht et al., 2019). People encounter porous structures in many places in nature (wood, bone, corals, pumice, lava, etc.). The porous form observed in the structure of lightweight but strength materials in nature has attracted the attention of scientists and they have studied material production in these forms (Banhart, 2001; Bauer et al., 2013; Liu and Chen, 2014). Manmade porous materials that people encounter at many points in daily life can basically be polymeric, ceramic, and metallic. Porous plastics are found in many different applications such as foam cups, food packaging, and airbags. Polymer foams can't show rigidity under loading and are not resistant to high temperatures. Ceramic foam structures are often preferred in filtering applications. This material is limited in use because it is brittle under suddenly loading and is difficult to machining (Qin et al., 2016; Sivertsen, 2007; Yilong et al., 2016). For these reasons and owing to the unique characteristics of metallic ones have the potential for many applications. Since the pore structure can be controlled, the usage areas of metallic foams are varied (Garcia-Moreno, 2016). Basically, the pore structure of metallic foams is divided into two categories and usage areas are accordingly diversified. Pores are named according to whether they are connected or not: open (through) or closed (Qin et al., 2016). Foams with open porous structures are used in heat exchangers and absorbers, especially implants and filters, due to their thermal and permeability properties (Gülsoy and German, 2008). Closed porous metallic foams are preferred in structural applications due to their specific mechanical properties (Vendra et al., 2011). It is used in applications such as crash absorbers in vehicles and sound absorbers in machines with the increase in the thickness of the pore walls and the development of energy absorption properties compared to open pores structures (Vendra et al., 2011; Andure et al., 2012; Bauer et al., 2013; Yilong et al., 2016).

Metallic foam production technique should be selected by considering factors such as usage area, desired properties, cost and continuity. Therefore, all production techniques should be known in detail and the relationship between product-feature-structure should be understood. Studies on the production of metallic foams were first made by Sosnick in 1943. Benjamin Sosnick melted the mixture of aluminium and mercury in a high-pressure vessel. Then, due to the melting temperature of aluminium with the releasing of the pressure, mercury was evaporated and formed a foamy structure (Banhart and Weaire, 2002). Since then, many new methods have been discovered in metallic foam production. New techniques are explored for reasons such as cost of production, commercialization, being able to apply to different metals, and better quality of products. This chapter of the book, it is aimed to create an up-to-date source by dealing with production methods from past to present and focusing on developments.

Production Techniques

As a new type of material, metallic foams have attracted the attention of scientists. "Foam" is defined in the literature as the structures obtained by the distribution of the gas phase in a liquid or solid phase (Banhart, 2001). Metallic foam means in the solid phase, liquid metallic foam can only be during the production stage. In the literature, porous structures have been given different names according to different pore morphologies such as cellular, porous, sponge and foam (Banhart, 2016). In this chapter,

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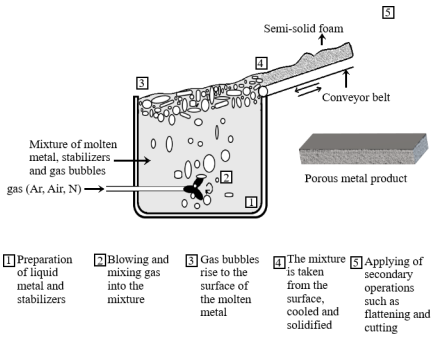
porous structure production techniques of metals are generally mentioned in order to provide a broad perspective and a detailed resource.

Direct Foaming of Metals

These methods are based on the foaming of liquid metal. Foam structure can be obtained in two different ways: by direct gas blowing and by using a foaming agent. The production method of metallic foam by gas injection is based on the foaming with gas bubbles injection from an external source into the molten metal. However, gas bubbles tend to rise to the surface due to the high buoyancy of the liquid metal (Banhart, 2001). In order for the gas bubbles to dissipate and remain in the liquid metal, they must be stabilized by increasing viscosity. This can be achieved by adding alloying elements or fine ceramic particles (Rajak and Gupta, 2020). For this purpose, powders such as aluminium oxide, silicon carbide or magnesium oxide are added to the molten metal (Banhart, 2001; Banhart, 2004; Bhatt et al., 2015). Schematic representation and steps of the process are shown in Figure 1. The first step of the process is to prepare the molten metal and the stabilizers. It is important that stabilizers are wetted by the molten metal and distributed evenly in it. Then, the melt is foamed by blowing air, argon or nitrogen gas into the melt from an external source using a rotating impeller or vibrating nozzles (Banhart, 2000). Thanks to the use of this impeller or nozzle, fine gas bubbles distributed uniformly in the melt are obtained (Degischer et al., 2002). This is important for the mechanical properties of the product. A mixture of gas bubbles and molten metal is obtained. The resulting mixture is taken from the upper surface of the liquid with the help of a conveyor belt, and then it is cooled and solidified so that a porous structure is obtained (Benouali et al., 2002; Bhatt et al., 2015). Then, the desired product is obtained by applying secondary processes such as flattening and cutting to the semi-solid foam (Banhart, 2001).

Figure 1. Porous metallic part production with gas injection technique (Kranzlin and Niederberger, 2015)



Production of aluminium foams by gas injection method is licensed by CYMAT Aluminium Corporation. Aluminium is melted with stabilizer additives such as SiC, aluminium oxide, titanium diboride, zirconium oxide, magnesium oxide and other production steps are applied (Wang et al., 2007; Kulshreshtha and Dhakad, 2020). A Closed foam structure is obtained and an open pore structure may occur on the surface due to the cutting process (Rajak and Gupta, 2020; Banhart, 2001). Zinc foam and other metals with low melting temperatures can be produced by this method (Banhart, 2001). The method is cost-effective compared to other metallic foam production methods, easy to apply, and suitable for continu-

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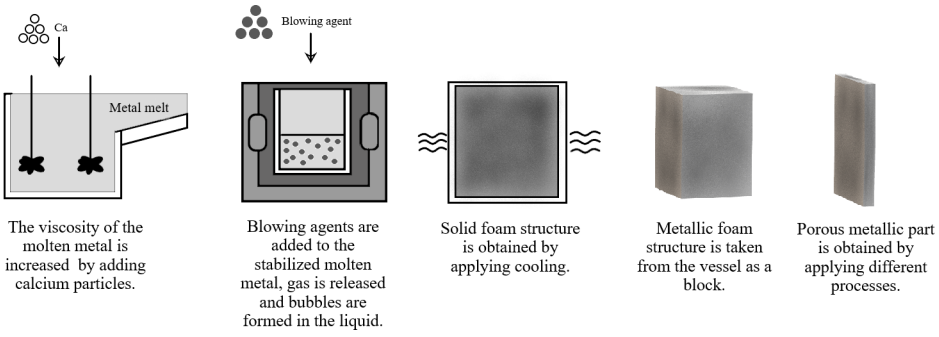
ous production. However, the size and distribution of the created gas bubbles cannot be controlled and thus the mechanical properties of the products are not superior since gas bubbles are not distributed uniformly. It can only be produced in slab form and is suitable for the production of low-density metals.

A new technique has been developed by ALUINVENT to improve the distribution of pores and to reduce the pore size of metallic foams produced by the gas injection method. In the technique, while gas bubbles are given into the liquid metal, gas bubbles are separated with the help of ultrasonic sound waves (Garcia-Moreno, 2016).

In the other method, the liquid metal is directly foamed by adding blowing agents to the molten metal. Metal hydrides (TiH2, CaH2, ZrH2, etc.) are generally preferred as blowing agents (Matijasevic-Lux, 2006). As a result of the using of hydride blowing agents, hydrogen gas is released from these particles and bubbles are formed in the molten metal (Banhart, 2001; Kulshreshtha and Dhakad; 2020). Metal oxide or metal carbonate compounds can also be used as blowing agents (Patel et al., 2018). Figure 2 shows schematically the foaming of aluminium with this method patented by ALPORAS. In the process, calcium is added and mixed to the molten aluminium metal in order to increase its viscosity, and the molten metal becomes stabilized due to the formation of some oxide compounds (CaO, CaAl2O4) or intermetallics (Banhart, 2003; Degischer et al., 2002). The hydride blowing agent is then added, and with the release of gas, the melt expands slowly. Foaming occurs at constant pressure and the vessel is filled with a liquid foam structure. Then, while the vessel is cooled, the structure is solidified. The foam removed from the vessel in block form then can be given into the desired shape with other processes (Srivastava and Sahoo, 2007; García-Moreno, 2016; Gábora and Mankovits, 2019). Zinc, magnesium, copper alloys, and steel foams are manufactured in a similar way to aluminium foam production with this method (Banhart, 2001; Srivastava and Sahoo, 2007; Banhart, 2013).

Figure 2. Schematic depiction of the method using blowing agents for aluminium foam production (Banhart, 2000)



It is an easily applicable method for aluminium foam production. A relatively uniform structure can be obtained and the process can be controlled. However, it is a high-cost method due to the use of metal hydrides. Complex metal foam forms cannot be produced. It is difficult to control porosity and pore sizes, cracks may occur in the pore walls due to the rapid cooling process and the presence of hydrogen.

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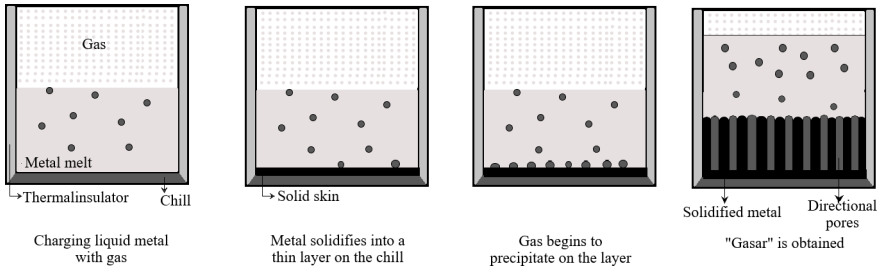
Solid-Gas Eutectic Solidification

This method is mainly based on the difference in gas solubility of metals of the liquid and solid phase. Firstly, the molten metal is charged with gas (Banhart, 2001). This is achieved by melting the metal under high pressure in a gas atmosphere. Then the temperature is lowered below the eutectic transition temperature. Thus, the charged gas precipitates (Babscan et al., 2003). When suitable conditions are provided, gas bubbles become trapped in the molten metal. Later, with the solidification of the structure, long pores are formed depending on the solidification direction (Banhart, 2003; Babscan and Banhart, 2006). This technique is also known as "Gasar Process" and a regularly oriented (lotus-type) porous structure can be obtained (Zhang et al., 2013a; Zhang et al., 2013b). Schematic representation of lotus-type porous structure production is given in Figure 3.

Figure 3. Regularly oriented porous structure production using solid-gas eutectic solidification technique (Shapovalov and Boyko, 2004)



The method is cost-effective as no blowing agent is used, but the required equipment is complex and can be costly. It is advantageous in that many metals can be produced and porosity can be controlled. Single-type metallic foam production is possible and relatively slow. It is not a suitable method for high production capacities. Base metals and alloys such as aluminium, copper, magnesium, nickel, chromium, and iron are produced by this method (Kulshreshtha and Dhakad, 2020).

Foaming Powder Compacts

One of the starting materials is metal powders; it can be in the form of elemental metal powders, mixtures of different metal powders or alloy powders (Babcsán et al., 2003). Then metal powders mixed with the appropriate blowing agent. After that, the mixture is compressed to make a precursor material for the foaming process using a compression method suitably selected according to the starting materials (Banhart, 2001; García-Moreno, 2016). Any residual porosity is not desired in the structure after compression as it will cause defects in the foam structure (Babcsán et al., 2003). The precursor material is expanded by applying heat treatment and finally the foam structure is obtained. It is raised to a temperature near the melting point of the metal in order to decompose the blowing agent in the semi-solid precursor material (Banhart, 2003). As the metal begins to melt, the metal expands with the gas released from the blowing agent. After the foam formation is completed, the final product is obtained with cooling (Ashby et al., 2000; Benouali et al., 2002; Claar et al., 2018; Rajak and Gupta, 2020). Since the expansion in the

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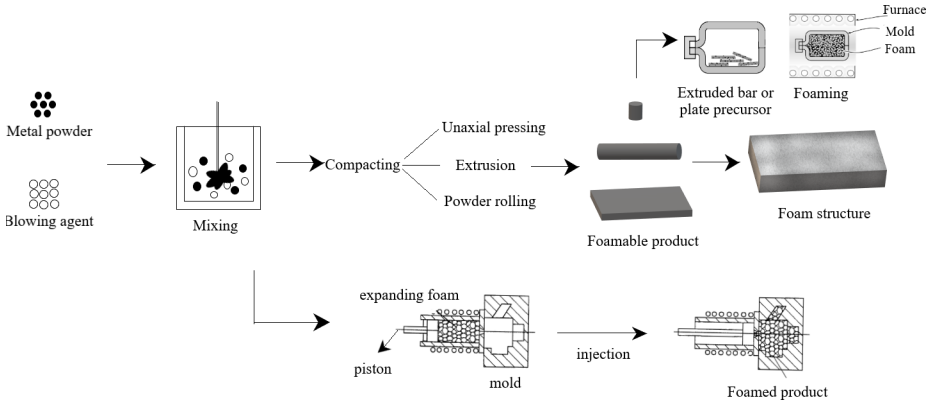
product obtained by this method cannot be controlled exactly, it is ensured that the foaming process is carried out in a mold to obtain the desired shape of foam product. The foam structure is either injected into the mold, or the parts coming from the extrusion are foamed in the mold (Banhart, 2001). Schematic representation of the foaming powder compacts technique is given in Figure 4.

Figure 4. Diagram of powder compact melting technique for producing metal foam (Banhart, 2001; Ashby et al., 2000)



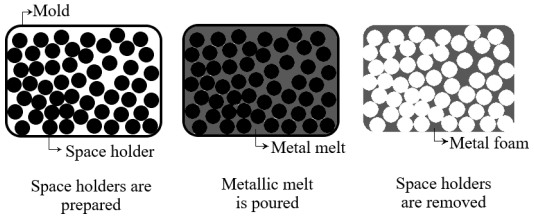
Many metals such as aluminium, tin, brass, zinc, lead, gold, bronze, and steel can be produced in foam form by this method. However, it is necessary to choose the appropriate blowing agent. Metal foams which are produced with this method have closed porous structure. Even complex shapes can be produced in high quality and in many metal foam forms with this method. However, it is high-cost manufacturing (Banhart, 2001; Srivastava and Sahoo, 2007; Claar et al., 2018; Kulshreshtha and Dhakad, 2020).

Casting Techniques

Metallic foam production with casting methods is based on the same point among themselves. A volatile material, which is the negative image of the porous structure to be produced with liquid metal, is the common point of the methods. The methods differ from each other in terms of the temporary material used. This material can be wax slurry or a space holder.

In the production of porous materials by casting using space holders, space holding fillers are placed in a mold and then molten metal is poured. Then, the porous structure is obtained by removing the space

Figure 5. Production steps of casting around space holder technique (Banhart, 1999)



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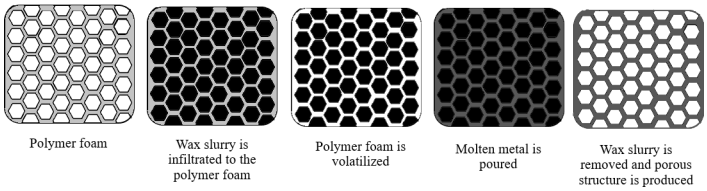
holder. Organic or inorganic granules can be used as space-holding filler. Leaching or heat treatment is required to remove them. Aluminium, magnesium, tin, zinc and lead metal foams are produced by this technique (Banhart, 1999; Banhart, 2001; Garcia- Moreno, 2016; Degischer et al., 2002; Ashby et al., 2000; Srivastava and Sahoo, 2007; Patel et al., 2018; Sutygina et al., 2020; Rajak and Gupta, 2020). A schematic description of the casting around the space holder method is given in Figure 5.

This method is cost-effective compared to other methods. It is an environmentally friendly method. It provides easy control for pore size and geometry, and thus net-shape and near-net-shape production is possible. Thus, it may not require a secondary production process. But metals with high surface tension are difficult to wet the particles, thus making it difficult to fill the mold uniformly.

When using the polymer foam method, a wax slurry made of heat-resistant materials is infiltrated and dried. Then, the polymer foam is volatilized by applying heat. Thus, liquid metal is poured into the remaining space. Metallic foam is obtained by removing the mold (Dukhan, 2013). The method is known as foam replication or investment casting. According to the shape and properties of the polymer foam, the properties of the metallic foam can be changed. Porous structure up to 97% porosity can be produced. Metallic foams are open-porous structures. Magnesium, copper, stainless steel and aluminium and alloys foams are produced by this method (Bauer et al., 2013; Salvo et al., 2014; Garcia-Moreno, 2016; Patel et al., 2018; Duan et al., 2019; Kulsheshtha and Dhakad, 2020). In Figure 6, a schematic representation of the method is given. High porosity can be achieved and the pore quality is superior with this method. It is an easy-to-apply method. However, filling the mold homogeneously can be difficult and the fine pore walls can be damaged during the removal of the wax slurry.

Figure 6. Investment casting technique for porous structure production (Atwater et al., 2018)



Deposition Techniques

Metal foams can be produced by different deposition methods. This can be spray deposition, electro-deposition or chemical vapor deposition. Schematic presentations of these techniques are given in Figure 7.

In the spray deposition technique, the metal is in liquid form as the starting material. Firstly, the molten metal is continuously atomized. The metal droplets are micron in size (Srivastava and Sahoo, 2007). Then, the blowing agent is added to this atomized metal spray. These droplets are deposited on a substrate material formed in the desired shape of the foam structure. During the deposition of the droplets, pores are formed in the deposited part due to the gas release of the blowing agent. Metals and alloys or metal matrix composites can be produced by this method (Banhart, 2001; Banhart, 2016). It is important to choose the appropriate production parameters and blowing agent for each metal. Metal foams produced by this method have fine equiaxed grain and low oxide content however pores are not distributed homogeneously. Less porosity is obtained compared to other methods (~%60). Steel and

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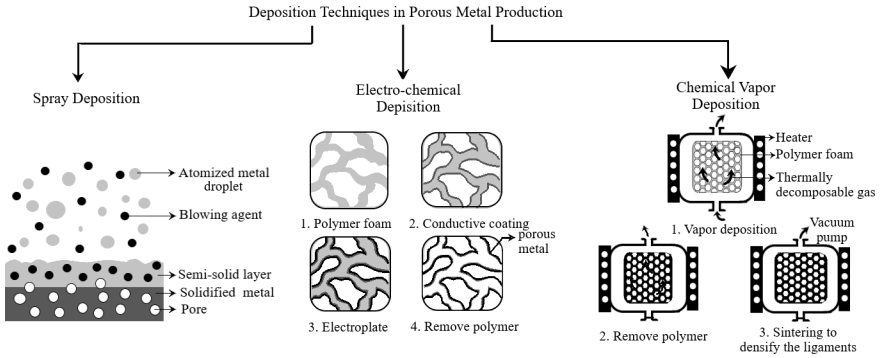
Figure 7. Deposition methods in production of porous metal (Banhart, 2001; Ashby et al., 2000; Rajak and Gupta, 2020)



copper alloy foams can be produced with this technique (Banhart, 2001; Srivastava and Sahoo, 2007; Patel et al., 2018).

In the electro-deposition method, the starting materials are metal in an ionic state and polymer substrate. The used polymer foam must have electrical conductivity. If the foam is a nonconductor, directly electrodeposition cannot be applied. It is one of the most important steps of the method. The polymer substrate is made electrically conductive by various methods such as vacuum evaporation, cathode sputtering, arc ion plating, electroless plating, and electrically conductive slurry coating (Banhart, 2001). The slurry coating method can be preferred because it is simple, cheap and applicable. However, it is difficult to obtain a batch coating with this method. In this respect, electroless plating may come to the fore (Tian and Guo, 2010). The ionic solution can be electrically conductive based on carbon black or graphite. After the electrically conductive coating is made, the metal ions are deposited with the electrodeposition technique. Later, the polymer foam is removed by thermal treatment, so that a porous structure is obtained. Copper, nickel, zinc, gold, titanium, and nickel-chromium foams can be produced with this technique (Banhart, 2001; Patel et al., 2018; Salvo et al., 2014). The foams are open-porous structures. The high cost of the process is its disadvantage. However, it is a method used in certain industries such as the production of porous electrodes (Ashby et al., 2000; Atwater et al., 2018; Duan et al., 2019; Kulshreshtha and Dhakad, 2020).

In the chemical vapor deposition method, the starting materials are metal or metallic compounds in the gaseous phase and a porous substrate material with the pore properties of the porous metal to be produced. The material used as substrate material can also be polymer foam or lattice block materials (Banhart, 2001; Patel et al., 2018). In this method developed by INCO, the metal vapor is created in a vacuum chamber. It is then allowed to deposit on the cold substrate. After the deposition process is completed, cooling carried out. Then the polymer substrate is removed and open-porous metal foam is obtained. After removing the polymer, sintering is applied to densify the ligament (Ashby et al., 2000; Salvo et al., 2014; Kranzlin and Niederberger, 2014). The metal can be chosen for this method is limited as it must be obtained in the vapor phase. Nickel, copper, iron, titanium, and tantalum metals can be produced as metal foams with this technique (Degischer et al., 2002; Garcia- Moreno, 2016; Atwater et al., 2018; Ryan et al., 2006; Rajak and Gupta, 2020). This technique is not economical. However, this method industrially preferred due to obtaining a porous product with high chemical purity and smooth pore structure (Kulshreshtha and Dhakad, 2020; Pasarin et al., 2003).

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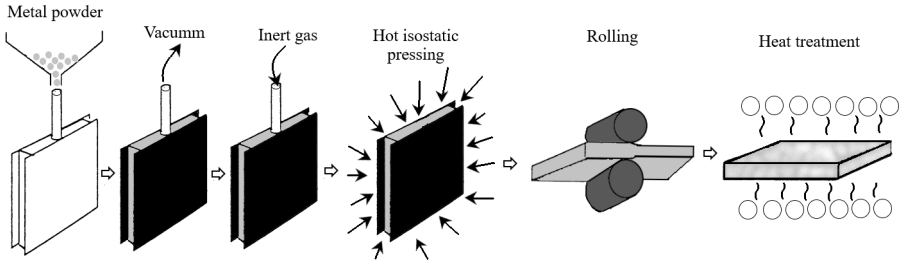
Figure 8. Gas entrapment process for porous metal production (Kennedy, 2016; Banhart, 2001)



Sintering Metal Powders and Fibers

In this method, which is frequently used in industry for the production of porous metallic materials, metallic powders or fibers are partially sintered at different temperatures and porosity can be obtained at varying rates. The amount and shape of pores vary according to the morphology and amount of the particle used (Banhart, 2001). The method has attracted attention by the industry due to its various advantages such as its simplicity, that it does not require additional processes and materials, and that it can be applied to all metals that can be obtained in powder form or as a fiber (Rechtin et al., 2018). In addition, it is one of the advantages of the method to work at lower temperatures, since the metal will not reach the molten state. The interconnectivity of the metal powders depends on the sintering success and size of the particles (Ryan et al., 2006; Kranzlin and Niederberger, 2014). Optimization of the sintering temperature is important. Interconnecting is less at low temperatures and the mechanical properties of the product may not reach the desired values. Porosity gradually decreases at high temperatures. The porosity amount obtained by the method is around 20-50% (Srivastava and Sahoo, 2007; Kennedy, 2016; Patel et al., 2018). Nickel and alloys, bronze, steel, titanium, and alloys can be manufactured in this technique (Banhart, 2001; Degischer et al., 2002; Oppenheimer et al., 2004).

Gas Entrapment Technique

It is one of the methods based on powder metallurgy for porous metal production. In the method, an inert gas is used instead of a blowing agent. It is benefited from the very low solubility of the inert gas in the metal (Ashby et al., 2000). The first step of the production process is to fill the gases into a metal can and vacuum. The can is vacuumed until to remove all oxygen, this is important in order not to damage the metal (Kennedy, 2016). Then, can is backfilled with inert gas at between 3-5 atmosphere. Hot isostatic pressing (HIP) process is applied to the metal can be filled with inert gas and metal powders (Banhart, 2001). During this step, the metal densifies and the gas disperses homogeneously in the structure. The number of pores in the densified sample by the HIP process is relatively low compared to the initial step of the process. For this reason, a rolling process is applied to create small pores and to create a more homogeneous distribution, thereby improving the structure (Ashby et al., 2000). During heat treatment, the inert gas expands and creates pores in the structure, thus porous metal is formed. Sandwich structure is produced due to the use of cans in the process. These structures are important for light-weight applications. It is a method applicable to all metal powders. 20-40% porosity as closed type is achieved. The

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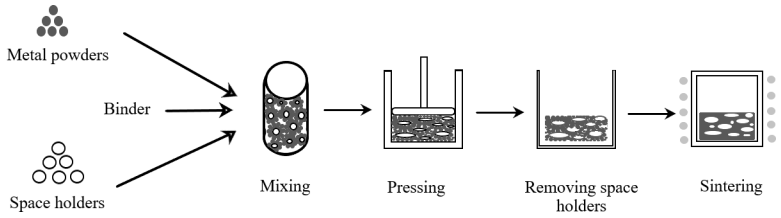
Figure 9. Porous metal production via blowing agents and metal powders sintering (Jain et al., 2020)



technique is often used for porous structures produced in Ti6Al4V alloy (Kennedy, 2016; Degischer et al., 2002; Kulshreshtha and Dhakad, 2020). Figure 8 shows a schematic representation of the process.

Sintering Hollow Spheres

The method is based on the principle of obtaining hollow metallic spheres and forming a porous metallic structure by sintering these spheres together. Hollow metallic spheres can be obtained as many different metals and alloys by many different methods (Degischer et al., 2002; Rajak and Gupta, 2020). After the spheres are obtained, compression and sintering processes are applied to obtain a structure with high porosity. It is important that the compression process is chosen properly so that the metallic spheres are not damaged (Ashby et al., 2000). After sintering, open and closed pores are formed. The porosity of up to 97% can be achieved (Srivastava and Sahoo, 2007; Kennedy, 2016). The most important advantage of the method is that the pore size can be controlled. One of the advantages of this technique is various materials such as superalloys, metals, and alloys and intermetallic compounds can be used in this method. Steel (Smith et al., 2012), aluminium (Duan et al., 2019), copper, nickel, cobalt, nickel-chromium, or titanium hollow spheres and thus porous structures can be obtained with this technique (Banhart, 2001; Bauer et al., 2013).

Sintering Blowing Agents and Metal Powders

It is an important method of metallic foam production by traditional powder metallurgy (Garcia- Moreno, 2016). Porous metal can be produced with metallic powders and many types of blowing agents (space holders, ceramic particles, polymer grains, salts, and even metals, etc.) (Kennedy, 2016). Using a mixer, metallic powders are coated around the blowing agent by means of a binder. Pore properties can be controlled by using different sizes, shapes, and amounts of blowing agents (Aşık and Bor, 2014). This is the most important advantage of the method. The green structure formed by the blowing agent coated with metal powders is compressed in order to provide better strength (Atwater et al., 2018). Then it is necessary to remove the used blowing agent. The removal process varies according to the amount of metal powder used. Completely removal may not occur due to closed type porosity. It can be removed by heat treatment, leaching, or with a solvent solution (Banhart, 2001). Finally, sinter neck growth is created by applying the sintering process between metallic powders (Ryan et al., 2006). Thus, a porous metallic structure is obtained. Both open and closed pores can be obtained (Smith et al, 2012; Jain et al., 2020). A wide range porosity rate (%20-80) can be obtained depending on the amount of space holder. This method is advantageous because of the ability to obtain desired pore properties and near-net-shaped or net-shaped products (Sazegaran and Nezhad, 2021). Titanium (Esen and Bor, 2007) and its alloys (Esen

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and Bor, 2011), steel (Bekoz and Oktay, 2013; Jain et al., 2021), magnesium (Wen et al., 2001; Hao et al., 2009), aluminium (Hakamada et al., 2007) metals can be produced by this technique as a porous form. The schematic representation of the method is given in Figure 9.

Additive Manufacturing

Additive manufacturing (AM) is a new method compared to traditional manufacturing methods. It is an increasingly widespread technology due to its advantages and potential. It attracts attention because it allows the design and application of different pore types especially for porous structure production, and the control of various pore properties such as the amount, shape, and size (Atwater et al., 2018; Chen et al., 2020). Porous material production with AM includes a 3D printing process (Patel et al., 2018). AM processes are used to fabricate three-dimensional complex geometries. This feature removes the design limit and AM technologies represent an interesting process to realize metal foams (Almonti and Ucciardello, 2019). The processes can be separated into two groups according to the way of processing the powder layer: powder deposition and powder bed techniques (Wang et al., 2017b). Schematic representation of the techniques is given in Figure 10.

In AM with powder deposition methods, metallic powders are directly added to the system with a nozzle and processed layer by layer with the laser (Frazier, 2014). The biggest advantage of these methods is also allowing the production of large parts. They can also be used to repair damaged parts. Directed Energy Deposition, Laser Metal Deposition, and Laser Engineered Net Shaping (LENS) techniques are used for porous metal production (Wang et al., 2017b; Shim et al., 2018).

Likewise, layer by layer production is carried out by using a laser beam in the production with the powder-bed system. However, the powder is transferred layer by layer through a moving system to form a powder bed in the production area (Wang et al., 2017b). The powders are contained in a chamber that can move up and down. There is a moving mechanism in the chamber to transfer the powders to the production chamber. The unit containing the powders moves up and the moving mechanism transfers the powders to the other unit. Powders are as a thin layer transferred to the production chamber is processed with a laser or electron beam (Frazier, 2014; Changdar and Chakraborty, 2021). The production chamber also moves down and this process is repeated. After the latest layer is carried out, the unfused powders in the bed are removed. Thus, a porous part is obtained (Kennedy, 2016; Sola and Nouri, 2019; Dani et al., 2020). Selective laser melting, electron beam melting, direct metal laser sintering, and selective laser sintering techniques are powder bed systems (Takezawa et al., 2017; Wang et al., 2017b; Hernández-Nava, 2015; Yuan et al., 2019).

The high cost of production is its main disadvantage (Patel et al., 2018). However, it is important because it provides precision in the production of special parts according to its use. It is used in the production of important materials such as aircraft parts and biomedical implants. Therefore, studies are focused on titanium and its alloys (Koike et al., 2018; Li et al., 2006; Hernández-Nava et al., 2015; Taniguchi et al., 2016; Shim et al., 2018). In addition, porous parts produced by additive manufacturing are used in applications such as micro battery architectures, microbial fuel cells, heat exchanger, and filters (Guddatti et al., 2019). Pure magnesium and Mg alloys, ferrous and Fe alloys, zinc and Zn alloys, Co-Cr alloys and many metals and alloys can be produced as porous metal form with AM techniques (Patel et al., 2018; Yuan et al., 2019; Li et al., 2020a; Xu et al., 2020; Ma et al., 2020).

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Figure 10. Porous product production with powder deposition and powder bed techniques (Guddati et al., 2019)

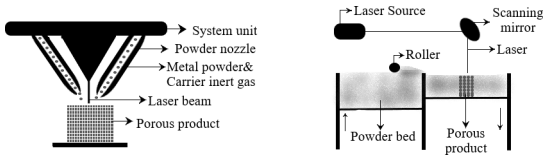

Table 1. Studies of different production methods of common metallic foams

Metals	Methods	References
Aluminium	Direct foaming with gas injection	(Wang et al., 2017a)
	Direct foaming with blowing agent	(Huang et al., 2019)
	Solid-gas eutectic solidification	(Komissarchuk et al., 2018)
	Foaming powder compacts	(Papantoniou et al., 2019)
	Sintering blowing agents and metal powders	(Sun et al., 2021)
	Casting techniques	(Dahil et al., 2020)
	Additive manufacturing	(Huo et al., 2020)
Copper	Sintering blowing agents and metal powders	(Guo et al., 2018; Parvanian et al., 2014)
	Sintering hollow spheres	(Sundarram, 2013)
	Casting techniques	(Nakajima, 2010; Nassef and El-Hadek, 2016)
	Foaming powder compacts	(Shum, 2020; Pop et al., 2017)
	Deposition techniques	(Gao et al., 2016; Balzarotti et al., 2019)
Gold	Deposition techniques	(Cherevko and Chung, 2011; Dong et al., 2013)
	Casting techniques	(Hodge et al., 2006; Li et al., 2017)
	Sintering blowing agents and metal powders	(Cox and Dunand, 2011)
Iron	Sintering blowing agents and metal powders	(Čapek et al., 2015; Sharma and Pandey, 2018)
	Casting techniques	(Rabiei et al., 2004)
	Additive manufacturing	(Sharma and Pandey, 2018; Li et al., 2019)
Steel	Casting techniques	(Mapelli et al., 2013)
	Deposition techniques	(Aal and Aly, 2009)
	Sintering metal powders and fibers	(Yuan et al., 2012)
	Gas entrapment technique	(Mad Rosip et al., 2015; Farhadi, 2018)
	Sintering hollow spheres	(Szyniszewski et al., 2014)
	Sintering blowing agents and metal powders	(Hsu et al., 2021; Tian et al., 2016; Bekoz and Oktay, 2012; Bekoz and Oktay, 2014)
	Additive manufacturing	(Meenashisundaram et al., 2020; Koike et al., 2020; Caiazzo et al., 2017)
Magnesium	Direct Foaming with blowing agent	(Lu et al., 2013)
	Casting techniques	(Gupta and Meenashisundaram, 2015)
	Sintering blowing agents and metal powders	(Hao et al., 2009; Aida et al., 2017)
	Additive manufacturing	(Allavikutty et al., 2021; Kopp et al., 2019)
Nickel	Sintering blowing agents and metal powders	(Unver et al., 2013)
	Additive manufacturing	(Cheng and Li, 2020; Kaur et al., 2020)
Titanium	Sintering blowing agents and metal powders	(Jakubowicz et al., 2013; Jha et al., 2013; Xie et al., 2017)
	Casting techniques	(Müller et al., 2013; Lee et al., 2010; Hasirci and Hasirci, 2018)
	Gas entrapment technique	(Tang et al., 2015; Prabhu et al., 2015; Murray and Dunand, 2004)
	Sintering hollow spheres	(Wally et al., 2015)
	Deposition techniques	(Carcel et al., 2009; Raihan et al., 2021)
	Additive manufacturing	(Harun et al., 2018; Matsushita et al., 2017)
Zinc	Casting techniques	(Mondal et al., 2014)
	Sintering blowing agents and metal powders	(Sadighikia et al., 2015; Mohbe and Mondal, 2021)
	Additive manufacturing	(Qin et al., 2020; Li et al., 2020b)

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CONCLUSION

Recent advancements in technology have led to the increased availability of manufacturing processes for various elemental or alloy metallic foams. As seen in the literature, relative densities ranging from 50% to 98% have been achieved in both open and closed cell foams, with anisotropic or uniform cell morphologies. Today, it is possible to obtain light structures that have 50-90% porosity with open and closed pores using the current production methods. According to production methods, different metallic foams are summarized in Table 1. Cheaper methods for metallic foams production increase the preference in the sector. Metallic foams have structural and functional applications in many industrial sectors. Research aimed at improving manufacturing processes focus on producing better quality metallic foams in a more economical way. It is possible to ensure the morphological and structural homogeneity of the porous structure with the quality production process. As understood from the research in the literature; there is no applicable theoretical or numerical model that allows estimation of the effect of changing parameters for most production processes. Improving production methods can be accelerated with the well-designed process models. Metallic foam production is currently on a relatively small scale, but manufacturers are trying to improve their processes and reduce costs. Some methods have demonstrated industrial-scale manufacturing potential through continuous production processes. Using cheaper starting materials, shortening processing steps, and reducing scrap during production are common strategies for reducing production costs. Developments in production techniques of metallic foams; it is very promising both on an industrial and academic scale.

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