

Comparison between methods used for manufacturing of aluminum foam

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Abstract: Metal foams with porosities exceeding 50% are used for production of advanced light-weight structures. In this study, the manufacturing methods of aluminum foam were reviewed and were compared with each other. There are number of processing methods that are currently used to manufacture Al foams (Körner and Singer, 2000; Banhart *et al.*, 1999). These methods can be categorized into foaming liquid melts, gasar, infiltration, casting, foaming of powder compacts and sintering-dissolution process (SDP). Furthermore, microstructure and properties of the final product were addressed for each manufacturing method. All these manufacturing routes have their own relative densities and cell structures. Open and closed pore morphologies and relative densities ranging from 50 to 98% can be achieved based on the applied method.

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1. Introduction

In many industrial applications, new materials are required for the production of light-weight structures. Metal foams with porosities exceeding 50% can meet this requirement (Banhart and Baumeister, 1998; Lehmhus and Banhart, 2003; Kenesei *et al.*, 2004; Zhu and Windle, 2002). These materials show an interesting combination of physical and mechanical properties that make them particularly versatile: the low apparent density, for example, allows obtaining a high stiffness/ specific weight ratio, the presence of cavities and the essential in-homogeneity provide them acoustic and thermal insulation properties, besides the possibility to absorb impact loads and to damp vibrations and sound insulation (Kenesei *et al.*, 2004; Zhu and Windle, 2002; Daxner *et al.*, 2002; Ramamurty and Paul, 2004; Hai-jun *et al.*, 2007; Haack *et al.*, 2008; Banhart *et al.*, 1998; Nieh *et al.*, 2000; Pcomston, 2006; Kiratisaevae and Cantwell, 2005; Simancik, 2000; Yu *et al.*, 2008; Seitzburger *et al.*, 1997). Finally, the metallic structure potentially gives those good electromagnetic shielding properties, special electrical conductivity and inalterability in time (Banhart and Baumeister, 1998; Lehmhus and Banhart, 2003; Kenesei *et al.*, 2004; Zhu and Windle, 2002; Daxner *et al.*, 2002; Ramamurty and Paul, 2004; Hai-jun *et al.*, 2007). The combination of these physical properties makes metallic foams able to be competitive in terms of performances and costs in several unusual advanced applications (Hai-jun *et al.*, 2007; Haack *et al.*, 2008; Banhart *et al.*, 1998; Nieh *et al.*, 2000; Pcomston, 2006). Metal foams show a cellular structure consisting in a solid and a gaseous phase. In this regard, these materials can be classified

based on their cells morphology (Kenesei *et al.*, 2004; Zhu and Windle, 2002; Daxner *et al.*, 2002; Ramamurty and Paul, 2004; Hai-jun *et al.*, 2007; Haack *et al.*, 2008). According to the connectivity of cells, metallic foams can be categorized as either closed- or open-celled. Closed cell metallic foams possess higher modules, strengths and impact energy absorbing characteristics than their open cell counterparts (Haack *et al.*, 2008). But the characteristics of which the open cell foams possess make the foams exploitable for multifunctional applications. In most cases, the functions such as filtration, separation, heat or mass exchange, and sound or energy absorption require open celled structures (Zhu and Windle, 2002; Hai-jun *et al.*, 2007).

An extensive amount of research has been performed on the processing and properties of lightweight metal foams since the early 1990's (Yu *et al.*, 2008; Banhart, 2001; Han *et al.*, 1998). Most of this work has been conducted on aluminum foams due to unique properties of these materials such as; low density for ultra-lightweight and buoyant structures, high degree of homogeneous and tailorable closed-cell porosity, very high specific stiffness, enhanced mechanical damping compared to bulk aluminum, reduced thermal and electrical conductivity, good machinability (drilling, sawing, turning, milling) and joining by adhesive bonding, soldering, active brazing, mechanical inserts, advanced welding methods (Han *et al.*, 1998; Han *et al.*, 2004; Rakow and Waas, 2004; Grenstedt, 1998; Kováčik *et al.*, 2003; Simancik, 2001; Miyoshi *et al.*, 2000; Akseli, 2005; Fusheng, 1999). In the last decades many attempts have been made to produce

aluminum foam structures, they were not successful, because of their relatively high costs. Furthermore, it was not possible to produce metallic foam with reproducible properties. Problems occurred with a low foam ability of the molten metal, the varying size of cellular structures or solidification shrinkage (Zhaojin and Deping, 2000). However, recently these issues have been solved by extensive research that has led to the development of new production technologies (Duarte and Banhart, 2000). These new foaming technologies allow the production of foam of a significant higher quality.

Despite comprehensive patents and literatures have been conducted on developing new methods for production of Al foam, only few old review papers dedicated to systematically addressing the issue and comparison between the methods (Ashby *et al.*, 2000). Therefore, the aim of this paper is to review and compare new manufacturing methods which are used to produce Al foams. Furthermore microstructure and properties of the produced foam were addressed for each manufacturing method.

2. Manufacturing methods

While several technologies had been developed for production of aluminum foams, only some of these processes are applicable for the economical production of aluminum foams in an industrial scale. The technologies can be divided into that start with the liquid metal or with a metal powder. Therefore, the manufacturing methods of aluminum foams can be divided in two different categories; liquid and solid state processing. The liquid state process includes foaming Al melts and the solid state process comprises of foaming of powder compacts. Al foam has a composite structure consisting of gaseous and solid phases, which exhibits a porosity of 70-90%. Therefore, in two ways a gas is used for producing of porosity (melt gas injection (air bubbling), gas-releasing article decomposition in the melt). Almost, a foaming agent is used to generate this gas and produce of porosity. During the process, the foaming agent must be able to generate desired amount of gas bubbles in appropriate sizes (Han *et al.*, 1998; Akseli, 2005; Friedrich *et al.*, 2003; Leitmeier *et al.*, 2002).

2.1. Liquid state processing

2.1.1. Foaming liquid metals

Metallic melts can be foamed directly under certain circumstances by creating gas bubbles in the liquid. Normally, gas bubbles which are formed in a metallic melt tend to quickly rise to its surface due to the high buoyancy forces in the high-density liquid, but this rise can be hampered by increasing the viscosity of the molten metal. This can be done by

adding fine ceramic powders or alloying elements to the melt, which form stabilizing particles, or by other means (Banhart, 2001; Miyoshi *et al.*, 2000; Akseli, 2005). In the past 10 years, however, a number of new developments have taken place so that nowadays some improved production routes are available. Currently there are two known ways of foaming metallic melts: gas injecting into the liquid metal and gas releasing blowing agent addition into the molten metal (Duarte and Banhart, 2000; Baumeister, 1990; Wei-min *et al.*, 2001).

2.1.1.1. Foaming melts by gas injection

The first manufacturing method of foaming aluminum melts is based on gas injection into molten metal (Figure 1). Alcan N. Hydro Aluminum in Norway and Cymat Corporations in Canada are the manufacturers, which apply this method to produce Al foams. Hence, this process sometimes is called as Alcan or Cymat process (Ashby *et al.*, 2000; Wei-min *et al.*, 2001; Steiner *et al.*, 1997). During this process, SiC, Al₂O₃ or MgO particles are used to enhance the viscosity of the liquid metal and adjust its foaming properties because liquid metals cannot easily be foamed by bubbling air through them. Drainage of the liquid down the walls of the bubbles occurs too quickly and the bubbles collapse. However, if a small percentage of these particles are added to the melt, the flow of the liquid metal is impeded sufficiently to stabilize the bubbles. In the next stage, the gas (air, argon or nitrogen) is injected into molten aluminum by using special rotating impellers or air injection shaft or vibrating nozzles, which constitute gas bubbles in the melt and distribute them uniformly and easily through the melt. The resultant viscous mixture of bubbles and melt floats up to the surface of the liquid where it turns into fairly dry liquid foam as the liquid metal drains out. A conveyor belt is used to pull the foam off the liquid surface, and is then left to cool and solidify (Rakow and Waas, 2004; Grenstedt, 1998; Kováčik *et al.*, 2003; Simancik, 2001).

a) Microstructure & Properties:

Average cell size, average cell wall thickness and density can be adjusted by varying processing parameters including gas injection rate and parameters including gas injection rate and rotating shaft speed. The volume fraction of particles varies from 10% to 20%, and the mean size of the particles ranges between 5 μm and 20 μm. This process allows the production of closed-cell foams of 1 m wide to 0.2 m thick slabs with diameters ranging between 5 mm and 20 mm and the foam relative densities between 0.03-0.1.

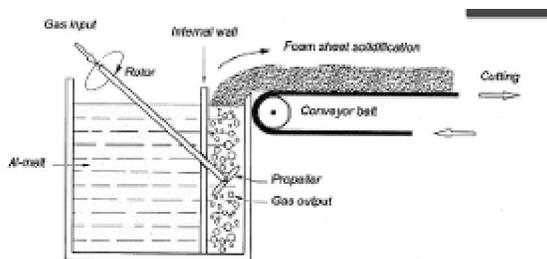


Figure 1. Schematic diagram of manufacturing of aluminum foam by melt gas injection method (Simancik, 2001).

This process allows the production of closed-cell foams of 1 m wide to 0.2 m thick slabs with diameters ranging between 5 mm and 20 mm and the foam relative densities between 0.03-0.54 g/cm³.

b) Advantage & shortcomings of the method:

This process is the cheapest one among all others, and the only one to have been as a continuous production. Foam panels can be produced at rates of up to 900 kg/hour.

A possible disadvantage of the direct foaming process is the eventual necessity for cutting the foam, thereby opening the cells. Also, the brittleness of the produced foam due to the reinforcing particles contained in the cell walls is in general an unwanted side effect of the foaming technique. Furthermore, the main disadvantage of this process is the poor quality of the foams produced. The cell size is large and often irregular, and the foams tend to have a marked density gradient. Although various methods have been developed to improve the drawing of the foam, the size distribution of the pores is still difficult to control (Figure 2) (Akseli, 2005; Ashby *et al.*, 2000).

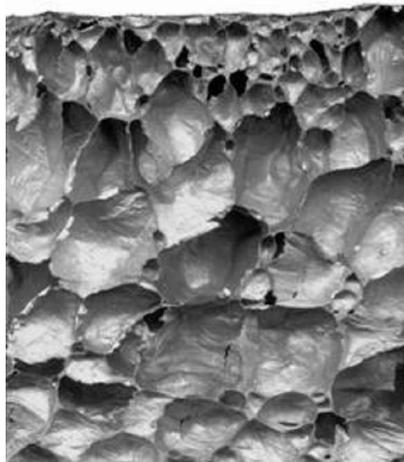
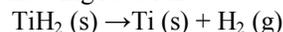


Figure 2. Al foam produced by a continuous process of gas injection to a viscous melt (Banhart, 2001)

2.1.1.2. Foaming melts with blowing agents

Adding a blowing agent into the melt is another way of foaming melts. The blowing agent decomposes under the influence of heat and releases gas, which then propels the foaming process. Shinko Wire Co. Ltd. (Osaka, Japan) has developed this method, known as the Alporas process (Banhart, 2001; Han *et al.*, 1998; Akseli, 2005; Fusheng, 1999; Friedrich *et al.*, 2003). The Al foams produced via Alporas-process, is the most homogeneous foams currently available. The method is shown schematically in Figure 3, in the first stage of the foam production about 1.5 wt.% calcium metal is added to the Al melt at 680 °C. The melt is then stirred for several minutes. During the stirring, viscosity of the melt continuously increases by a factor of up to 5. This is the result of formation of oxides, e.g. CaAl₂O₄, or Al₄Ca intermetallics, which thicken the liquid metal. Calcium volume fraction and stirring time can influence the viscosity of Al melt. Upon reaching an optimum melt viscosity, typically 1.6 wt.% titanium hydride (TiH₂) is added as the blowing agent. This material decomposes according to the following reaction:



The melt starts to expand slowly and gradually fills the foaming vessel. The whole foaming process can take 15 minutes for a typical batch of about 0.6 m³ (Kováčik *et al.*, 2003; Simancik, 2001; Leitmeier *et al.*, 2002; Stanzick *et al.*, 2002; Garcia-Moreno *et al.*, 2005; Malekjafarian *et al.*, 2011; Matijasevic and Banhar, 2011; Jufen *et al.*, 2002). After cooling the vessel below the melting point of the alloy, the liquid foam turns into solid Al foam and can be taken out of the mould for further processing.

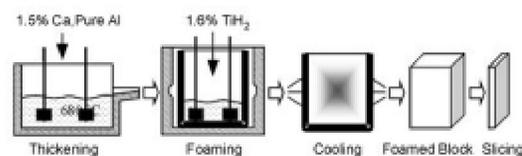


Figure 3. The process steps of aluminum foam forming by gas releasing agent (Degischer and Krist, 2002)

a) Microstructure & Properties

The pore morphology of such foam is shown in Figure 4. It is empirically found that the melt viscosity affect the average cell diameter as well as the final foam density. Moreover it was observed that carbonate foaming ensured smaller pores but similar densities as foaming with TiH₂ (Cambronerio *et al.*, 2009). In the literature, zirconium hydride (ZrH₂) has also been recommended as a blowing agent for the

production of foams with preferred concentrations of 0.5-0.6 wt% and foaming temperatures ranging from 670 to 705 °C (Banhart, 2001). The mass of one cast foam block is approximately 160 kg, corresponding to an overall density including outer skins of 0.27 g/cm³ (Banhart, 2001). Typical densities after cutting off the sides of the block are 0.18-0.24 g/cm³, with the average pore size of 2-10 mm (Friedrich *et al.*, 2003; Leitmeier *et al.*, 2002; Stanzick *et al.*, 2002; Garcia-Moreno *et al.*, 2005).

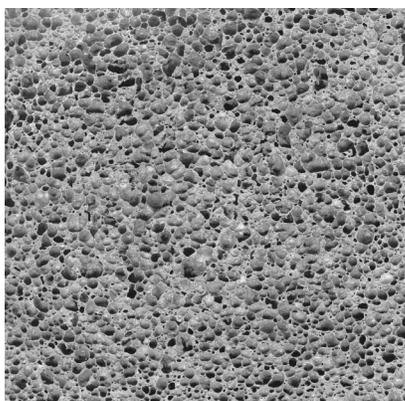


Figure 4. Pore structure of aluminum foamed by gas releasing agent (TiH₂) (Duarte and Banhart, 2000)

b) Advantages & shortcomings of the method

The foam manufactured via this method, has very uniform pore structure and do not require the addition of ceramic particles, which makes the foam brittle. However, the method is more expensive than foaming melts by gas injection method owing to more complex equipments are required (Ashby *et al.*, 2000).

2.1.2. Solid-gas eutectic solidification

A method developed about two decade ago exploits the fact that some liquid metals form a eutectic system with hydrogen gas. By melting one of these metals in a hydrogen atmosphere under high pressure (typically 5–10 atmospheres of hydrogen), one can obtain a homogeneous melt charged with hydrogen (Steiner *et al.*, 1997; Cambronerio *et al.*, 2009; Sharpalov, 1993). Now, with a comprehensive decrease in the temperature, the melt will eventually undergo a eutectic transition to a heterogeneous two-phase solid/gas system. If the composition of the system is sufficiently close to the eutectic concentration, there will be a segregation reaction at one temperature. Because the eutectic composition depends on the system pressure, the external pressure and the hydrogen content must be coordinated. For this reason an autoclave is required in which the melt can be produced, charged with hydrogen and finally direction ally solidified (Figure 5) (Banhart, 2001).

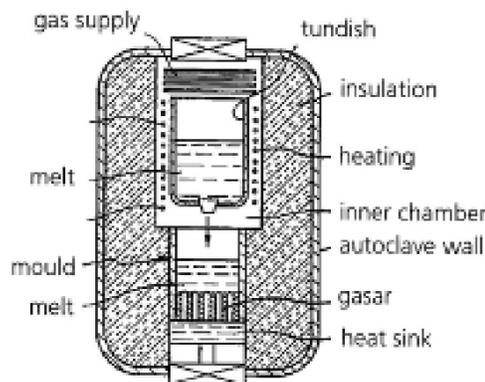


Figure 5. Apparatus used for solid-gas eutectic solidification (Banhart, 2001)

For the porous materials formed by solid/gas eutectic solidification, the word “gasar” was coined meaning “gas-reinforced” in a Russian acronym. Removal of heat from the melt causes directional solidification. As the solidification front advances through the liquid, typically at velocities of 0.05-5 mm/s, the hydrogen content near the solidification plane increases and gas bubbles are formed (Duarte and Banhart, 2000). The process parameters have to be chosen such that the bubbles do not float out into the remaining liquid and disappear but remain near the solidification zone and are entrapped in the solid (Banhart, 2001; Friedrich *et al.*, 2003; Leitmeier *et al.*, 2002; Stanzick *et al.*, 2002; Garcia-Moreno *et al.*, 2005).

a) Microstructure & Properties

The resulting pore morphologies are largely determined by the hydrogen content, the pressure over the melt, the direction and rate of heat removal, and the chemical composition of the melt. Generally, largely elongated pores oriented in the direction of solidification are formed. They only appear spherical when observed in this direction as shown in Figure 6.

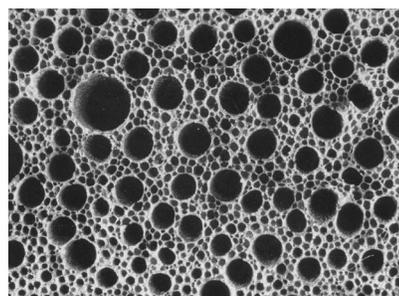


Figure 6. Pore structure of aluminum foamed by solid-gas eutectic solidification (Banhart, 2001)

Pore diameters range from 1 mm to 10 mm, pore lengths from 100 mm to 300 mm, aspect ratios from 1 to 300 and porosities from 5 to 75% (Friedrich *et al.*, 2003). The pore size distribution is non-uniform because of concurrent growth of small and large pores and coalescence.

b) *Advantages & shortcomings of the method*

Pores may be conical or even corrugated. If the casting vessel is cylindrical, radial and axial pores can be made depending on how the sample is cooled. However, the homogeneity of gasars is sometimes unsatisfactory and further improvements are needed to allow for applications of the material (Banhart, 2001; Miyoshi *et al.*, 2000; Duarte and Banhart, 2000; Friedrich *et al.*, 2003; Leitmeier *et al.*, 2002; Stanzick *et al.*, 2002; Garcia-Moreno *et al.*, 2005).

2.1.3. Replication method

The replication technique consists of three basic steps: preparation of an open-pore pattern, infiltration of the pattern with the desired metal, and subsequent removal of the pattern to produce a metal sponge (Sharpalov, 1993). Hence, this process sometimes is called as infiltration. Pure aluminum foams are produced by infiltration of porous salt patterns and subsequent dissolution of the salt as outlined in Figure 7. The pattern is prepared by sintering a packed bed of coarse chemical grade sodium chloride powder. The particles of this high-purity salt are about 500 μm in diameter, and their shape is equiaxed, varying somewhat from cubic to spherical depending on the as-received lot (Goodall *et al.*, 2005). To produce the pattern, loose salt powder is poured into alumina crucibles that have been coated with boron nitride. The crucible is then tapped until a stable density is achieved. This crucible is placed in a cold furnace and heated to a sintering temperature of 785 $^{\circ}\text{C}$ in air, followed by furnace cooling. No significant deviations in the properties of the foams have been noted for sintering times ranging from a few hours to 144 h Kennedy, 2002. The temperature of the furnace is controlled to within ± 5 $^{\circ}\text{C}$ over a length of 120 mm, such that homogenous pre-forms with a length of about 100 mm and a diameter up to 38 mm can be produced (Marchi and Mortensen, 2001).

After sintering, the salt pattern is removed, inserted into a similar alumina crucible coated with graphite, and a billet of high-purity (99.99%) aluminum is placed on top of the pattern. This assembly is placed in a hot-wall gas-pressure infiltration apparatus, where it is heated to 750 $^{\circ}\text{C}$ under vacuum. Once the temperature has stabilized, the system is pressurized with argon to a pressure of 0.5 MPa, such that the liquid aluminum infiltrates the

pre-form. After infiltration is complete, directional solidification is initiated from the bottom of the crucible upwards by lowering the crucible onto a cold copper chill within the infiltration apparatus. After solidification, the material is removed from the infiltration apparatus and machined to the desired dimensions prior to removal of the salt. The salt is subsequently leached by submersion in distilled water.

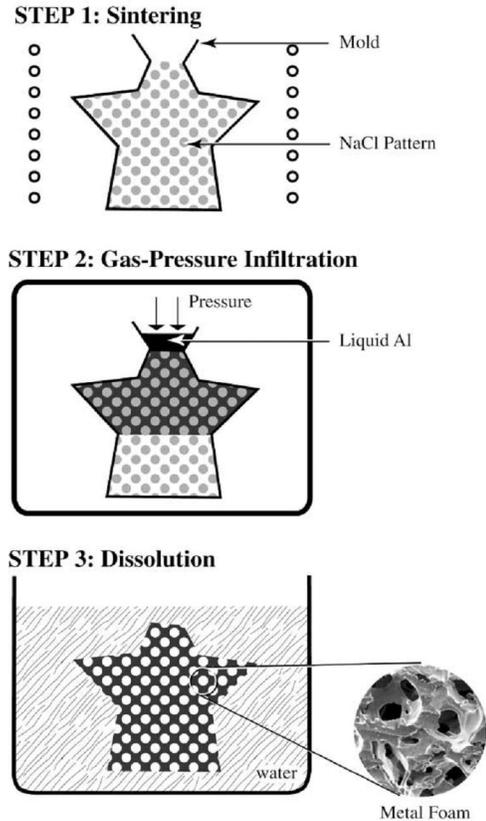


Figure 7. Schematic of the replication process for the production of metallic foam (Marchi and Mortensen, 2001)

a) *Microstructure & Properties*

SEM micrographs of the as-cast foam reveal a uniform architecture that clearly demonstrates the detailed replication of the salt pattern structure (Figure 8).

Facets on the salt can be replicated as well as pits that apparently existed on the salt grains prior to infiltration, possibly as a consequence of thermal etching during sintering (these infiltrated pits become metal protrusions after dissolution of the salt). The foam consists of nonperiodic arrays of struts (or beams) with an hour-glass shape that meets at large irregular nodes. The relative density of the foams is about 0.20-0.27 gr/cm^3 and is difficult to control within this range (although the variation within each

casting is small, being less than 1 vol%). The average density is partially determined by the shape of the salt grains, which, as mentioned, varied somewhat from lot to lot (Marchi and Mortensen, 2001).

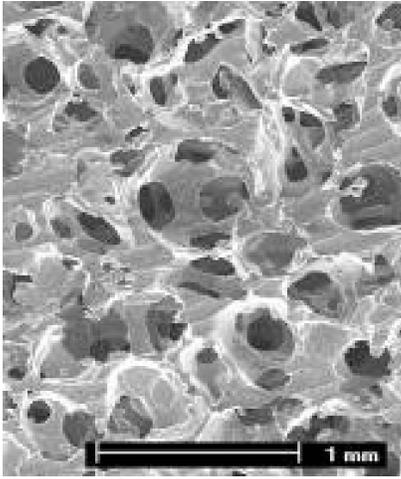


Figure 8. SEM micrograph of pure aluminum foam produced by replication (Marchi & Mortensen, 2001)

b) Advantages & shortcomings of the method

Compared with foaming techniques which require an alloy or slurry that can resist collapse of the foam structure until it solidifies, this method has the advantage that virtually any alloy can be used to produce metal sponges.

2.1.4. Casting methods

2.1.4.1. Investment casting with polymer foams

Investment casting can be used to obtain ordered, highly porous metals called lattice block materials (LBMs) (Lucai *et al.*, 1991). According to this process (Figure 9), a polymer foam, e.g. polyurethane foam, is used as a starting point. If the polymer foam has closed pores, it has to be transformed into an open porous one by a reticulation treatment. The resulting polymer foam with open cells is then filled with a slurry of sufficiently heat resistant material, e.g. a mixture of mullite, phenolic resin and calcium carbonate or simple plaster.

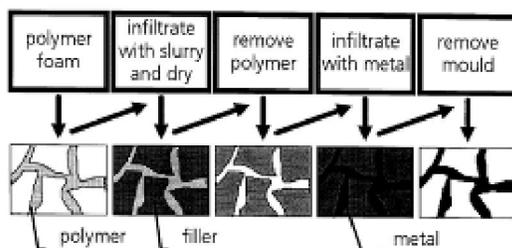


Figure 9. Production of cellular metals by investment casting (Banhart, 2001)

After curing, the polymer foam is removed by thermal treatment and molten metal is cast into the resulting open voids which replicate the original polymer foam structure. Application of pressure and heating of the mould may be necessary if no filling of the narrow cavities with the liquid metal can be achieved in simple gravity casting. After removal of the mould material (e.g. by pressurized water), a metallic structure is obtained which is an exact replicate of the original polymer foam. Such structures can be made from pre-fabricated injection moulded polymer elements in a comparably similar manner by bonding such elements together layer by layer with adhesives. The resulting structure is then used as a model for the following investment casting step which yields a metallic material that represents exactly the highly ordered polymer precursor.

a) Microstructure & Properties

Figure 10 shows a micrograph of a cellular aluminum material made by this technique. Complex shaped parts can be fabricated by pre-forming the polymer foam. Of course, the densities and foam morphologies of the final metal product are determined by the polymer precursor. Porosities typically range from 80 to 97%.

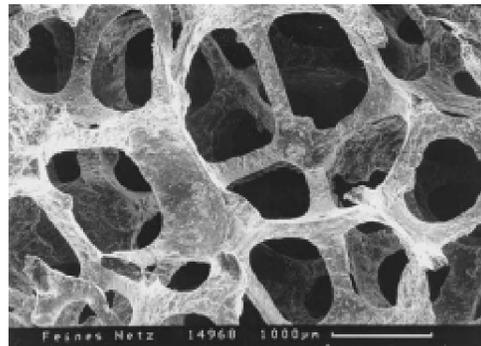


Figure 10. SEM image of Al foam parts made by investment casting (Banhart, 2001)

b) Advantages & shortcomings of the method

The main advantage of these foams are their mechanical properties which are close to the theoretical optimum limit and which are easily predictable and reproducible (Banhart, 2001; Miyoshi *et al.*, 2000; Akseli, 2005; Duarte and Banhart, 2000; Friedrich *et al.*, 2003; Leitmeier *et al.*, 2002; Garcia-Moreno *et al.*, 2005; Lucai *et al.*, 1991).

Difficulties in this process include achieving a complete filling of the mould (Figure 9).

2.1.4.2. Casting around space holder materials

Light-weight porous metals can be produced by casting liquid metal around inorganic or even

organic granules or hollow spheres of low density, or by introducing such materials into a metallic melt. The granules might remain in the metallic product after casting (a syntactic foam) or can be removed via thermal treatment, leaching in suitable solvents/acids, etc.(see Figure 11).

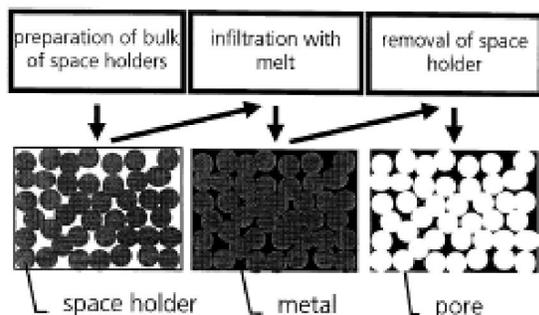


Figure 11. Production of cellular metallic materials using space-holding fillers (Banhart, 2001)

This can be done successfully if the content of space holding fillers is so high that all the granules are interconnected. Vermiculite or fired clay pellets, soluble salts, loose bulks of expanded clay granules, sand pellets, foamed glass spheres or aluminum oxide hollow spheres can serve as inorganic filler material. But, commercially available alumina hollow spheres of 2.1–3.6 mm diameter and 100–200 nm wall thickness were used. The spheres were stacked into a steel mould and vibrated to ensure a high packing density. Polymer spheres can be used as organic space holders if the solidification of the melt is sufficiently fast. The latter requires high pressure infiltration, e.g., in a die-casting machine. Pre-heating of the bulk of space holders is usually necessary to avoid premature solidification of the melt, especially when the heat capacity of the bulk is high or infiltration pressure is low. Owing to the high surface tension of liquid metals, wetting of the granules might cause a problem, since; in general, the interstices between the granules will not be filled completely. Creating a vacuum between the granules or pressurizing the melt is therefore an important prerequisite for infiltration. Space-holding salts are removed by leaching in water. Sand pellets can be easily removed if the binder decomposes under the influence of heat, whereas the polymer spheres are brought out by thermal pyrolysis. The structure is very uniform and the foam properties are nearly isotropic. Sandwich panels can also be made. For this, the ceramic spheres are placed into a prefabricated skin structure between two sheets of metal, and are then infiltrated by the melt. The skin is melted at its surface to be able to achieve a metallurgical bond. Alternatively, the skin can be

produced by placing a pre-sintered bulk of hollow spheres into a mould and casting the outer skin structure and the porous core at the same time (Banhart, 2001; Lucai *et al.*, 1991).

a) *Microstructure & Properties*

The Structure of Aluminum foams produced by this method is very uniform and the foam properties are nearly isotropic. Figure 12 shows the microstructure of these foams (Banhart, 2001).

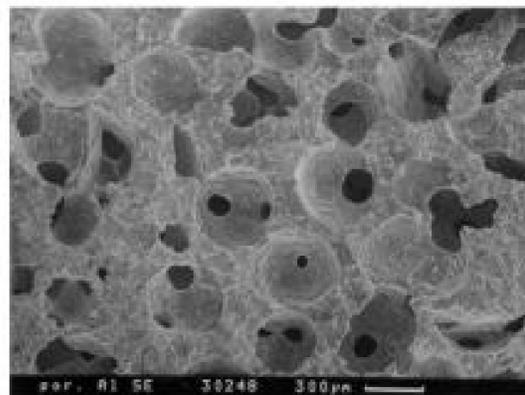


Figure 12. Cellular aluminum material made by using space-holding fillers. Density 1.1 g/cm³.

b) *Advantages & shortcomings of the method*

One of the main advantages of using space holders is the close control of the pore size distribution which is given by the distribution of particle sizes of the filler granules. On the other hand, the maximum porosities which can be achieved using space holders are limited to values below 80%. The filler material has been removed completely in this case and the density is as low as 1.1 g/cm³ (Banhart, 2001; Friedrich *et al.*, 2003; Leitlmeier *et al.*, 2002; Stanzick *et al.*, 2002).

2.2. *Solid state processing*

2.2.1. *Foaming of powder compacts*

The process starts with the mixing of metal powders - elementary metal powders, alloy powders or metal powder blends - with a powdered blowing agent (TiH₂, ZrH₂, less than 1%), after which the mix is compacted to yield a dense, semi-finished product (Figure 13). Therefore, this method is often called powder metallurgical because the starting materials are metal powders (Banhart, 2001; Akseli, 2005; Duarte and Banhart, 2000; Baumgartner *et al.*, 2000; Kunze *et al.*, 1993). Compaction techniques include uni-axial or isostatic compression, rod extrusion or powder rolling, extrusion can be used to produce a bar or plate and helps to break the oxide films at the surfaces of the Al powders. However, extrusion seems to be the most economical method at the

moment and is therefore the preferred way. Foaming agent decomposes and the material expands by the released gas forces during the heating process (at 350°C-450°C) thus a highly porous structure is formed. The precursor material can be processed into sheets, rods, profiles, etc. by conventional techniques. The mixture of powders, metal powder and foaming agent, was cold compacted and extruded to give solid metal material containing a dispersion of powdered foaming agent. When this solid was heated to the metal's melting temperature, the foaming agent decomposes to release gas into the molten metal, creating a metal foam.

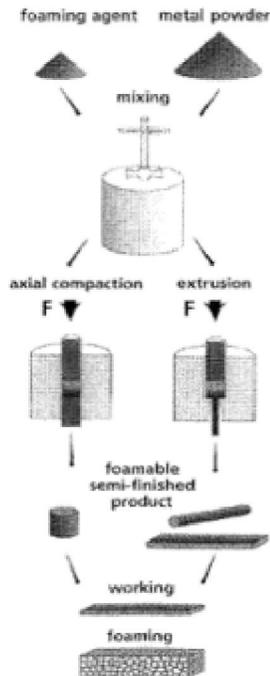


Figure 13. Foaming from powder compacts process (Steiner *et al.*, 1997)

a) *Microstructure & Properties*

The foam has a closed-cell structure with pore diameters in the range of 1 mm to 5 mm and the process is called baking. Figure 14 shows expansion curves of an aluminium/TiH₂ powder compact. In this Figure the volume of a metal sample as a function of time and images of four different expansions (including the unexpanded precursor which is 9 mm in height and 32 mm in diameter) are shown. An expansion maximum is shown which corresponds to fairly uniform foam morphology, after which the foam collapses. The degree of maximum expansion, and therefore, the density of the solid metal foam, can be controlled by adjusting the content of blowing agent and several other foaming parameters, such as

temperature and heating rates (Banhart, 2001; Akseli, 2005; Kunze *et al.*, 1993; Rossella, 2007).

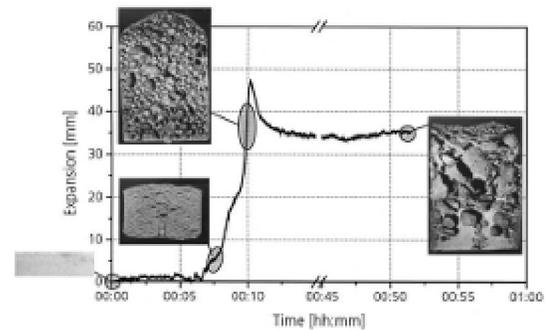


Figure 14. Expansion behavior of aluminium/TiH₂ compacts when foamed at 750 °C (Banhart, 2001)

b) *Advantages & shortcomings of the method*

The manufacturing process of the precursor has to be carried out very carefully because residual porosity or other defects will lead to poor results during further processing (Banhart, 2001).

During powder compacts process, cooling the foam is a problem since after heating the precursor for foaming; the heat source could be turned off quickly. However, the metal would still be hot, and is prone to collapsing back into molten metal before it solidifies. Water-cooling or heating the foam only locally may avoid this problem; however the problem may become a significant challenge for the reliable foam production (Banhart, 2001; Akseli, 2005).

2.2.2. *Sintering of metal powders and fibers*

Wet powder spraying consists of spraying fine powder/binder slurries containing a carrier liquid onto a porous support, then drying and diffusion bonding this coating in a vacuum or under a hydrogen atmosphere. In this way, very fine porosities down to 1 mm can be achieved. Making porous metals from aluminum alloy powders or granules is more difficult than using the other metals because aluminum is usually covered by a dense oxide layer which prevents the particles from sintering together. To circumvent this problem, one may deform the mixture of powders or granules during pressing to break up the oxide films and to create metallic bonding between the particles. Alternatively, sintering aids may be employed such as copper, silicon or magnesium powders that form a low melting eutectic alloy during sintering at 595–625 °C (Banhart, 2001). For pressureless sintering the aluminum granules and the sintering aids can be milled to initiate mechanically induced alloying processes prior to sintering. Replacing powders by

metal fibers opens new possibilities for making porous metal structures (Banhart, 2001; Friedrich *et al.*, 2003; Leitmeier *et al.*, 2002; Stanzick *et al.*, 2002).

2.2.3. Foaming of slurries

Metallic foams can also be produced by preparing a slurry of metal powders, blowing agents and some reactive additives. The slurry is poured into a mould after mixing and left there at elevated temperatures. Under the influence of the additives and the blowing agent, the slurry turns viscous and starts to expand as gas begins to evolve. If sufficient stabilizing measures have been taken, the expanded slurry can be preserved and dried completely after which it is sintered to yield a metal foam with considerable strength. Foams have been produced from aluminum powders using orthophosphoric acid with aluminum hydroxide or hydrochloric acid as a blowing agent. Relative densities down to 7% have been achieved. Still, problems with insufficient strength and cracks in the foamed material may occur (Banhart, 2001; Friedrich *et al.*, 2003; Leitmeier *et al.*, 2002).

The two last methods are not used commercially, so details aren't noted

2.2.4. Sintering-dissolution process

The sintering-dissolution process (SDP) consists of the mixing, compacting, sintering and dissolution stages as shown schematically in Figure 15. The raw materials are Al and NaCl powders. The particle sizes of the Al powder are not critical but generally required to be smaller than 1 mm (Surace *et al.*, 2009). The particle sizes of the NaCl powder depend on the intended pore sizes of the final foam. The Al powder is first mixed thoroughly with the NaCl powder at a pre-specified volume or weight ratio. The resultant Al/NaCl powder mixture is compacted into a net-shape pre-form under an appropriate pressure. The pre-form is then sintered at a temperature either above or below the melting point of Al (660 °C) but far below that of NaCl (801 °C) (Zhao and Sun, 2001).

After the Al in the pre-form forms a well-bonded networked structure, the pre-form is cooled to room temperature. The imbedded NaCl particles are finally dissolved in water, leaving behind an open cell Al foam with the same chemical composition as that of the original Al powder. In manufacturing the Al foam, a commercial purity gas atomised Al powder with particle sizes below 450 mm and a commercial purity NaCl powder with nodular particles and particle sizes of 300-1000 mm are used. The two powders are mixed thoroughly at different weight ratios with the Al weight fractions in the

range 0.20–0.75. The mixtures are compacted into pre-forms in steel moulds using a hydraulic press with a pressure typically of 200 MPa. The pre-forms, together with the moulds, are sintered in an electric furnace at 680°C for 180 min and are then allowed to cool to the room temperature. The sintered specimens are removed from the moulds and placed into a warm, running water stream for 45 min to dissolve the NaCl particles embedded in the Al matrices (Zhao and Sun, 2001).

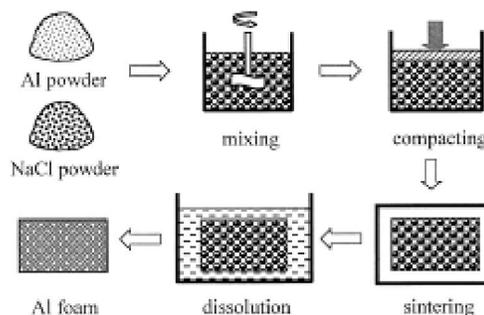


Figure 15. Schematic of the sintering-dissolution process for manufacturing Al foams (Zhao and Sun, 2001)

a) Microstructure & Properties

Figure 16 shows the SEM micrograph of typical Al foam with an Al weight fraction in the initial Al/NaCl pre-form of 0.2. The foam has a homogeneous structure with open pores and pore sizes in the range 300-1000 mm, which represent the particle characteristics of the original NaCl powder. It is demonstrated that the morphology and sizes of the pores in the foam can be easily controlled by selecting an appropriate NaCl powder. It is also possible to obtain a purposely tailored distribution of pore size or relative density in the foam by using NaCl powders with different particle size ranges or by varying the local Al weight fraction in the Al/NaCl pre-form (Friedrich *et al.*, 2003; Zhao and Sun, 2001).

b) Advantages & shortcomings of the method

Foams based on powder mixes of aluminum alloys with sodium chloride have

successfully been made in large sections with uniform structures. The resulting cell shapes differ markedly from those of foams made by other methods. In practice the method is limited to producing materials with relative densities between 0.3 and 0.5. The cell size is determined by the powder particle size and lies in the range 10 μm to 10 mm (Ashby *et al.*, 2000).

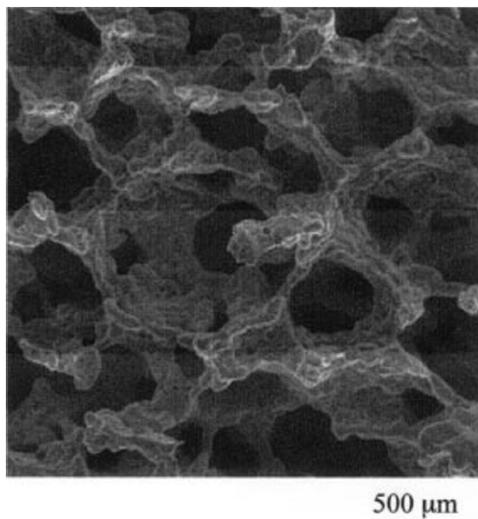


Figure 16. SEM micrograph of a typical Al foam manufactured by SDP (Zhao and Sun, 2001)

3. Conclusions

Aluminum foams have received a considerable amount of attention in recent years because of their extremely low density and unique functional properties such as impacting energy absorption, sound absorption, flame resistance and heat resistance. Many methods for their manufacture were developed. Among these methods the processes are of great importance for the production of aluminum foams, which are basing on the use of a foaming agent. Instead of foaming agents inert gases can be directly entrapped in the precursor. All these manufacturing routes have their own relative densities and cell structures. Open and closed pore morphologies and relative densities ranging from 50 to 98% can be achieved. There are a variety of ways to produce open-celled aluminum foams, in which investment casting, pre-form infiltration and SDP are the most widely used routes. Other methods such as; Alcan, Alporas and gasar are the most widely used to produce closed-celled aluminum foams. With a rapidly increasing demand for high quality Al foams, there has been a growing need for developing other cost effective manufacture technologies. There are many factors influencing aluminum foam properties. A key point is the use of an appropriate blowing agent which releases gas at the right temperature to ensure high expansion and the formation of a uniform porosity.

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