

16 Production of Metal Foams

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Abstract

Metal foams are produced by creating a multitude of gas-filled bubbles in a metallic melt and allowing these to agglomerate, after which the liquid is solidified to a solid foam. There are different ways to form such foams, differing by the type of gas source, the state of metal used (solid or liquid), the way the bubbles are stabilized and by the procedures applied. Besides the common aluminium alloys, a range of metals and alloys can be processed to foams. This chapter will review the most important production methods for metal foams and explain the background of each method.

Keywords

- Aluminium alloy
- Blowing agent
- Bubbles
- Cell walls
- Foam
- Gas injection
- Magnesium alloy
- Particles
- Powder
- Stability
- Titanium hydride

16.1 Introduction

Most natural materials are not dense but contain gas-filled voids. The volume fraction of the gas phase can by far exceed that of the solid phase in which case one speaks of cellular, spongy or foamy materials. What makes such materials interesting are some unique combinations of properties. The materials are light and possess high specific surfaces, while they are stiff and strong.

Metals can also be processed to cellular structures and metal foams are one special case. What makes metal foams special is that they always contain solid particles owing to the requirement of stabilisation during foaming. Particles embedded in metal matrix composites are known to improve their Young's modulus, strength, thermal conductivity or wear properties and this is the reason why they are added. Metal foams are a very special use of metal/particle composites since the main function of the particles is to modify the properties of a metallic melt and allow for processing it into a metal foam. In this respect, metal foams are composites on two levels: the solid matrix is a composite of a metal (or alloy) with a second type of solid while the entire foam is an air/metal composite. Therefore, this chapter presents a very special aspect of MMC technology.

16.2 Definition of Foams and Classification of Production Processes

A foam is a dispersion of gas-filled bubbles in a liquid. It is typically disordered with its internal local arrangements conforming to the so-called Plateau rules dictated by surface tension. Those rules

require that only three of the thin films that separate bubbles can meet on a line (called a Plateau border), and only four of those lines can meet at a point. Films and lines meet symmetrically, at equal angles. As these rules strictly apply only in the limit of zero liquid fraction and the liquids in real foams (especially metallic ones) are not ideal, deviations occur. Many liquids may form a foam, including aqueous liquids, liquid polymers or metallic melts. A solid foam is obtained from a liquid one by solidification. Except for some changes during solidification the solid foams inherits the structure of its liquid precursor.

What should not be called 'foam' are cellular structures not generated via a liquid foam. Engineered structures (e.g. welded wire structures), sintered metal powders or hollow spheres or replicated polymer foams are different materials. Some of them shall be described in **Chapter 17**. A recent review describes some of them (Garcia-Moreno 2016).

Metals can be foamed in many different ways. The different processing variants are classified for the sake of clarity. Various classifications have been proposed:

1. Distinction according to whether metallic melts or powders are used as starting materials (Gergely, Degischer et al. 2000; Körner and Singer 2000; Banhart 2001)
2. Distinction between direct foaming and indirect foaming (Banhart 2013)
3. Emphasising the different modes of bubble formation, internal vs. external (Babcsán and Banhart 2006)
4. Defining the type of melt used, i.e. melt stabilised with different kinds of particles (Babcsán and Banhart 2006)

We shall chose a combination of 1., 2. and 3. here as outlined in **Figure 1**. *Direct foaming* means that gas is generated in a melt and foam is generated continuously. Indirect foaming is a two-stage process, the first stage involving the preparation of a solid precursor that has the capacity of expanding in a second step that involves melting of the precursor. *External bubble formation* is the injection of gas a certain defined entry points such as by injection lances. *Internal bubble formation* takes place in the bulk of the foaming liquid at random points. Finally, whether liquid metal or powdered metal is used in the process defines another difference.



16.3 Direct Foaming of Metallic Liquids

16.3.1 Foaming by Gas Injection

16.3.1.1 General Characteristics of Technique

The most straightforward method to produce metal foam is to inject gas from an external source through a nozzle into a metallic melt. This was first suggested by A. De Meller (De Meller 1926) and was later elaborated in the USA (Fiedler 1965). The former author proposes using inert gas, the latter oxygen or steam as blowing gas, but it is doubtful whether metal foam has ever been produced in this way since no measures for stabilising the foam are mentioned. The first working versions of the process were developed by researchers of the Aluminum Company of Canada (Alcan) (Jin, Kenny et al. 1990) and of the Norwegian Norsk Hydro Company (Ruch and Kirkevåg 1994). Both applied essentially the same foaming method.



The basic layout of the process is given in **Figure 2a**. Gas is injected to below the surface of a melt containing ceramic particles and bubbles are formed that float to the top, accumulate there and form a metal foam layer. The particles dispersed in the liquid act as stabilisers. They adhere to the gas/metal interfaces of the rising bubbles. Without them, the bubbles burst as soon as they reach the surface or merge with other bubbles. There is a minimum content of particles required for stability that depends on particle size (schematically visualised in **Figure 2b**) and also on the distance between the injection point and the surface: (Ip, Wang et al. 1999; Leitmeier, Degischer et al. 2002), see **Figure 2c**. The larger the particles are, the higher the particle volume fraction required. The larger the immersion depth of the injector is, the lower the necessary volume fraction. The foam layer forming on the melt surface can be drawn off continuously to form long slabs of foam as shown in **Figure 2a**.

16.3.1.2 Typical Process Parameters

Typical processing parameters are related to the particle type (usually SiC or Al₂O₃ are used), particle size (commonly 15 µm), composition of blowing gas (normally air), suitable alloys (often A356=AlSi7Mg alloy), melt temperature (typically, first 710 °C then decreasing to 650 °C), the distance between the gas injection point and the surface, varying from 50 mm (Jin, Kenny et al. 1990) to 300 mm (Linke, Jungk et al. 1992).

16.3.1.3 Gas Injection

Gas injection can be done by a rotatable air injection shaft connected to a number of outlet nozzles through which the gas escapes into the liquid. The cell size of the foam is said to be controlled by the gas flow rate and other parameters (Jin, Kenny et al. 1990). Beside the gas injection shaft shown in **Figure 2a**, use of a rotating shaft equipped with various blades is suggested. It creates a strong vortex through which gas is dragged into the liquid to form additional bubbles there (Jin, Kenny et al. 1992). Dispersing bubbles by means of vibrating or rotating impellers was initially believed to be a prerequisite for good foam. Improved designs were suggested such as using porous frits to disperse gas more uniformly, to use mechanical choppers or stirrers to assist in detaching the gas bubbles from the injector or to create diverging gas jets (Linke, Jungk et al. 1992). In practice, operating such impellers is not easy and sealing can be a challenge (Nichol and Manley 2009). Research carried out at the Light-Metals Competence Centre (LKR) in Ranshofen (Austria) showed that some of the ideas behind the impeller concepts are misleading. In order to obtain a uniform foam it is more favourable to carefully create and maintain individual equally sized bubbles instead of producing a statistical mixture by the techniques mentioned above. It was proposed to use specially designed stationary injectors made of a ceramic material that have a defined conical geometry instead of applying vibrating or oscillating nozzles or vortices (Dobesberger, Flankl et al. 2007). The new nozzle design provides stable bubble separation criteria and allows one to make foam with a plurality of bubbles of approximately the same volume. The key point is that the detachment of a bubble from a nozzle after it has been filled with gas often takes place at different filling stages for each bubble because the detachment conditions are irreproducible, i.e. different for each bubble, when mechanical agitation is applied to the melt. The result of the efforts is a clearly improved pore uniformity compared to foams made by 'traditional' gas injection techniques. **Figure 3a,b** shows such optimised foams. The foam not only looks more regular than previous ones but also has a narrower measured bubble size distribution.



The interdependence of bubble generation parameters such as gas flow rate and pressure and orifice diameter has been studied (Liu, Li et al. 2015; Yuan, Li et al. 2016). Different parameters lead to different cell morphologies and sizes, see [Figure 4](#).



Bubble injection can be further improved by using the defined injection points as describe above but also applying translational or vibrational movements to the injector to facilitate bubble detachment and to create smaller bubbles (Garcia-Moreno, Siegel et al. 2015). This principle has now been transferred to small-scale industrial production (Babcsan, Beke et al. 2012; Babcsan, Beke et al. 2014). The corresponding parts feature very small pores, see [Figure. 3c](#).

16.3.1.4 Influence of Oxygen

Oxygen plays an important role in the blowing process (Babcsán, Leitlmeier et al. 2003; Babcsán, Leitlmeier et al. 2004; Babcsán, Garcia-Moreno et al. 2006). Blowing with pure argon leads to markedly increased bubble coalescence and drainage. Oxidation of the inner surfaces of the bubbles during blowing is essential for foam stability. Oxidation of the inner bubble surface has been studied in detail (Zhou and Li 2015; Zhou and Li 2015) and its role discussed (Zhou, Li et al. 2015). By tracking individual SiC particles flowing through a vertically arranged liquid film and analysing their interaction with the oxidised surfaces of the metallic film it was shown that stabilisation of this type of foam is caused by at least two mechanisms, by the segregation of particles to the gas/metal interfaces and by the oxide films that cover the interfaces and pin the particles (Heim, Vinod-Kumar et al. 2015). However, some fundamental questions concerning the stabilisation mechanisms are still open (Haibel, Rack et al. 2006).

16.3.1.5 Shaping of Foams

The technologies described so far are mainly designed for making flat products. Manufacture of foam components with a complex 3D shape is also desirable. Pressing a liquid foam into a mould is the easiest way of shaping, (Kenny and Thomas 1994) but damage of the fragile films in the liquid state is a problem (Nichol 2006). This problem can be avoided by allowing a metal foam to be generated directly inside a mould, e.g. by using an open mould that is immersed into the melt to be foamed and then bubbling gas into the melt and let the bubbles fill the mould without the need for any shaping (Åsholt and Tokle 2005). One version of this mould-filling process comprises pressing molten metal into a die through an opening in the bottom die wall by applying a low external gas pressure and then filling the mould with foam by bubbling air through the melt during which the melt is drained off by controlling the gas pressure (Nichol, Killingbeck et al. 2005). In general, the outer surface of such shaped metal foam parts will have the thickness of an individual film within the foam, i.e. be very (too) thin. A procedure to overcome this limitation has been suggested (Dobesberger, Flankl et al. 2006): The opening of a mould pointing downwards is first brought into contact with the meniscus of the melt to be foamed. By pushing the melt first up into the mould and then down again by controlling the external gas pressure, a dense outer skin is created in the mould because its inner walls are kept cold enough to solidify a thin skin of metal. After this and without an interruption, gas is sparged through the melt and bubbles are allowed to slide into the mould in a gentle way without exerting mechanical forces and bonding to the previously formed skin. The resulting parts, see [Figure. 3b](#),

have a very uniform thick skin and a regular pore structure. Such parts are used as cores for low-pressure die casting, during which the foamed core is completely embedded in a dense casting (Leitmeier, Degischer et al. 2002).

16.3.1.6 New Directions

Another activity is directed towards overcoming the need for using expensive and brittle materials such as MMCs for foaming, while still using the gas injection principle. One approach is to combine the material used for the 'Alporas' process (e.g. Al melts thickened by adding Ca and stirring in the presence of oxygen, see Sec. 16.3.2) and the gas injection principle of this section. Air was blown through a variety of different melts including an 'Alporas'-type melt containing 3% Ca and it was found that foaming is inferior to the foaming of MMC melts. (Babcsán, Garcia-Moreno et al. 2007). In other words, 'Alporas-type' melts are not as easy to foam by gas injection through an injector as by addition of TiH_2 powder. However, by carefully tuning the thickening conditions it might be possible to make such foams and one embodiment of a process has been disclosed in a patent. (Hur, Cho et al. 2005) Thickening is carried out in one heated vessel here, after which the thickened melt is transferred to a foaming vessel where gas is injected and the foam floating up to the surface is continuously removed.

16.3.2 Foaming by Decomposition of Blowing Agents

16.3.2.1 General Characteristics of Technique

Instead of injecting gas into a melt a gas-releasing blowing agent can be added (De Meller 1926). The idea is simple: a compound that releases gas at the temperature at which the molten metal is held is dispersed in the melt and allowed to release gas there. The gas nucleates in bubbles that grow and eventually create an assembly of bubbles of a volume higher than the original melt. The first attempts to make aluminium foam in this way were undertaken at the Bjorksten Research Laboratories (BRL) (Elliott 1956). TiH_2 or ZrH_2 were used as blowing agents and mainly a range of Al-Mg alloys foamed.

16.3.2.2 Aluminium Foam Stabilisation

Foams at that time had to be cooled quickly after foaming (Elliott 1956; Elliott 1961), indicating that foam stability was an issue, possibly leading to non-uniform pore sizes and a limitation of production to small foam components. It was realised that in order to make liquid foams more stable appropriate measures had to be taken. Only in a second step could the added blowing agent create stable foam.

To achieve foam stability many methods have been suggested: (i) Dispersing a finely divided, wetted inert powder in the molten metal which remains solid there (Ridgway 1967). Particles should have diameters ranging from 20% to 50% of the metal film thickness, (ii) Addition of MnO_2 to the aluminium alloy melt. This leads to the formation of alumina particles that are dispersed in the melt. (Graper 1968; Han, Zhu et al. 1998; Han, Wei et al. 2003), (iii) Thickening the metallic melts to be foamed by sparging oxygen, air or CO_2 through them (Berry 1972). For example, a liquid AlMg7 alloy is treated by bubbling oxygen through a melt while running an agitator. Oxide particles are formed in the melt in-situ due to this treatment. (iv) Adding to a melt prior to foaming either 2–6 wt.% (or more) dross collected from surfaces of molten alloys (Berry 1972) or recycled Al with a high oxide content (Yang, Chueh et al. 1997). This stabilises the foam generated via the oxides contained in the dross, (v) Adding 3-5% Al powder, after which the mixture is stirred until viscosity has increased to 1.7 times the original value (Yang and Nakae 2000; Yang and Nakae 2003; Zhao, Zhang et al. 2011), (vi) Dispersing Cu-coated carbon fibres (Cao, Du et al. 2010), AlN particles (Song, Tane et al. 2010), fine fly ash particles (Mondal, Goel et al. 2009) or scrap swarf chips (Kumar, Heim et al.

2013; Kumar, Garcia-Moreno et al. 2015) in the alloy matrix has been reported to stabilise foams, (vii) Creating nanoparticles in a melt by an in-situ reaction instead of adding them. Such reactions are also used to make grain refiners in a melt and it is shown that such melts can indeed be foamed (Babcsán, Vinod-Kumar et al. 2007; Babcsán, Vinod Kumar et al. 2008; Atturan, Nandam et al. 2016). Another in-situ reaction produces sub- μm spinel particles in a AlMg5 melt to which SiO_2 has been added (Kumar, Chakraborty et al. 2011). 3.4 vol.% of such spinel particles have been found to be sufficient for efficient foam stabilisation, (viii) Dispersing a ball-heimmilled mixture of Al powder and multi-walled carbon nanotubes (Zhang, Ding et al. 2015).

Current foam production is mostly based on procedures developed by The Shinko Wire Co. Ltd., Osaka, Japan, a subsidiary of Kobe Steel (Akiyama, Ueno et al. 1987; Akiyama, Ueno et al. 1989), also known as 'Alporas' technique. Here, 1.5% metallic calcium (Miyoshi, Itoh et al. 1998) is added to molten aluminium alloy at 680 °C (Miyoshi, Itoh et al. 1998) or 720 °C (Akiyama, Ueno et al. 1989), after which the melt is stirred for several minutes, e.g. 6 min (Miyoshi, Itoh et al. 1998) at ambient atmosphere. During stirring the viscosity increases (Ma and Song 1998; Miyoshi, Itoh et al. 1998). The patent and subsequent publications do not emphasise that thickening is caused by the contact of the melt with air but it should be understood that oxidation causes the formation of particles that are crucial for foam stability. The structure of the products is complex and depends on the Ca content (Nayebi, Bahmani et al. 2016).

16.3.2.3 Foaming

After melt conditioning, the next step is the addition of a blowing agent which propels foaming. The procedure applied by the Shinko Wire Co. involves pouring the thickened melt into a foaming vessel after a predefined level of viscosity has been reached and admixing 1.6% TiH_2 while stirring continues at 680 °C for some time (Miyoshi, Itoh et al. 1998; Miyoshi, Itoh et al. 2000). After this, the melt is left for foaming for ~15 min (Miyoshi, Itoh et al. 1998). As soon as the foam has filled the foaming vessel the gas vents of the vessel are closed. The associated pressure increase is described as crucial for obtaining a uniform bubble size distribution especially near the foam surface (Akiyama, Ueno et al. 1987; Akiyama, Ueno et al. 1989). Cooling the foam is done by air blowing. A typical foam made by the 'Alporas' technique is shown in **Figure. 5**. Cell sizes of 'Alporas' vary from 2 mm to 10 mm with a mean of ~5 mm (Miyoshi, Itoh et al. 1998).



Carbonates have been suggested as a replacement of TiH_2 for reasons of safety and cost. The possibility of using CaCO_3 in the standard 'Alporas' process has been demonstrated for the alloy AlSi7Mg. Reasonable results are obtained for CaCO_3 powders containing a chemical CaF_2 conversion layer on the surfaces of the powder particles which improves wetting by the melt (Nakamura, Gnyloskurenko et al. 2002).

The 'Alporas' process was further developed by The Aluminum Company of America (Alcoa) (Bryant, Crowley et al. 2008; Bryant, Kallivayalil et al. 2008). Here, 2 – 8% CaCO_3 are used as a blowing agent. CaCO_3 not only liberates the blowing gas CO_2 and leaves behind CaO , but CO_2 also reacts with the Al-Mg-Si alloy and forms stabilising alumina, magnesia, carbide and other particles. As a result, the molten alloy can be turned into a foamable suspension by intense mixing and stirring. In this way, thickening and blowing can be combined in a clever way into an integrated process and AlSi7Mg2 alloys with very fine pores have been created, see **Figure. 6**. The process can be extended

to a continuous casting process for sheets unlike most other Alporas-type foaming routes that convert a fixed batch of liquid into a block of foam.



Melts can also be foamed without adding any blowing agent powder as shown for magnesium. The idea is to melt under normal ambient pressure pieces of scrap left over from Mg die casting and, after melting, to evacuate the recipient containing the melt (Renger and Kaufmann 2005; Kretz, Renger et al. 2008)- As the scrap contains plenty of oxides, hydroxides and other impurities, stabilisation is guaranteed, while the gases adsorbed to the scrap or bound as hydroxides blow the foam as they are expanded by the pressure drop. In a certain sense, these impurities in the melt are both the stabilisers and the blowing agent with the difference that they are contained in the starting melt already and do not have to be added.

16.3.2.4 Metals Other Than Aluminium

Beside aluminium, magnesium alloys have been in the focus of attention already in early work (Ridgway 1967). The vacuum foaming method described in the previous paragraph shows that such foams can be made from melts. The 'Alporas' process can be directly generalised to make pure Mg, (Yang, Hur et al. 2008) alloy AZ91 or AZ31 (Mg-Al-Zn) foams (Seo, Jeong et al. 2008; Wei, Zhao et al. 2012). Ca metal is again used for melt treatment (2% wt.% (Seo, Jeong et al. 2008) or 6 wt.% (Wei, Zhao et al. 2012)), but TiH_2 is replaced by $CaCO_3$ as the blowing agent. The resulting foams have porosities up to 72% and pore sizes around 2 mm (Seo, Jeong et al. 2008). Their pore uniformities and properties are claimed to be superior to those of Al foams (Yang, Yang et al. 2010). TiH_2 is found not to be a suitable blowing agent for Mg alloys as neither an AZ91 nor AM60 alloy stabilised with Ca or SiC addition exhibits satisfactory foaming (Park, Song et al. 2006). In another variant of foaming, Mg-12 wt.%Al-3 wt.%Ca alloy is processed: First SiC particles are added to stabilise the foam that is created by admixing $MgCO_3$ (Luo, Zhang et al. 2013; Huang, Luo et al. 2016)

Pure zinc has been foamed with TiH_2 as a blowing agent (Thornton and Magee 1975). Zinc-based ZnAl22 foams stabilised with SiC were blown with TiH_2 (Ishikawa, Sekido et al. 2012; Sekido, Ishikawa et al. 2012) and $CaCO_3$ (Yu, Liu et al. 2007). Sufficient foamability is reported even without the need for melt conditioning (Yu, Liu et al. 2007; Sekido, Ishikawa et al. 2012). The foams blown with $CaCO_3$ have small pores (of the order of 2 mm) and porosities up to 92%. It is very likely that the blowing agent particles act as foam stabiliser in non-conditioned melts, i.e. they have a dual function, blowing and stabilising. By adding a preform consisting of a compacted blend of milled ZnAl22, SiC and $CaCO_3$ powders to a ZnAl22 melt, stirring the mixture and foaming, reinforced Zn-base foams are manufactured in a slightly modified way (Yu, Liu et al. 2007). Lead-zinc alloys have been foamed with 1.5 to 5% Zn (thickened with CO_2 gas, foamed with TiH_2) (Niebylski and Jarema 1974).

16.3.2.5 Shaping of Foams

Processing foams into practical shapes by foaming inside complex moulds or filling moulds with foam has been investigated (Jarema and Niebylski 1973) (Masuda and Kanbayashi 1996; Miyoshi, Nishi et al. 2006). For example, melt can be poured into a mould after the addition of TiH_2 just before the expansion process sets in. However, 'Alporas' foam is mostly known as a product obtained by

slicing large slabs of foam (typical batch size = 2050×650×450 mm³, mass = 160 kg) into thin sheets. (Miyoshi, Itoh et al. 1998)

16.3.2.6 Fast Foaming

Stabilisation is necessary for retarding degradation processes such as coalescence during foaming until the foam solidifies. The faster foaming can be carried out the less pronounced such degradation processes and the less difficult stabilisation will be. Already early researchers realised this (Elliott 1956). Both the University of Erlangen, Germany, on one side (Körner, Hirschmann et al. 2005) and the manufacturers of MgH₂, Goldschmidt GmbH in Essen, Germany, and of die casting machines, Bühler Druckguss GmbH, Uzwil, Switzerland, on the other (Niedermann, Knott et al. 2005) suggested to inject a melt into the mould of a die casting machine and to add a blowing agent powder shortly before the melt reaches the die. The parameters were set in a way that the melt that is intimately mixed with the blowing agent powder can expand and forms a foam component in the mould, see [Figure 7a](#).



The University of Erlangen presents Al and Mg foams: Thixomolding or cold chamber die casting machines are used to foam Mg alloys (Hirschmann, Körner et al. 2005; Hirschmann, Körner et al. 2007), die casting machines to foam Al alloys (Hartmann, Trepper et al. 2011). The blowing agent is MgH₂ in both cases. The resulting foams have a dense skin due to the solidification conditions in the die. One such sample is shown in [Figure 7b](#) and demonstrates that structural foams with a closed skin can be produced. More details of the high pressure integral foam moulding technique are discussed in the literature (Wiehler, Heinel et al. 2008; Wiehler, Körner et al. 2008). It has become possible to manufacture integral foams with pore sizes well below 1 mm (Hartmann, Trepper et al. 2011). No stabilizing particles are added unlike in the slow foaming processes discussed previously. The very short processing times and some self-stabilisation of the melt in the semisolid range ('endogeneous stabilisation') (Körner, Hirschmann et al. 2004; Hartmann, Trepper et al. 2011) can be assumed to be the reason for temporary stability.

16.3.3 Foaming by Release of Dissolved Gas

16.3.3.1 General Characteristics of Technique

Liquid metals can dissolve gas and this gas can be utilised as a source to blow foams. The solubility of many gases in metals is highly temperature dependent and shows abrupt changes at temperatures where phase transformations occur, e.g. at the melting point. Moreover, the solubility is pressure dependent according to Sievert's law. Therefore, if one charges a metallic melt with gas and solidifies it, possibly accompanied by a pressure drop, gas will precipitate and trigger foam formation.

16.3.3.2 Foaming through pressure control

At ambient pressure (1 bar) the solubility of hydrogen in aluminium drops by more than one order of magnitude at the solidification temperature (660 °C). This is more than for other elements such as Cu, Mg, Fe etc., but the absolute value of solubility is low. In order to blow foams with high porosity (e.g. >75%), the volume of the available gas has to be augmented by producing a pressure drop. This has been demonstrated for Al, AlMg5 and AlSi9Mg5 alloys: (Vinod Kumar, Garcia Moreno et al. 2011; Vinod Kumar, Mukherjee et al. 2013). Melt charged with hydrogen is cast into a crucible in which during solidification the gas pressure is reduced from 1 bar to a few mbar. Even for pure Al a foam

with 80% porosity can be obtained without adding stabilising particles. Additional stabilisation of the melt, e.g. by adding 5% SiO₂ particles, further improves stability and yields a more uniform distribution of smaller cells. Note that the process described here bears similarities with the one introduced in Sec. **16.3.2.3**.

16.3.3.3 Gas-eutectic decomposition

A different class of materials can be obtained by releasing gas from a gas-charged melt during solidification in a controlled way. Instead of allowing a free mixture of bubbles to be generated as described in the previous paragraph, bubble growth is controlled by directional solidification. If the solidification front is planar and advances along a temperature gradient, an initial pattern of bubbles that have nucleated heterogeneously at the bottom of the container will grow into an array of tubular voids as new gas preferentially nucleates at existing pores, see **Figure 8**. This principle was first discovered by V. Shapovalov (Shapovalov 1993; Shapovalov 1994) and was later further developed by H. Nakajima in Osaka, Japan. The former scientist coined the name ‘Gasar’ for the material, whereas the latter chose the name ‘Lotus Metal’. The variety of metals, alloys and ceramics that can be processed is large. Not only hydrogen, but also nitrogen and oxygen can be used as blowing gases (Nakajima 2007). Among the first successful gasar/lotus materials is Cu (Hyun, Shiota et al. 1999; Hyun, Murakami et al. 2001; Shapovalov and Boyko 2004). Later, Fe, Ni, Ag and brass were processed. In order to increase the available volume of gas that drives pore formation a process variant was designed that uses additional gas liberated from TiH₂ powder that is added to a melt (Nakajima 2008). In this way, the density range can be extended to lower values. Gasars/Lotus structures are foams in the sense of the definition given in the introduction, namely free bubble arrangement in a melt without using a template. It is just the pore morphology that makes them look like a different class of material.



16.4 Foaming of Solid Precursors

Another way to make metal foam is by first preparing a solid metallic precursor that can in a second step be expanded to a foam by thermal treatment (foaming step, foam ‘baking’), see second row in **Figure 1**. Such precursors can be made by processing blends of metal and blowing agent powders. This approach is sometimes also called the ‘powder metallurgical’, the ‘powder compact foaming’ or just the ‘powder’ route. An alternative is to produce such precursors applying casting methods.

16.4.1 Precursors made by powder compaction

16.4.1.1 General characteristics of technique

The idea for this metal foaming technique is very old (Allen, Mote et al. 1963). It comprises mixing metal powder (e.g. aluminium) and a blowing agent (TiH₂, ZrH₂ or CaCO₃), extruding the mixture after an optional cold pre-compaction step and then foaming the extruded precursor by controlled heating to at least the melting point of the metal or alloy. During extrusion, the oxide films around each powder particle are broken and thus good consolidation is achieved. The process was later refined and parameters such as the compaction procedure and temperature of the powders optimised. (Baumeister 1991; Baumeister and Schrader 1992; Baumeister and Schrader 1992)

16.4.1.2 Compaction methods

Uniaxial hot-pressing can also be applied to densify powders sufficiently, but extrusion is more efficient to consolidate larger quantities. For example, mixtures of Al powder, alloying elements and the blowing agent TiH_2 are filled into thin-walled aluminium cylinders. These are preheated to 400°C and inserted into the horizontal extrusion die with a lifting tool, after which they are extruded, mostly to flat plates or rods. Production of foamable precursor by continuous extrusion – sometimes called ‘Conform extrusion’ – has also been developed, aiming at making large quantities of precursor material of small cross section. For this, powder is continuously fed into a channel leading to a rotating wheel (typ. 300 to 600 mm diameter) that conveys the powder to a die opening by frictional transport. During flowing to and through the die opening, the powder is heated up by friction, densified and shaped, e.g. to a wire of typically 9.5 mm diameter at a rate of 20 m/min. Another way to produce foamable alloy is by powder rolling (Baumeister 1993). Powders are filled into flat containers and are then hot rolled and therefore densified in various passes. The container material remains as a dense outer skin. Foamable material of acceptable quality is obtained, but no upscaling effort is known to have been successful up to now.

16.4.1.3 Alloy selection

Beside pure aluminium, various alloys were used to make foams such as Al-Cu (Kunze, Baumeister et al. 1993), Al-Si (Simancík, Degischer et al. 1995; Banhart, Baumeister et al. 1996), Al-Mg (Simancík, Degischer et al. 1995), Al-Si-Cu (Banhart and Baumeister 1998), Al-Mg-Si (Simancík, Degischer et al. 1995; Lehmus, Banhart et al. 2002; Lehmus and Busse 2004; Ota, Kobashi et al. 2006; Helwig, Garcia-Moreno et al. 2011), Al-Mg-Zn (Lehmus, Banhart et al. 2002; Ota, Kobashi et al. 2006) and Al-Sn (Aguirre-Perales, Jung et al. 2012; Aguirre-Perales, Jung et al. 2012) are studied, just to give some examples. It is found that it is neither necessary nor desirable to use prealloyed powders, but that one can mix elemental powders in the appropriate fractions. In this case the soft Al powder facilitates compaction and the process of alloy formation takes place during melting and foaming.

Foaming of aluminium alloys is in the focus of most studies, but metals other than Al are also considered. The transfer of aluminium foaming technology to brass, bronze (Baumeister 1991) and zinc (Banhart, Baumeister et al. 1995; Banhart 1999; Banhart, Bellmann et al. 2001) or superplastic Zn-Al (Kitazono and Takiguchi 2006) merely requires minor adjustments of the hydride content and the pressing and foaming temperatures. Gold can be foamed with TiH_2 as a blowing agent, but only after adding some 2% silicon to lower the melting temperature (Banhart 2008). Pure magnesium initially turns out to be difficult to foam, probably due to problems with compaction or the properties of the oxide layers on the powder particles (Bach, Bormann et al. 2005). Only after adding 33 wt.% Al good foams are obtained (Banhart 1992). Only recently, the conditions under which Mg foams can be made have been elucidated (Neu, Mukherjee et al. 2012). Using CaCO_3 as the blowing agent has been shown to be successful provided that 20% Al are added and compaction of the powder mixtures involves cold pre-compaction, intermediate sintering and final hot pressing (Yang, Hu et al. 2016)

Lead and lead-tin foam can be produced by using lead carbonate as a blowing agent (Banhart, Baumeister et al. 1995; Irretier and Banhart 2005). Using a salt of the metal to be foamed – e.g. PbCO_3 for foaming Pb – is an advantage whenever the absence of metallic impurities in the foam is an issue (Banhart 2002). A lot of effort has been put into the manufacture of iron and steel foam (Kriszt, Falahati et al. 1997; Weber and Knüwer 1997; Yu, Eifert et al. 1998; Kunze and Knüwer 1999; Park and Nutt 2000; Rausch, Weber et al. 2000; Park and Nutt 2001; Rausch and Banhart 2002; Demetriou, Duan et al. 2007). Due to the much higher melting range of steel, different blowing agents are required, e.g. carbonates with a high decomposition temperature. Manufacture of titanium foams

using a gas releasing blowing agent is even more difficult due to the strong reactivity of Ti with all gases and success has been very limited (Rausch, Hartwig et al. 2000; Rausch and Banhart 2002).

16.4.1.4 Non-metallic additives

Metal foams made by expanding compacted powder mixtures owe their stability to the presence of oxides that formed the surfaces of the individual powder particles prior to compaction. Usually, these oxides are sufficient to stabilise the liquid foam. Still, in a number of studies additional powders have been added to the metal-blowing agent mixture with two objectives: (i) to further increase foam stability, (ii) to strengthen the metallic matrix of the foam. Addition include SiC, TiB₂, alumina, yttria and AlN as reviewed recently (Duarte and Ferreira 2016). A special case are multi-walled carbon nanotubes that are added in a special colloidal mixing process and are expected to improve mechanical properties (Duarte, Ventura et al. 2015).

16.4.1.5 Selecting and tailoring the blowing agent

Many gas-releasing blowing agents have been screened for their suitability to foam different metals, including the hydrides of Ti, Zr, Hf, Ca, Sr, Ba, Mg, La and Li, the carbonates of Mg, Ca, Sr, Ba, Li, Pb, Zn and Co and the nitrides of Mn and Cr (Banhart 1992). For foaming aluminium alloys, titanium hydride is still the most used and probably best suited blowing agent. Still, the mismatch between the melting range of most Al alloys and the decomposition range of TiH₂ causes problems because a gas pressure is built up in the precursor during heating before melting sets in. This can give rise to non-spherical and irregularly shaped pores. One possible remedy is to use alloys with a lower melting range that comes closer to the decomposition range of the blowing agent (Lehmhus and Busse 2004; Helwig, Garcia-Moreno et al. 2011). Another possibility is to shift the range of hydrogen release to higher temperatures. One way to do this is to oxidise the TiH₂ powders (Speed 1972; Speed 1976) (Gergely and Clyne 1998; Gergely and Clyne 2000; Kennedy 2002; Kennedy and Lopez 2003; von Zeppelin, Hirscher et al. 2003; Lehmhus and Rausch 2004; Matijašević-Lux, Banhart et al. 2006; Matijašević and Banhart 2006; Lehmhus, Wichmann et al. 2008) (Anfilov, Kuznetsov et al. 2015). The mechanism of hydrogen retardation is complex and linked to the phase transformations in the hydride during decomposition (Malachevsky and D'Ovidio 2006; Jiménez, Garcia-Moreno et al. 2011; Jiménez, Garcia-Moreno et al. 2012; Jiménez, García-Moreno et al. 2012). Other ways to retard hydrogen evolution from include chemical filming (Han, Zhu et al. 1998), coating TiH₂ particles with a thin nickel layer (Proa-Flores and Drew 2008) or using a low melting alloying element such as Sn that encapsulates the TiH₂ particles during early melting of the precursor and leads to a more adapted release of hydrogen (Aguirre-Perales, Jung et al. 2012). The beneficial effect of TiH₂ pretreatment on foaming of powder compacts has been studied (Matijašević and Banhart 2006; Helwig, Garcia-Moreno et al. 2011). The notable effect of the particle size of the blowing agent powder on hydrogen release and foaming behaviour has also been reported (Ibrahim, Körner et al. 2008) (Guo, Ma et al. 2015).

Besides TiH₂, other hydrides were explored. ZrH₂ is an obvious choice (Matijašević, Görke et al. 2006) but does not seem to have an advantage over TiH₂ for foaming Al alloys (Baumgärtner, Duarte et al. 2000). In a recent study, the compounds MBH₄ and MAIH₄, where M=(Li, Na, K), are shown to be possible potent blowing agents for Al foams (Kamm 2011).

In addition to metal hydrides, carbonates have been proposed as blowing agents. Carbonates release CO₂ upon heating and after decomposition leave behind an oxide, unlike hydrides where a metal atom remains that will form an alloy with the matrix. In addition to this, reactions between the gas released

(CO and CO₂) with the liquid aluminium alloy (Gergely, Curran et al. 2003; Bryant, Crowley et al. 2008) give rise to pronounced differences in the foaming characteristics between carbonate and hydride driven foaming. It was found that 1 wt.% of CaCO₃ in addition to 0.5 wt% TiH₂ leads to much higher expansions and very small cells and explain this by the drastically reduced melt mobility, i.e. increased viscosity of the melt, however, without specifying a mechanism (Arnold, Körner et al. 2003). Marble powder and CaCO₃ were used to foam aluminium alloys (Cambroner and Ranninger 2003). Comparing the foaming of 6061 alloy by these two blowing agents to foaming with TiH₂, they find smaller pores for the former than for the latter blowing agents and densities down to 0.53 g/cm³ (Cambroner, Ruiz-Roman et al. 2009). This difference between TiH₂ and CaCO₃ is also reported by other researchers (Byakova, Sirko et al. 2006). Kevorkijan et al. foam pure Al with CaCO₃ and achieve a reasonable foam (Kevorkijan 2010; Kevorkijan, Škapin et al. 2010). Finally, Koizumi et al. compare different blowing agents from the group of carbonates, hydroxides and hydrides and foam an Al-Si-Cu alloy (Koizumi, Kido et al. 2011). A mixture of dolomite and MgCO₃ is found to minimise shrinkage effects that may occur during foaming when just CaCO₃ is used (Koizumi, Kido et al. 2012). The efficiency of dolomite can be improved by mechanochemical activation, i.e. milling in the presence of SiO₂ (Gnyloskurenko, Koizumi et al. 2012).

A recent development is foaming of metals without any of the usual chemical blowing agents. The starting point is the observation that metal powders release gas when they are heated due to the decomposition of reaction products on the powder surfaces, e.g. hydroxides. Compacted aluminium powder not containing any blowing agent was found to expand by as much as 15% when melted due to the liberation of such gases (Banhart, Baumeister et al. 1995). This is far below the level required for a foam at normal pressure but it was found that Al50Mg50 powder has a much larger potential to store and release gas than pure Al. Such powder is used to foam Al-Mg-base alloys made from a mixture of pure Al powder, Al50Mg50 powder and optionally other elemental powders (Mukherjee, Jiménez et al. 2009; Mukherjee, Garcia-Moreno et al. 2010). Very uniform and well expanded foams can be produced.

The phenomenon that aluminium powder surfaces contain adsorbed gases or hydroxides which can act as a gas source upon heating is exploited by a technique called pressure-induced foaming (Garcia-Moreno and Banhart 2007; Garcia-Moreno, Mukherjee et al. 2015). Aluminium powders are compacted and then melted under pressures up to 40 bar. After reaching the liquid state, the pressure is released to 1 bar within a few seconds. This pressure drop triggers expansion of gases contained in the precursor and expands the material so that it eventually grows to a foam.

16.4.1.6 Manufacture of composite structures

Aluminium or steel sections can be filled by foaming a foamable precursor inside the section. Various arrangements of the precursor have been proposed (Yu, Eifert et al. 1998) and foam filling studied (Kobashi, Sato et al. 2006; Garcia-Moreno, Raffaele et al. 2009; Garcia Moreno, Mukherjee et al. 2012). If the sections are made of aluminium alloy, their melting temperature must be higher than the foaming temperature of the foam core alloy to prevent the section from melting, because the section and precursor have to be heated jointly to the foaming temperature. Interdiffusion of alloying elements during foaming can accelerate melting of the sections (Shabestari, Wanderka et al. 2006) and therefore a precise temperature control is mandatory (Banhart and Seeliger 2008). With steel or other higher melting metals, melting is not an issue, but the high temperatures needed to foam aluminium might still deteriorate the mechanical properties of the section or lead to oxidation.

Sandwich parts consisting of a foamed core and dense face sheets can be made by roll-cladding metal sheets to a sheet of foamable precursor and then foaming the composite (Baumeister, Banhart et al. 1994). Aluminium (Banhart, Seeliger et al. 2002), steel (Baumeister 1999) or titanium face sheets can be used. By shaping the roll-clad three-layer precursor before foaming, 3D shapes are obtained (Yu, Eifert et al. 1998; Banhart, Seeliger et al. 2002). Aluminium foam sandwich (AFS) with aluminium face sheets can be obtained in complex geometries such as that of the rear bulkhead of a car (Banhart, Baumeister et al. 1998; Yu, Eifert et al. 1998). The development of AFS technology has been documented in a series of publications (Banhart, Seeliger et al. 2002; Seeliger 2002; Seeliger 2004; Banhart and Seeliger 2008; Banhart and Seeliger 2012).

Precursor manufacture is a crucial step in the manufacture of foams and especially of large AFS sheets. Small defects in the precursor can evolve into large ones such as cavities, cracks etc. in the final foam. This can be demonstrated by deliberately inducing such defects and following foam evolution in-situ with X-ray radiography (Stanzick, Wichmann et al. 2002). It is also found that the compaction conditions such as the atmospheric pressure influence subsequent foaming (Jiménez, Garcia-Moreno et al. 2009). Building on such studies, the industrial fabrication of precursor material has been revised. By carefully degassing the powders and avoiding contaminations the quality of aluminium foam sandwich parts has been notably improved (Banhart and Seeliger 2012) The AFS sample shown in [Figure 9](#) demonstrates foam uniformity over a large area.



Instead of roll-cladding previously densified foamable precursor material to face sheets, direct powder compaction between two face sheets could be an alternative to reduce the number of processing steps (Baumeister 1993; Vatchiants and Manukyan 2003; Vatchiants and Manukyan 2006) (Song, Yao et al. 2011; Zu, Song et al. 2011; Srivastava, Singh et al. 2012) (Wang, Ren et al. 2015). Making large panels in this way will be technologically difficult and feasibility remains to be demonstrated.

Another concept to reinforce metal foams is to integrate wires or meshes into them (Simančík, Lúčan et al. 2001). Stainless steel woven fabrics, perforated steel or expanded steel meshes are placed in the foaming mould and are subsequently incorporated into the expanding metal foam. Such reinforcing meshes are much lighter than sheets and strong enough to improve the tensile properties of the foam significantly. Especially the bending behaviour of sheets can be improved The type of reinforcement to be used has to be adapted to the mode of loading (Solórzano, Rodriguez-Perez et al. 2006).

Another kind of composite is obtained by bonding together small spheres of aluminium foam to either ordered or disordered 3D stackings (Stöbener, Baumeister et al. 2005; Stöbener, Lehnhus et al. 2005; Baumeister, Weise et al. 2008; Lehnhus, Baumeister et al. 2010). for the former see [Figure 10](#). The spheres can be produced continuously at low costs. The composite can have complex shapes or fill hollow sections.



16.4.1.7 Alternate routes for precursor or foam production

Semisolid processing is proposed as an alternate way to compact metal powder/blowing agent mixtures (Stanzick, Wichmann et al. 2002). Accordingly, the same powder mixtures as used for the route based on pressing or extrusion are used. The powders are first consolidated by cold isostatic

pressing, then heated to a temperature at which the material is semisolid (e.g. 595 °C for alloy AlSi6Cu4), after which the billets are transferred into the sleeve of a horizontal cold-chamber die casting machine and are then pressed into a die. Foaming of the resulting precursor material leads to good expansion to foams exhibiting round bubbles with a uniform size distribution (Garcia-Moreno, Babcsán et al. 2005). Application to a variety of alloys is reported, including a series of alloys containing various trace elements (Weise, Marchetto et al. 2006), alloys based on recycled material and alloys foamed by using carbonates as a blowing agent (Baumeister, Weise et al. 2008; Haesche, Lehmus et al. 2010). For example, AlMg4.5Mn sawing chips or AlSi9Cu3 cutting chips are mixed with the blowing agent CaCO₃ and stabilising CaO powder. The mixture is first briquetted, heated to the semi-solid state and then cast. The resulting precursor show a reasonable foaming behaviour (Haesche, Lehmus et al. 2010).

16.4.2 Precursors made by casting techniques

16.4.2.1 *General characteristics of technique*

In the foaming processes described in Secs. 16.3.2 and 16.3.3 – ‘Alporas’ and ‘Alcan’ lines, – a liquid foam is created in a foaming vessel in one step. The liquid foam is usually solidified to a block unless it is cast into a mould. Therefore, net-shaping of foams to complex components or thin sheets is difficult. The precursor-based processes described in 16.4.1 avoid this problem since foam can be generated in moulds or between face sheets of a sandwich panel by expanding a precursor. However, the necessity to use metal powders makes the process more expensive. In order to combine the advantages of the melt-based routes of Secs. 16.3.2 and 16.3.3 and the precursor-based routes of Sec. 16.4.1, a combination was sought. The basic idea is to start processing along the line described in Sec. 16.3.2, i.e. by adding a blowing agent to a melt, but then to interrupt the incipient foaming process by swift cooling, e.g. by casting the liquid mixture into a cold crucible. The precursor obtained in this way will then be foamable upon reheating and can be further processed in analogy to the powder compacts described in Sec. 16.4.1. For example, a ZnAl22 alloy is used to which 0.5 wt.% TiH₂ powder is admixed at 457 °C. Mixing and solidifying takes about 3 min and no notable foaming occurs. After solidification, the precursor is heated to 471 °C and foamed there, which takes about 15 min (Ptashnik 1973). Use of 20 µm carbonyl iron powder to thicken the melt is proposed. Such additional ‘thickening’ and the solid phase present in the semisolid range provide additional foam stabilisation.

16.4.2.2 *Foaming of reinforced alloys*

One way to make a foamable precursor was developed at the University of Cambridge, UK (Gergely and Clyne 1998; Gergely and Clyne 2000). The starting point is a liquid Al alloy containing SiC particles, i.e. a liquid aluminium matrix composite. Such melts are also the starting point for the processes described in Sec. 16.3.3. TiH₂ is first added to the melt accompanied by vigorous stirring. The TiH₂ powder has been preoxidised before admixture to prevent it from releasing too much gas during mixing. Moreover, to prevent burning of the hydride, the TiH₂ powder is mixed with some Al powder and pressed to pellets that are added to the melt. After stir-homogenising, the melt is cast into a cold crucible and heat is removed as fast as possible. The resulting solid composite material contains some porosity but is predominantly dense. This precursor is converted to foam in the subsequent foaming (‘baking’) step in analogy to the technique described in Sec. 16.4.1. Very uniform foams can be produced and all the advantages of the precursor route can be exploited. The acronym ‘*Formgrip*’ has been coined, standing for ‘foaming of reinforced metals by gas release in precursors’. An

analogous process based on the use of CaCO_3 as a blowing agent is known, called ‘foaming of aluminium MMC by the chalk-aluminium reaction in precursors’ (*Foamcarp*) (Gergely, Curran et al. 2003). In this case, the reactions between the metal and the carbonate contribute notably to foam stabilisation.

16.4.2.3 Process variants

Another procedure is based on a die casting machine. Aluminium alloy is injected into the die of a cold-chamber die casting machine. At the entrance of the die, a small reservoir contains TiH_2 powder and some aluminium powder. During melt injection, the powders and the melt are intensely mixed. In the die, the metal solidifies quick enough to avoid notable decomposition of the blowing agent and therefore a largely dense precursor with embedded blowing agent particles is obtained that can be foamed by reheating (Banhart, Baumeister et al. 2000). As the oxide content in the cast material is low, the resulting foam is not very stable if too little aluminium powder is added. The process resembles the one described in Sec. 16.3.2.6, with the only difference that there the die is underfilled and the injected melt is allowed to foam in the die, whereas here, the die is completely filled and foaming is carried out in a separate step outside the die.

A modification of the ‘Alporas line’ techniques described in Sec. 16.3.2 (stabilising an Al melt by adding Ca and foaming by adding a blowing agent) has been proposed (Babcsán, Garcia-Moreno et al. 2007; Kadoi, Babcsán et al. 2008). Here, the foaming process is interrupted immediately after stirring the melt and adding the blowing agent. A solid precursor with some amount of porosity is obtained which can be foamed upon reheating. This has been called ‘two-step foaming’ (Shang and He 2005; Shang, Chu et al. 2008). The latter authors melt an AlCu4 alloy, add Ca while stirring and then add untreated TiH_2 , after which the foaming process is interrupted. The resulting precursors have considerable porosities but can be foamed to large volumes by reheating to a temperature about 100 K higher than applied during manufacture of the precursor. The kinetics of foam expansion has been represented well by a model (Wang, Zhang et al. 2016).

Another variation has been reported: aluminium powder is melted, stabilising SiC particles admixed, after which CaCO_3 as a blowing agent is added, stirred to homogenise the mixture and solidified to a precursor that can be foamed in a second step (Kevorkijan, Škapin et al. 2010).

16.4.3 Spray-processed Precursors

Sputter deposition is used to manufacture a metallic material in which a multitude of gas atoms are entrapped. If this material is then heated to a temperature above the melting temperature of the metal and held there for a while, the gas will nucleate to small bubbles and form a porous body (Patten 1978). Spray forming involves atomising a melt and depositing the metallic spray on a substrate, usually forming a dense material. If one adds a blowing agent to the spray, a foam can be obtained (Banhart and Knüwer 1998). Cold gas dynamic spraying has been used to manufacture foamable aluminium alloy precursors containing TiH_2 that can be expanded to foams of currently still insufficient pore morphology (Viscusi, Ammendola et al. 2016).

16.5 Summary

Metal foam can be produced in many different ways. All processes have in common that gas is injected into or released in a liquid or semisolid alloy where a dense distribution of bubbles is formed that arrange to a metastable arrangement under the influence of surface tension, capillary forces and gravity. Solid foam is obtained by solidification before decay sets in. The differences between the various production techniques are the way the blowing gas is generated and the way the liquid foam is

stabilised. Aluminium alloys have clearly in the focus of research activities up to now but other metals might gain importance in the future.

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Relevant Websites

Collection of links to metal foam producers and other information: www.metalfoam.net

Author Biography and Photograph

John Banhart is a professor in the Faculty of Material Science and Technology at the Technical University of Berlin and head of the Institute of Applied Materials at Helmholtz-Centre Berlin. Current working fields and research interests are light-weight materials including aluminium alloys and metal foams and materials used for energy conversion and storage. His department runs facilities for X-ray and neutron tomography.

He is a physicist and earned his PhD in physical chemistry at the University of Munich in 1989. After working in theoretical alloy physics he changed to application oriented work at the Fraunhofer-Institute in Bremen where processes for foaming metals were developed in close cooperation with industry. He obtained his second degree (habilitation) in 1998 in Solid State Physics at the University of Bremen.



Figures and Tables

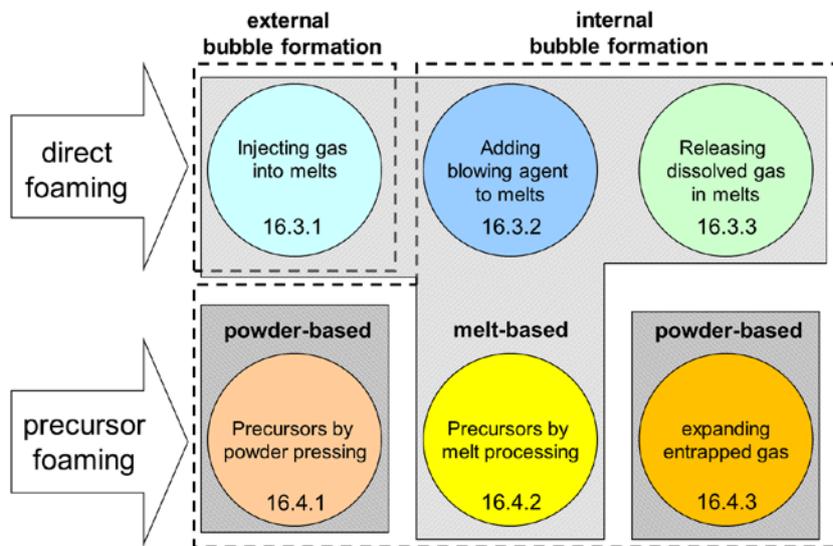


Figure 1. Classification of different processing routes for metal foams. The numbers in each of the 6 circles specify the chapter in which the method is described.

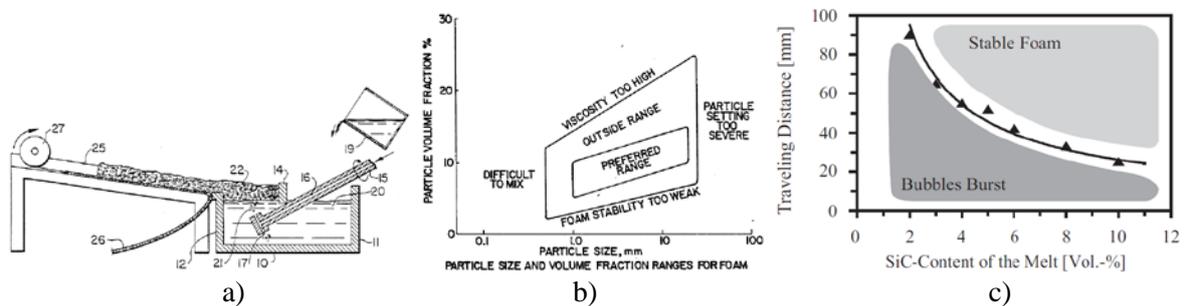


Figure 2. a) Schematic of direct foaming of metallic melts (Jin, Kenny et al. 1990), b) Range of good foaming in the parameter space defined by SiC particle diameter and particle fraction (Jin, Kenny et al. 1990), c) foam stability in the parameter space defined by injector immersion depth (= travelling distance of bubbles) and SiC particle fraction (Leitlmeier, Degischer et al. 2002).

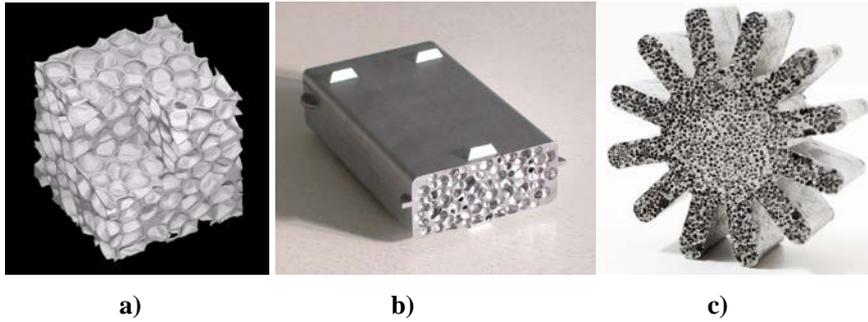


Figure 3. Metal foams with improved pore morphology. a) foam cube (width 34 mm) made by LKR applying optimised bubble injection conditions, X-ray tomographic image (Leitlmeier, Degischer et al. 2002). b) Moulded Al foam core with dense outer skin with foam corresponding to a) (courtesy: D. Leitlmeier). c) Foam component (diameter 55 mm) made by Aluivent using vibrating injection nozzle (courtesy: N. Babcsán).

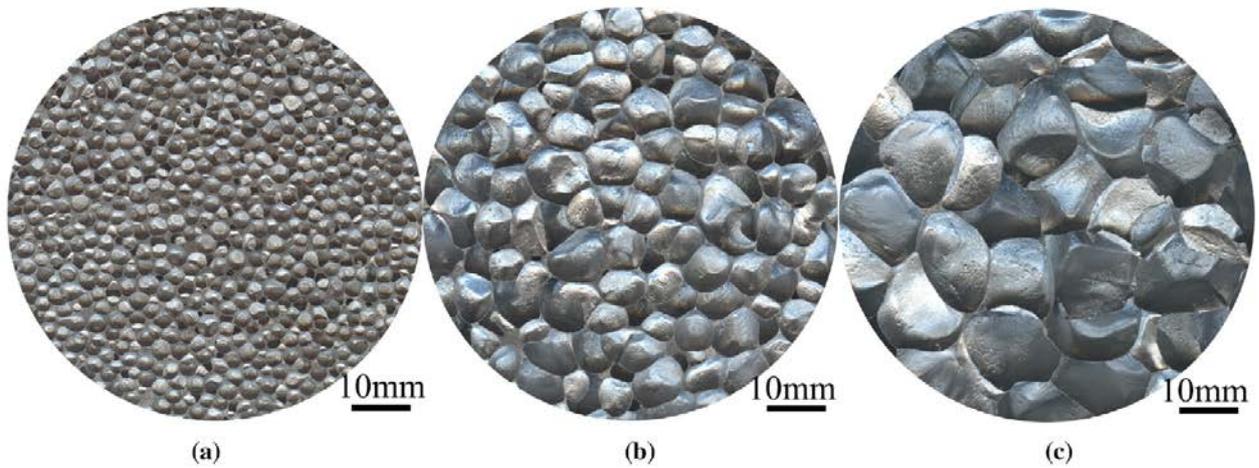


Figure 4. Morphology of AlSi7Mg foams containing 10 vol.% Al_2O_3 particles blown by injecting air under different conditions (Yuan, Li et al. 2016).



Figure 5. Typical morphology of an 'Alporas' foam. Picture taken from a sample handout by Shinko Wire. Co. Width of field 90 mm.



Figure 6. Aluminium alloy foam made by applying the Alcoa process involving CaCO_3 as a blowing agent. a) entire foam panel, b) microstructure (Courtesy Dan Bryant).

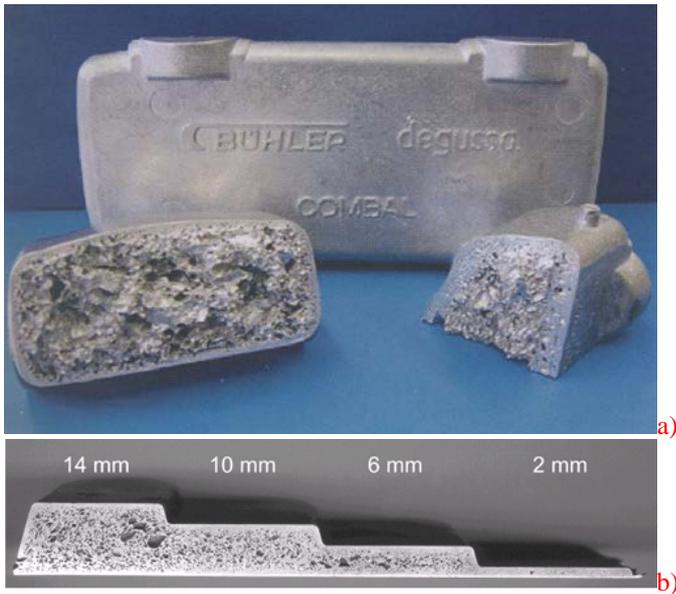


Figure 7. a) Aluminium foam part made in a die casting machine. (Binder, Fritsche et al. 2006) b) Mg alloy AZ91 integral foam part made by foam moulding. (Hirschmann, Körner et al. 2007).

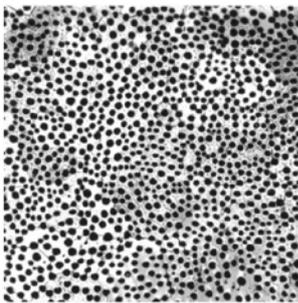


Figure 8. Copper gasar produced by gas-eutectic decomposition (Shapovalov and Boyko 2004). Width of field is 40 mm.

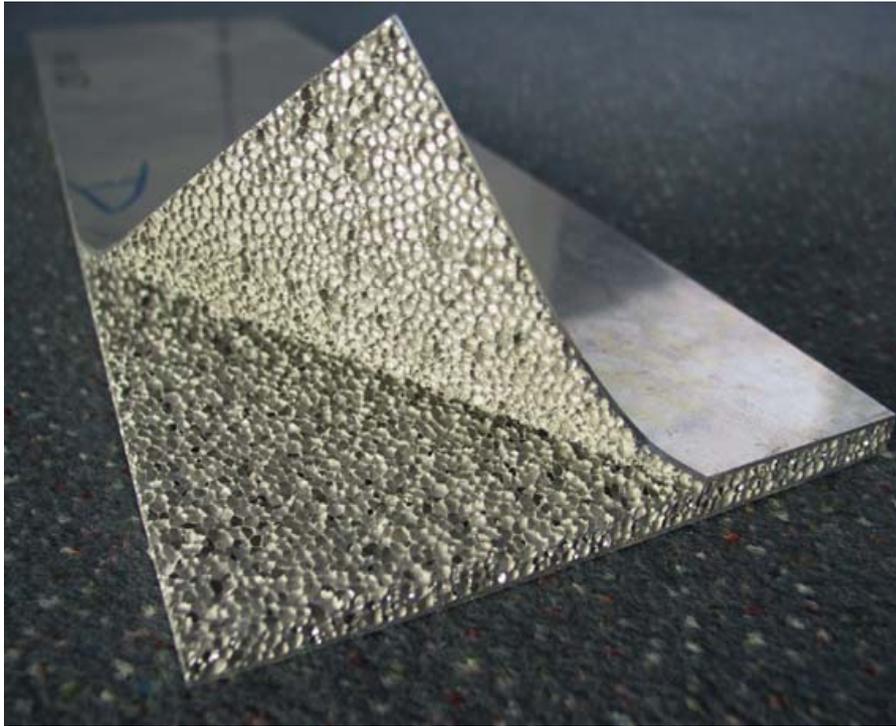


Figure 9. Aluminium foam sandwich panel with two Al face sheets. One sheet has been peeled of to make the foam visible. Width of sample is 300 mm. Courtesy of H.-W. Seeliger.



Figure 10. Composite structure comprising aluminium foam spheres that have been bonded together to form a filling of a tube. Courtesy Fraunhofer IFAM, Bremen.