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Review on Manufacturing of Metal Foams

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Metal foams possess excellent physical and mechanical properties. This paper reviews the common manufacturing process of metal foams. Various ways used to produce metal foams based on metal properties are described. The manufacturing process follows four primary routes: liquid state, solid state, ion or vapour processing. Liquid-state processing produces porosity to liquid or semi-liquid metals, and solid-state foaming produces metal foams with metal powder as starting material. For ion and vapour processing methods, metals are electro-deposited onto a polymer precursor. The polymer precursor is removed by chemical or heat treatment to produce metal foams. The advantages and limitations of each manufacturing process are also described.

Keywords: Metal foams; solid-state foaming; liquid-state foaming

I. INTRODUCTION

Metal foams are metals that comprise a large number of pores. Metal is strong and durable and has high strength, while the pore structure makes the material lighter. Metal foams have unique physical and mechanical properties because of the existence of pores. Unique properties include high specific strength to weight ratio, high gas permeability, high thermal conductivity and good energy and sound absorption properties (Ashby *et. al.,* 2000; Banhart, 2001; Tulasiram *et. al.,* 2017; Mahadev *et al.,* 2018).

Metal foams can be classified based on pore type. The two types of pores are closed pores and open pores, as shown in Figure 1. The pore type will determine the function and application of metal foams. For example, metal foams with open pores are ideal for filtering applications. Metal foams are closely related to porous metals. In general, the properties of these two materials are the same. However, they have some differences in terms of phase dispersion and pore morphology. Such differences are as follows (Banhart, 2001; Sufizar, 2010; Tan, 2016):

(a) Metal foam - It has a wide array of cells. Cells are located near the membrane cell separated by the adjacent cell or the cell is open. The term 'metal foam' is used only when the hollow metal is formed by the dispersion of the gas phase in the metal or solid metal.

(b) Porous metal - It has spherical cell blocks. Cells are separated, isolated and coarse. Total porosity is usually less than 70%. The term 'porous metal' is used when the hollow metal is not produced by the dispersion of gas phases in metal or solid liquids.

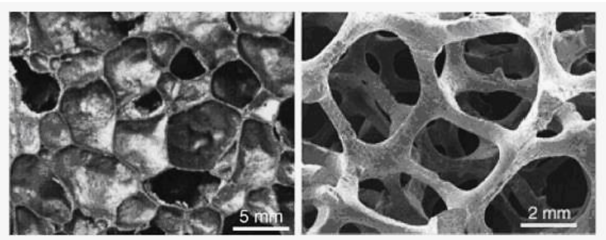

Figure 1. SEM images of (a) closed pore and (b) open pore (Banhart, 2001)

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The term 'metal foam' is widely used because of the misinterpretation of definitions. This term has been adopted by researchers to represent hollow and porous structures (Banhart, 2001). Another very common term used to describe hollow metal is 'cellular metal'. Cellular metal refers to a metal that has many types of a cavity. All three terms have one thing in common, that is, they have cavities or pores.

The four main methods of producing foam metals are production by liquid state, production by solid state, vapour deposition and ion deposition (Banhart, 2001). Figure 2 shows a general overview of the four methods. The method used to manufacture metal foams and porous metals must be selected by considering the physical properties and chemical properties of the metal used. For example, aluminium with a low melting point is suitable for processing under liquid conditions, while the high melting point metals such as steel and titanium are produced under solid conditions. At high temperatures, undesired chemical reactions may occur. The production techniques and processing parameters of metal foams are still being carefully and extensively studied to obtain metal foams with good physical properties and mechanical properties. This paper aims to review the manufacturing methods used to produce metal foams.

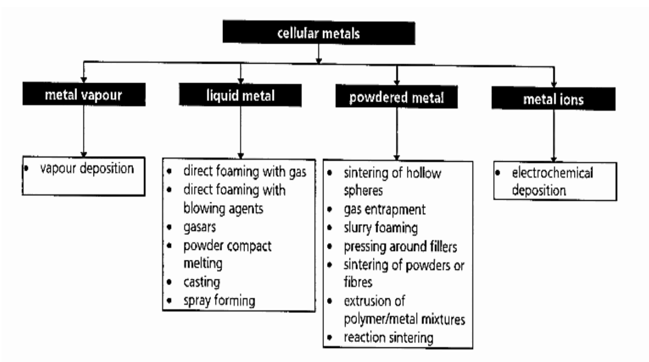

Figure 2. Overview of methods for fabricating cellular metals (Banhart, 2001)

II. LIQUID-STATE PROCESSING OF METAL FOAMS

Liquid-state processing is the most widely used method and is suitable for metals and metal alloys with low melting point. Liquid metals can be made to foam either through direct foaming or by indirect methods, such as casting on polymer foams. The techniques categorised in liquid processing methods are:

i. Foaming by gas injection
ii. Foaming with blowing agents
iii. Solid–gas eutectic solidification ('gasars')
iv. Casting methods
v. Powder compact melting technique.

A. Foaming by Gas Injection

This method is the first developed for aluminium foams (Sufizar, 2010; Tan, 2016). Figure 3 shows the foaming of melts by gas injection. The molten metal is prepared by heating the metal to its melting point. The molten metal is then added with stabilisers and binders, such as silicon carbide and aluminium oxide. The next step is to inject gas to form a gas bubble in the molten metal. The gas injection can be done by injecting air, nitrogen or argon with a specially designed rotary or vibrating nozzle. The gas bubbles will float on the surface of the molten metal and form metal foams (Yuan *et al.,* 2012). The metal foams formed will be drained out by the conveyor belt as shown in Figure 3. Banhart (2000) stated that the process parameters, such as gas-injection pressure, conveyor speed and nozzle vibration frequency, must be controlled carefully to obtain the desired thickness and density. This process can produce metal foams in large quantities and pores. However, it has weaknesses, such as difficulty in controlling pore morphology and unsuitability for highly reactive metals, such as titanium.

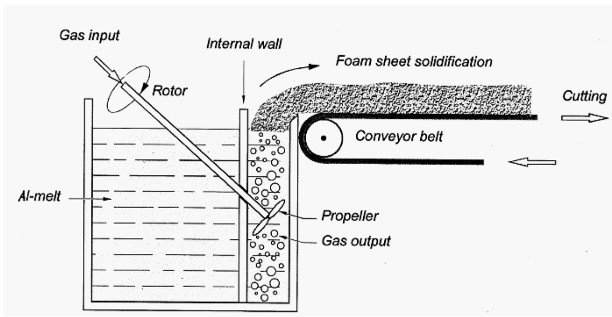

Figure 3. Direct foaming of melts by gas injection (Mahajan & Ganesh, 2015)

B. Foaming with Blowing Agents

Instead of blowing gas into metal melts, metal melts can be foamed directly with a blowing agent. Blowing agents will decompose when heated and produces gas to foam the molten metal. Shinko Wire Company, Ltd. at Amagasaki, Japan in 1986 developed and patented this method (Akiyama *et. al.,* 1987; Miyoshi *et al.,* 2000). Figure 4 shows the foaming process with blowing agents. This process starts with the melting of aluminium at 680 °C. The molten aluminium is added to calcium to increase the viscosity. Calcium has a high electron affinity; thus, it can form calcium oxide and calcium-aluminium oxide to thicken the melts. A blowing agent, namely, titanium hydride (TiH2), is then added into the melt. The titanium hydride will decompose and release hydrogen and thus expand the melt to fill the mould. After cooling, the aluminium foam block is removed from the mould and the manufacturing cycles are repeated. The entire process takes about 15 minutes. The metal foams produced by this method use the trade name ALPORAS (Asbhy *et. al.,* 2000; Banhart, 2000; Korner & Singer, 2000). This method can produce relatively homogeneous foam in a short time, but controlling the pore size and shape is difficult.

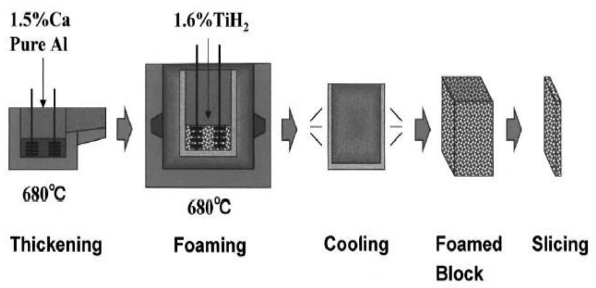

Figure 4. Direct foaming of melts with blowing agents (‘Alporas’ process) (Miyoshi *et al.,* 2000)

C. Solid–gas Eutectic Solidification (‘gasars’)

This method was developed because some liquid metals, such as aluminium, magnesium and copper fluids, form eutectic systems with hydrogen gas (Shapovalov, 1993). The heating of liquid metal in high-pressure hydrogen atmosphere produces a two-phase eutectic system, melt charged and hydrogen gas. When the liquid metal is cooled and solidified, the hydrogen gas is absorbed into the metal and will form pores within the metal. This method is named GASAR, which means gas-reinforced porous material in the Russian acronym. Pore morphology depends on hydrogen gas content, gas pressure over the melt, cooling rate and chemical composition of the molten metal. Pores are formed as elongated pores oriented towards solidification. This method is suitable for continuous casting (Smith *et al.,* 2012). Banhart (2000) pointed out that this process cannot produce metal foams with uniform pore size distribution.

D. Casting Methods

Casting methods are indirect liquid-state processing methods. Researchers can cast metal foams with polymer foams or space holders. Figure 5 shows the casting of metal with polymer foam. Slurry with high heat resistance is poured into polymer foam. After drying, the polymer foam is removed by heat treatment. The newly formed mould is then infiltrated with a molten metal. The molten metal fills the mould, which is finally removed after cooling. The casting method with the space holder material is shown in Figure 6. The space holders used are normally organic or inorganic materials in granular form. The space holder is initially placed at the mould, and the molten metal is poured into the mould. Upon cooling and solidification, the filler material is removed using a solvent or by heat treatment. The pore morphology can be easily controlled by adjusting the space holder’s size and shape. However, this technique is still unsuitable for highly reactive metals, such as titanium.

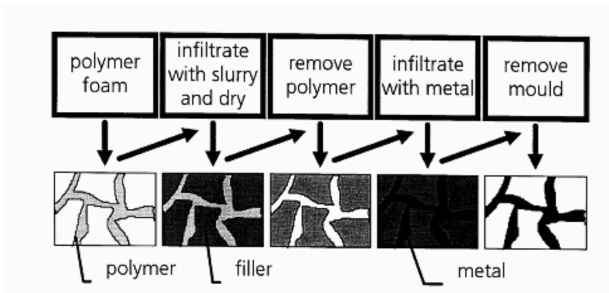

Figure 5. Production of metal foams by casting with polymer foams (Yamada *et al.,* 2000)

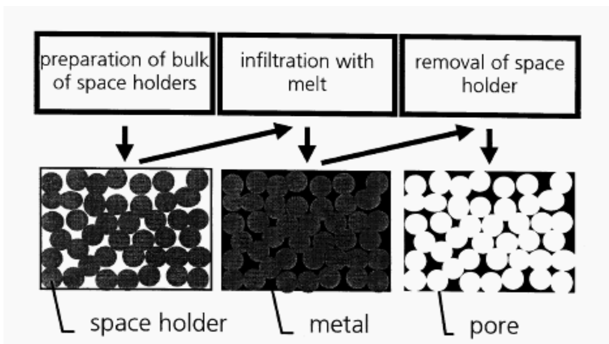

Figure 6. Production of metal foams by casting with the space holder (Banhart, 2001)

E. Powder Compact Melting Technique

The Fraunhofer-Institute in Bremen Germany developed this technique (Banhart, 2001). This method uses metal powder as starting material. However, the foaming occurs during melting, so it is still categorised under production via the liquid state. The metal powder is initially mixed with the blowing agent. The mixture is compressed by compression or extrusion (Lee, 2005). Heat treatment is conducted around the metal melting temperature, so the blowing agent can decompose. The released gases will expand the parts and form pores in the molten metal. Altering the type and composition of the blowing agent can control the density of metal foams. However, this method cannot control the pore morphology and is unsuitable for metals with a high melting point because the processing cost would be high.

III. SOLID-STATE PROCESSING OF METAL FOAMS

Metal powder is the main raw material used when processing metal foams via solid state. Sintering is carried out to produce metal foams. This method is ideal for producing foam metals, whose metals are reactive and have high melting points, such as titanium and stainless steel. The easiest solid-state processing method is sintering loose powder. The metal powder is sintered at about 70%–80% of the sintering temperature to produce metal foams. Bronze foams, titanium foams and stainless steel foams can be produced by sintering loose powder. (Banhart, 2001; Kok, 2013). The pore morphology is greatly influenced by the size and shape of the metal powder used. To improve the properties of foam metal, engineers and scientists have developed various alternative methods of production under solid conditions. These methods include (i) metallic hollow sphere sintering, (ii) gas entrapment, (iii) slurry decomposition and (iv) space holder method.

A. Metallic Hollow Sphere Sintering

This method is similar to loose metal powder sintering. The difference is that sintering is conducted on hollow spherical powder. The hollow spheres of metal particles bind to one another when they are sintered to produce metal foams. Metal hollow spheres are fabricated in various ways. The simplest method is to coat the metal onto a polymer sphere by chemical deposition. Andersen *et al.* (2000) performed coating by using a metal powder coating and binders. This process is shown in Figure 7. After the coating, debinding is performed to remove the polymer spheres and the metal spheres are sintered. Another method to produce metal hollow spheres is blowing the metal powder slurries into microspheres with coaxial nozzles (Asbhy *et. al.,* 2000; Lee, 2005). The closed pore structure can be obtained by filling the metal powder in the gaps between the spheres. Metallic hollow sphere sintering can produce metal foams with uniform pore size distribution. This method can be applied to many types of metal powders, including titanium alloys.

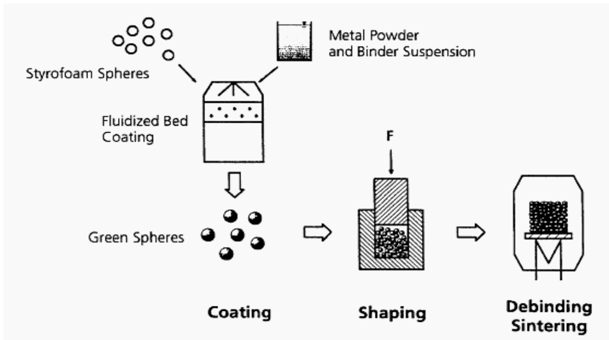

Figure 7. Styrofoam coating for making hollow sphere structures (Andersen *et al.,* 2000)

B. Gas Entrapment Technique

Gas entrapment is a method of producing metal foams without using blowing agents and melting metals. As shown in Figure 8, metal powder is initially placed into a vacuum container. Thereafter, the container is filled with argon gas at a pressure of 3–5 atm. The metal powder is then sealed and subjected to hot isostatic pressing, and argon gas is trapped inside. The compressed material is processed according to the required requirements by annealing. The annealing process is carried out at 0.6 times the melting point of the metal and usually takes 6–24 hours. The heat treatment causes argon gas to expand and reduce its internal pressure until the equilibrium state of pressure and part's strength is reached. Banhart (2001) mentioned that gas entrapment can produce metal foams with 20%–40% unconnected porosity. Elzey and Wadley (2001) argued that this process is difficult to use to produce metal foams with porosity greater than 50%. Moreover, uneven gas expansion may cause pore coarsening.

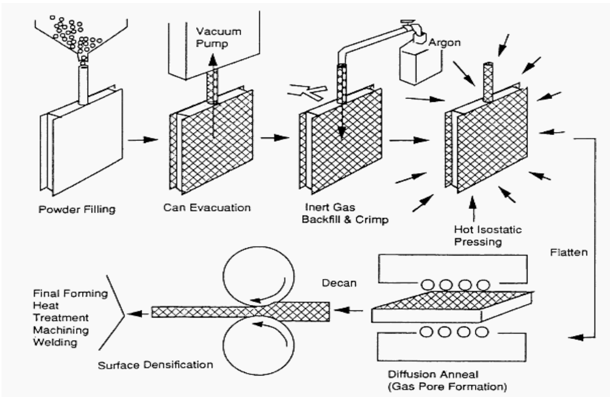

Figure 8. Gas entrapment for producing metal foams (Tan, 2016)

C. Slurry Decomposition

This method has been successfully used to produce ceramics-based metal foams, such as hydroxyapatite (HAP) to replace human bones (Ramay & Zhang, 2003; Woesz *et. al.,* 2005; Potoczek, 2007). Noor *et al.* (2017) used slurry decomposition to produce porous SS316L for biomedical implants. In this method, slurry is prepared with metal powder, blowing agents and additives, such as binders. The slurry is then poured into a mould and heated. Heating causes the slurry to be viscous and expand as the gas evolves. Sufficient stabilising measures should be employed while drying the slurry. The slurry is then sintered to obtain high-strength metal foams. An alternative method for slurry processing is to immerse the polymer into the slurry. After coating, the coated polymer foam is heated to remove the polymers. The parts will then be sintered to obtain metal foams. This method can produce open-pore metal foams with high porosity. For example, Kato *et al.* (2013) produced stainless steel with 85% porosity by using this method. However, the process has limitation in controlling cell morphology because it is difficult to obtain polymer foams with desired pore size and pore shape in the market.

D. Space Holder Method

A space holder can produce metal foams with controlled pore morphology. This method has gained considerable research interest because the pore size and pores shape of metal foams can be easily tailored (Mutlu & Oktay, 2011b). Figure 9 shows the processing of metal foams by using space holder method. The space holder material is initially mixed with metal powder. The space holder could be ceramic particles, polymeric materials or salts. Approximately 1%–2% binders are usually added to the mixture to increase the part's strength. The mixture is compressed or injection moulded to obtain the desired parts. After compression, the space holder material is removed by heating or dissolution. The removal of space holder material will produce connected pores. The pores formed may be open or closed. Finally, the green body is sintered to enhance its structural strength.

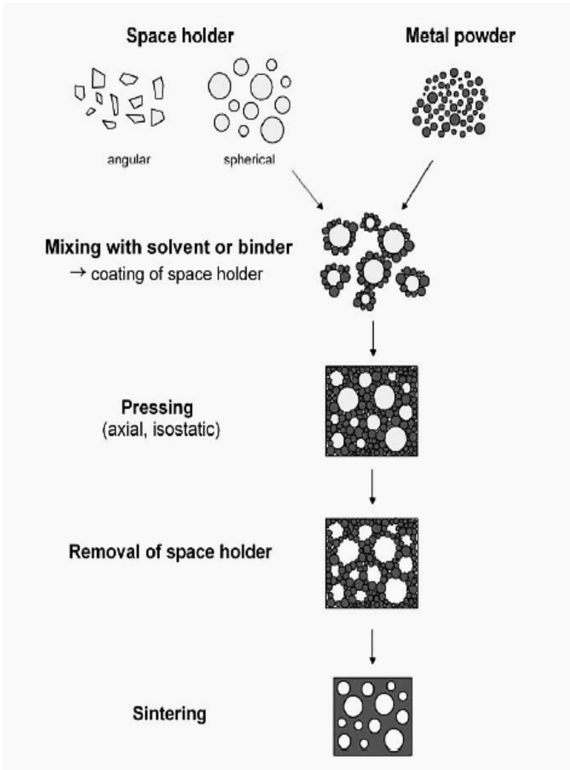

Figure 9. Space holder technique for making metal foams (Bram *et. al.,* 2000; Tan, 2016)

The space holder method is a relatively simple method of producing metal foams. However, many processing parameters that, if not properly controlled, will detriment the quality of parts. Many researchers have used this method to produce metal foams. Among them are Jiang *et al.* (2005), Brothers *et al.* (2005), Bakan (2006), Ozan and Bilhan (2008), Kotan and Bor (2007), Mariotto *et al.* (2011), Mutlu and Oktay (2011a), Abudullah *et al.* (2017), Wahab *et al.* (2018); Joshi (2019). They focused on feasibility, effectiveness and processing parameters. Jiang *et al.* (2005) concluded that metal foams produced by a spherical space holder have higher compressive strength. Bekoz and Oktay (2012) investigated the effects of space holder shape and content. They also obtained a similar finding because spherical pores have a more uniform cell wall, which increases the contact between metallic particles during sintering. Furthermore, Bekoz and Oktay (2012) and Tan (2016) commented that compressive stresses would be easy to concentrate on uneven pores; thus the compressive strength is lower on metal foams with uneven pores.

IV. ION-DEPOSITION AND VAPOUR DEPOSITION TECHNIQUE

The production of metal foams through ion and vapour deposition is not commonly used. The main reason may be due to the high cost of processing metal ions and metal vapour. Both methods apply the same processing principle, which is deposition. Depending on the raw material used, the production method is called ionisation deposition or vapour deposition. In ionisation, metal ions are deposited or electro-deposited onto open-pore polymer foam. As shown in Figure 10, certain polymer foams require conductive coating before the electrical ion or vapour deposition occurs. The purpose is to improve the electrical conductivity of the polymer foams. The polymers foams can be coated with electrically conductive materials, such as graphite. After deposition, the polymer is removed by heat treatment and three-dimensional metal foams are produced.

Vapour deposition methods have been successfully used to produce nickel foams called Incofoam (Babjak *et al.,* 1990). A solid structured precursor must be used so that metal vapour can be deposited on the precursor surface. The most common precursor is polyurethane (PU) foams. In this process, nickel carbonyl is heated in a vacuum chamber and is decomposed into nickel vapour. Nickel vapour will condense and settle onto the surface of the polyurethane. The thickness of the coated metal layer depends on vapour density and exposure time. The precursor coated with metal vapour will cool, and the polymer is removed through heat or chemical treatment. Finally, nickel foams that resemble the shape of the precursor are produced.

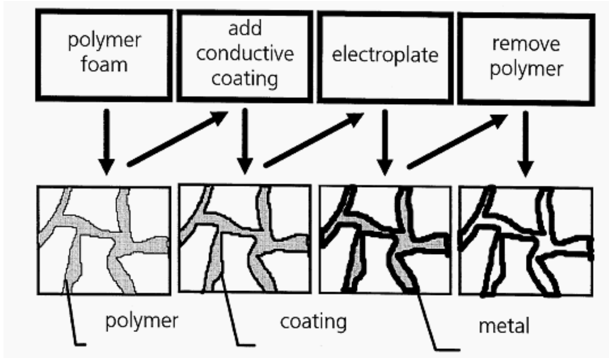

Figure 10. Electro-deposition technique for making metal foam. (Bram *et al.,* 2000)

V. CONCLUSION

A number of metal foaming technologies have been developed in the past decade. These techniques can be applied in a wide range of different metallic materials. The study concludes:

[a] Liquid-state processing methods are only suitable for unreactive metals or metals with a low melting point.

[b] Space holder method can control or adjust pore size and pore shape easily.

[c] The processing parameter of each technique affects the pore morphology.

[d] Ion deposition and vapour deposition are not commonly used due to their high processing cost.

VI. ACKNOWLEDGEMENT

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