

Metallic foams: challenges and opportunities

John Banhart

Fraunhofer-Institute for Advanced Materials, Bremen, Germany

Abstract

Metallic foams have become an attractive research field both from the scientific viewpoint and the prospect of industrial applications. Various methods for making such foams are presented and discussed. Some techniques start from specially prepared molten metals with adjusted viscosities. Such melts can be foamed by injecting gases or by adding gas-releasing blowing agents which cause the formation of bubbles during in-situ decomposition. A further way is to prepare supersaturated metal-gas systems under high pressure and initiate bubble formation by pressure and temperature control. A further class of techniques starts from metal powders. One mixes such powders with a blowing agent, compacts the mix and then foams the compact by melting. The various foaming processes, the foam stabilising mechanisms and some known problems with the various methods are addressed and some possible applications for metallic foams presented.

1 Introduction: cellular metals

Solid metallic foams are known to have many interesting combinations of physical and mechanical properties such as high stiffness in conjunction with very low specific weight or high gas permeability combined with high strength. For this reason, the past ten years have seen an increase in interest for these materials. In the literature and in practical use there is some confusion concerning the term "metallic foam". The term is mostly used in a quite general way although the materials described are often not foams in the strictest sense. One has to distinguish between

- cellular metals*: the most general term, refers to a metallic body with any kind of gaseous voids dispersed in it,
- porous metals*: general term but restricted to a special type of voids: pores are usually round and isolated from each other,
- (solid) metal foams*: a special class of cellular metals with a special history (originating from a liquid metal foam),
- metal sponges*: refers to a special morphology of a cellular metal with usually interconnected voids.

Figure 1 provides an overview of the methods available for making cellular metals [1]. The methods are categorised according to the state of matter the metal which is to be processed is in. Metal vapour and metal ions can be deposited onto pre-prepared open-pored polymer foams after which the polymer is removed. A metallic image of the original foam is obtained. Although the result is a foam, the physics of foaming has nothing to do with the metallic state. The strategy of using a polymer foam as a precursor and adding the metallic component after the foaming has been completed can be further pursued, e.g. by casting liquid metal over appropriate space holders or by pressing metal powders with light filler materials followed by

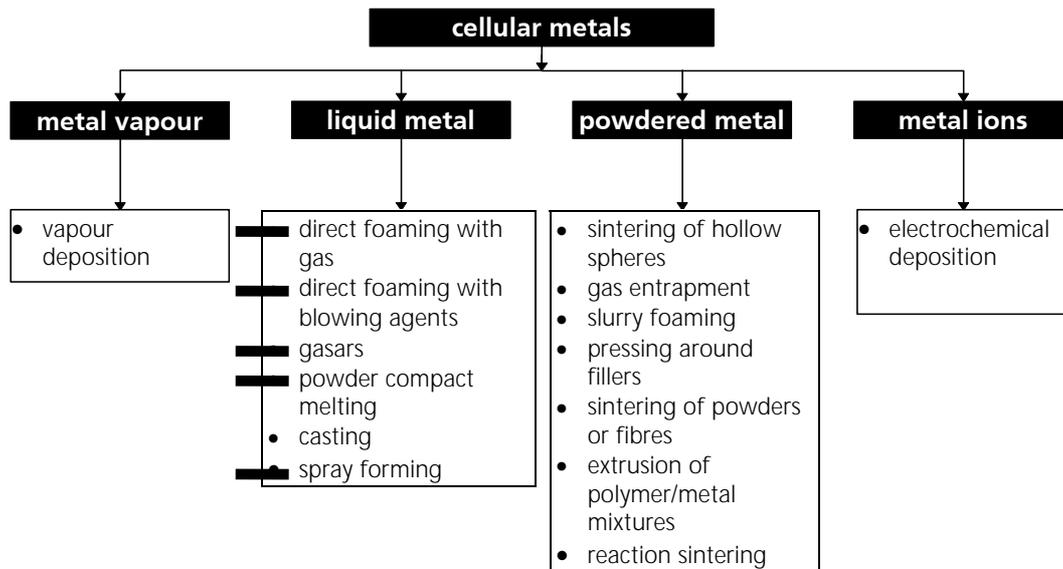


Figure 1: Overview. Methods for making cellular metals [1]. Arrows mark true foams.

a sintering step. The filler materials can remain in the resulting metal or be removed. Metal powders, fibres or even metallic micro-spheres can be used to make porous metals without space holders by simple loose sintering. Alternatively, one can compact metal powder and allow gas to be entrapped which is then expanded in a second step by a thermal treatment which leads to a creep expansion of the compact and the formation of fairly uniform porosity.

All methods described in the previous paragraph do not lead to what is commonly known as (solid) foams that are uniform dispersions of a gaseous phase in a solid. The cells are entirely enclosed by the solid and are not interconnected. This morphology stems from the liquid precursor foam in which surface energy minimisation governs the distribution of the metal. The various possibilities for foaming metals shall be briefly described in Section 2.

2 Production methods for metallic foams

Metallic melts can be foamed 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 which form stabilising particles in the melt or by other means. Currently there are three ways for foaming metallic melts: one by injecting gas into the liquid metal from an external source, the other by causing an in-situ gas formation in the liquid by admixing gas-releasing blowing agents to the molten metal, the last one by causing the precipitation of gas already solved in the liquid.

2.1 Foaming of melts by gas injection

The first way for foaming aluminium and aluminium alloys is currently exploited by Hydro Aluminium in Norway and by Cymat Aluminium Corp. in Canada [2,3]. According to this process described schematically in **Figure 2**, silicon carbide, aluminium oxide or magnesium oxide particles are used to enhance the viscosity of the melt. Therefore, the first step requires the preparation of an aluminium melt containing one of these substances. This step reportedly requires some sophisticated mixing techniques to ensure a uniform distribution of particles. A variety of aluminium alloys can be used.

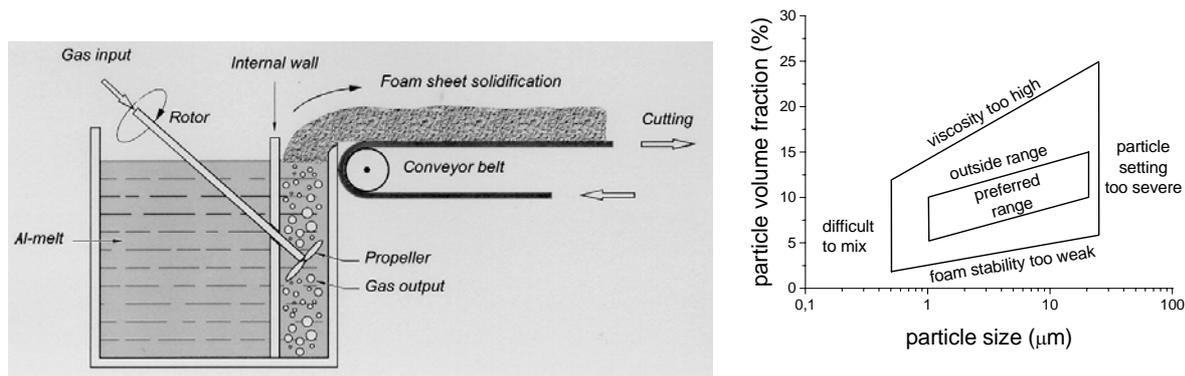


Figure 2: Left: direct foaming of melts by gas injection [2], right: preferable range of stabilising powders [4].

The melt is foamed in a second step by injecting gases (air, nitrogen, argon) into it using specially designed rotating impellers or vibrating nozzles. These generate very fine gas bubbles in the melt and distribute them uniformly. The resultant viscous mixture of bubbles and metal melt floats up to the surface of the liquid where it turns into a fairly dry liquid foam as the liquid metal drains out. The foam is relatively stable owing to the presence of ceramic particles in the melt. It can be pulled off the liquid surface, e.g. with a conveyor belt, and is then allowed to cool down and solidify. The resulting solid foam is in principle as long as desired, as wide as the vessel containing the liquid metal allows it, and typically 10 cm thick. The volume fraction of the reinforcing particles typically ranges from 10 to 20% and the mean particle size from 5 to 20 μm . The choice of particle size and content has been carried out empirically. Too high or too low content or particle sizes create various problems as shown in **Figure 2** (rhs). The densities of aluminium foams produced this way range from 0.069 to 0.54 g/cm^3 , average pore sizes from 25 mm down to 3 mm, and wall thicknesses from 50 to 85 μm . The average cell size is inversely related both to the average cell wall thickness and to the density and can be influenced by adjusting the gas flow, the impeller speed or nozzle vibration frequency, and other parameters.

In order to avoid some of the unwanted side effects of stabilising additives to metallic melts (e.g. brittleness), it was suggested to foam pure, additive-free metallic melts with inert gases [1]. In order to keep viscosity low the foaming process has to take place at temperatures very close to the melting point. This can be done by bubbling gas through a melt which is constantly cooled down, e.g. in a continuous casting process. The bubbles are then caught in the solidifying liquid and form a foam-like structure. In the liquid state such systems are very unstable in contrast to particle-stabilised metals which can be kept liquid for some time.

2.2 Foaming liquid metals with blowing agents

A second way for foaming melts directly is to add a blowing agent to the melt instead of injecting gas into it. The blowing agent decomposes under the influence of heat and releases gas which then propels the foaming process. This is shown in **Figure 3** (lhs) for a currently used implementation of the method [5]. Shinko Wire Co., Amagasaki (Japan) has been producing foams in this way since 1986 with production volumes reportedly up to 1000 kg foam per day. In a first step about 1.5 wt.% calcium metal is added to an aluminium melt at 680°C. The melt is stirred for several minutes during which its viscosity continuously increases by a factor of up to 5 owing to the formation of calcium oxide (CaO), calcium-aluminium oxide (CaAl_2O_4) or perhaps even Al_4Ca intermetallics which thicken the liquid metal. **Figure 3** (rhs) shows the effect of stirring on the viscosity of aluminium melts with various calcium additions [6]. After the viscosity has reached the desired value, titanium

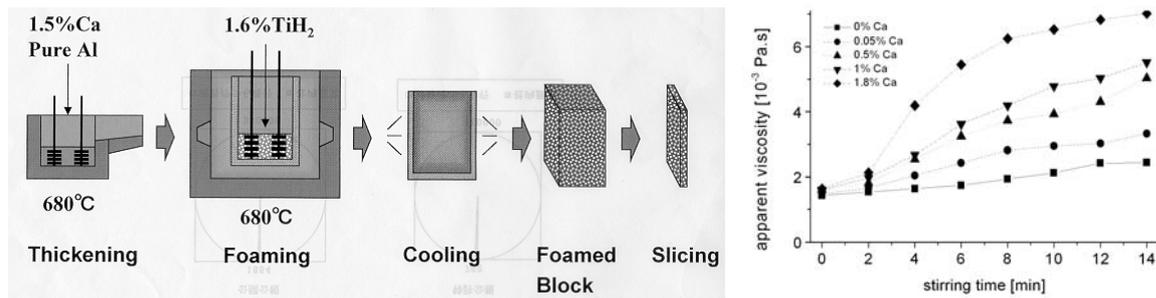


Figure 3: Left: direct foaming of melts by adding gas-releasing powders (ALPORAS-process), right: dependence of viscosity from stirring time.

hydride (TiH_2) is added (typically 1.6 wt.%) which serves as a blowing agent by releasing hydrogen gas in the hot viscous liquid. The melt soon starts to expand slowly and gradually fills the foaming vessel. The foaming takes place at constant pressure. After cooling the vessel below the melting point of the alloy the liquid foam turns into solid aluminium foam and can be taken out of the mould for further processing. The entire foaming process can take 15 minutes for a typical batch (2050x650x450 mm). It has been shown that a careful adjustment of process parameters leads to very homogeneous foams. In fact, the foams produced in this way - trade name "Alporas" - seem to be the most homogeneous aluminium foams currently available. There is an empirical relationship not only between average cell diameter and the viscosity of the melt but also between the final foam density and viscosity. Typical densities after cutting off the sides of the cast foam blocks are between 0.18 and 0.24 g/cm^3 , with the average pore size ranging from 2 to 10 mm. A viscosity enhancement of molten aluminium can also be obtained by bubbling oxygen, air or other gas mixtures through the melt, thus causing the formation of alumina, by adding powdered alumina, aluminium dross or scrap foamed aluminium or by using metallic viscosity enhancing additives. However, the proper adjustment seems to be quite difficult and requires complicated temperature cycles and mechanical agitation.

2.3 Solid-gas eutectic solidification (gasars)

A method developed about a decade ago [7] 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 (up to 50 atms.), one obtains a homogeneous melt charged with hydrogen. If one then lowers the temperature, the melt will eventually undergo a eutectic transition to a heterogeneous two-phase system, "solid + gas". If the composition of the system is sufficiently close to the eutectic concentration, there will be a segregation reaction at one temperature. As the melt is solidified gas pores precipitate and are entrapped in the solid. The resulting pore morphologies are largely determined by the hydrogen content, the pressure over the melt, by the direction and rate of heat removal and by the chemical composition of the melt. Generally, largely elongated pores oriented in the direction of solidification are formed. Pore diameters range from 10 μm to 10 mm, pore lengths from 100 μm to 300 mm, and porosities from 5 to 75%. The pore size distribution is non-uniform because of concurrent growth of small and large pores and coalescence. Pores may be conical or even corrugated. For the porous materials formed by solid-gas eutectic solidification, the word "gasar" was coined meaning "gas-reinforced" in a Russian acronym.

2.4 Foaming of powder compacts

Foamed metals can be also be prepared from metal powders [8]. The production process begins with the mixing of metal powders - elementary metal powders, alloy powders or metal powder blends - with a blowing agent, after which the mix is compacted to yield a dense, semi-finished product (see diagramme in **Figure 4**). In principle, the compaction can be done by any technique that ensures that the blowing agent is embedded into the metal matrix without any notable residual open porosity. Examples of such compaction methods are uniaxial or isostatic compression, rod extrusion or powder rolling. The manufacture of the precursor has to be carried out very carefully because residual porosity or other defects will lead to poor results in further processing. Heat treatment at temperatures near the melting point of the matrix material is the next step. The blowing agent, which is homogeneously distributed within the dense metallic matrix, decomposes. The released gas forces the melting precursor material to expand, thus forming its highly porous structure. The time needed for full expansion depends on temperature and the size of the precursor and ranges from a few seconds to several minutes. The method is not restricted to aluminium and its alloys: tin, zinc, brass, lead, gold and some other metals and alloys can also be foamed by choosing appropriate blowing agents and process parameters. Foaming a piece of precursor material in a furnace results in a lump of metal foam with an undefined shape unless the expansion is limited in certain directions. This is done by inserting the precursor material into a hollow mould and expanding it by heating. In this way near-net shaped parts can be obtained. Quite complicated parts can be manufactured by injecting the still expanding foam from a reservoir into suitable moulds. A recent development concerns a modification of the original process by making a foamable precursor material by incorporating titanium hydride particles directly into an aluminium melt instead of using powders. To avoid premature hydrogen evolution the melt has to be either quickly cooled down below its melting point after mixing or the blowing agent has to be passivated to prevent it from releasing gas already in the stage of mixing [9]. The powder compact melting method is now in the stage of a small-scale commercial exploitation by the German companies Schunk (Gießen) and Honsel (Meschede) and the Austrian companies Mepura (Ranshofen) and Neuman Alufoam (Marktl). The names "Foaminal" and "Alulight" have been coined for these foams.

3 Stability of metallic foams

Foams in general are unstable systems because their energy is far away from a minimum value owing to their large surface area. Foams can therefore be at the most metastable. Usually they are constantly decaying at a certain rate. What one means with "stability" in the context of foams is therefore "slow decay". Whereas the usual aqueous and non-aqueous foams are stabilised by surfactants which reduce surface tension, metallic foams are stabilised by different means. Pure metallic melts cannot be foamed and one seems to need additives which act as stabilisers. In some of the examples presented in Sec. 2 these additives are:

- *silicon carbide particles* which are *added* to the melt in the Hydro/Cymat foaming process

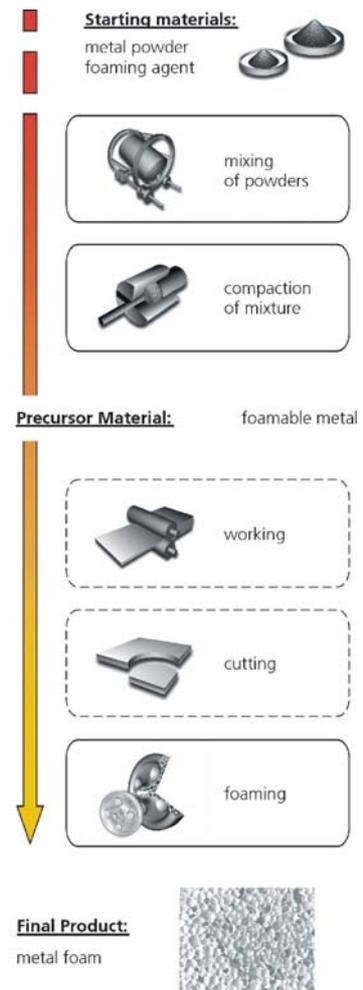


Figure 4: Principle of powder compact foaming method.

(Sec. 2.1). These particles are typically about 10 μm in diameter. That they are really necessary was shown by measuring the “foaminess” as a function of particle content. It was found that 8-20 vol.% SiC in Al were needed depending somewhat on the way the gas is injected into the liquid [10].

- Al-, Ca- or mixed *oxides* which are *formed* in the melt by internal oxidation after adding Ca metal and stirring in the Alporas process (Sec. 2.2). The diameter of such particles has not been specified in the literature.
- metal *oxide filaments* which *reside* in the powder compacts used (see Sec. 2), because oxides cover the surface of each powder particle prior to solidification and remain in the compact after pressing. These filaments are very thin, especially for aluminium where their thickness is believed to be below 100 nm. That these oxides indeed play an important role in foam stabilisation can be seen from **Figure 5**. Lead foams were manufactured by mixing lead powders with different degrees of oxidation with a blowing agent, compacting the mix and foaming it. One finds that powders with very low oxide contents lead to unstable foams: as the foam rises liquid drains out of the foam and limits its expansion. If one uses powders with higher oxide contents rather stable foams are obtained and a large part of the liquid lead is kept in the foam structure at least until maximum expansion has been reached. For aluminium there is also some evidence that the same mechanisms are effective [12].



Figure 5: Lead foams made from two different lead powders. Upper: low-oxygen powder (0.06 wt.%), lower: higher oxidised powder containing 0.46 wt.% O [13].

From what is known it can be strongly assumed that metallic foams are stabilised by solid particles. However, the stabilising mechanisms are definitively different from the mechanisms known for aqueous foams because, e.g., electrostatic forces are completely screened in liquid metal. The action of foam stabilisation is not entirely clear yet. An outline of the current ideas shall be given here using some of the sparse information on metal foams available in the literature [10,11] and the general literature on foams [14].

There are two questions to be discussed in this context:

Where are the solid particles located in the foam? Are they incorporated into the metal or do they rather segregate? Their behaviour is governed by the wettability of the particles by the melt commonly described by the contact angle between the two. This angle is primarily determined by the chemical composition of the particle but probably also by its size, shape, surface roughness and concentration in the liquid. For the SiC stabilised Al foams of the Hydro/Cymat-type it has been shown that particles actually accumulate on the inner walls of bubbles and are partially wetted [10]. For the foams made by powder compact melting the oxides have not yet been seen by direct observation. All one knows is that aluminium powder compacts have oxide contents up to 1wt.% and that the foams show oxide layers on their surfaces which are 30 nm thick after foaming under argon [12]. However, part of this oxide might have formed by reactions with residual oxygen in the foaming chamber.

How does a given configuration of ceramic particles and metal films influence foam stability? Various mechanisms have been proposed:

- Uniformly dispersed solid particles increase the bulk viscosity of melts. This slows down the vertical motion of liquid metal and contributes to kinetic foam stability. Espe-

cially in thin films there could be a progressive effect when the solid particle touch and built barriers. As the films get thinner these barriers build up and become less penetrable to the melt thus creating a self-stabilising mechanism by a kind of additional “structural viscosity”. Moreover, as viscosity drops with rising temperature, liquid metallic foams are more stable if one remains at temperatures close to the melting point.

- it was suggested [10] that solid particles lead to flatter curvatures around the Plateau borders and therefore to a reduced suction of metal from the films into the borders. However, no experimental verification for this is known and no theoretical explanation for this effect was given.
- It has been derived that the wetting angle has to be in a certain range to ensure that i) the bubble/particle interfaces are stable when the bubbles rises through the melt, i.e. the particles are not stripped off the bubbles, ii) that the particles on the interface lower the total energy of a pair of bubbles with particles in between, i.e. stabilise bubble/particle/bubble interfaces. For insufficient wetting (high contact angle) as well as for too good wetting (low contact angle) there is no stabilisation effect. In principle, from the known wetting angles of ceramic particles with a given melt particles can be selected which have an optimum stabilisation effect [11].

4 Challenges

The development of metallic foams has a long history. The first serious attempts to make such foams date back into the 1950's. However, none of the processes available nowadays and in the past has been brought to a level of sophistication comparable with that of, e.g., polymeric foams. Deficiencies of the various techniques can be found on many levels, namely, e.g., 1) A certain lack of understanding of the *basic mechanisms* of metal foaming. Knowledge is still speculative and some points remain unclear, e.g.: why does one need 10-20 vol.% stabilising particles for the Hydro/Cymat process, whereas very small contents of oxide filaments ($\approx 1\%$) are sufficient in the powder compact technique? 2) Insufficient ability to *make foams of a constant quality* with pre-defined parameters: Much of the research and development work in the past seems to have been carried out on a mainly empirical basis without a detailed knowledge of the underlying mechanisms of the foaming process. This procedure quickly leads to limits when applied to a very complex area such as metal foaming. One reason for this is that much of the work was carried out by companies or commercially oriented research institutes which have to earn money with a new technology very quickly. A solution would be an increase in fundamental research work. Only a detailed understanding of all process parameters would allow for making designed materials with a pre-defined profile of mechanical and physical properties. 3) Difficulties in *finding applications* for metallic foams: Beside some niche market applications there is no real industrial application of “true” metallic foams at the moment.

The reasons for the lack of industrial applications are multiple and different from case to case:

- *physical properties of foams are not good enough*. Solution: improvement of properties by optimising foaming process and materials selection. There seems to be still some potential for such optimisations,
- *knowledge of foam properties insufficient*. Solution: further characterisation of properties. Current scientific programmes in Germany, the UK and the USA aim on a systematic evaluation of metal foam properties,
- *transmission of research results to construction engineers not sufficient*. Solution: databases and design guidelines for metallic foams have to be created and disseminated. There has been some movement on this field recently [15],
- *foams are too expensive*. Mass production will lead to lower prices but metal foam will never be a really cheap material. Therefore, the selection of applications where the spe-

cific properties of foams are fully exploited is indispensable. Because this search cannot be done without a detailed knowledge of the properties of foams and of the limits of foaming processes design engineers will not start such a search: a vicious circle.

5 Opportunities

Real foams in the sense defined in Sec. 2 are mainly suited for structural, load bearing applications. Here one has to distinguish three ways of operation [1], namely

Light-weight construction: as foams can take a large volume while maintaining a low weight, their weight-specific mechanical stiffness is relatively high. The specific stiffness of flat panels, e.g., is approximately proportional to their thickness.

Energy-absorption: owing to their structure foams can absorb a large quantity of mechanical energy when they are deformed. Metal foams with their high strength can therefore act as high-capacity impact energy absorbers.

Acoustic and thermal control: Foams can damp vibrations and absorb sound under certain conditions. Moreover, their thermal conductivity is low.

Currently automotive industry has applications in mind that exploit one or more typical properties of metal foams. The AFS-sandwich of Karmann is one example: These sandwich panels are 3D-shaped and very stiff at a relatively low weight. In combination with new constructional principles they could replace not only conventional stamped steel parts in a car but also reduce the number of parts in the car frame, facilitate assembly and therefore reduce costs while improving performance. The future for such systems seems to be bright.

References

- [1] J. Banhart, Prog. Mater. Sci. **47**(1) (to appear in 2001)
- [2] P. Åsholt, in "Metal Foams and Porous Metal Structures", Editors.: J. Banhart, M.F. Ashby, N.A Fleck, MIT-Verlag, Bremen (1999), p. 133
- [3] J. Wood, in "Metal Foams", Editors J. Banhart, H. Eifert, MIT-Verlag Bremen (1997), p.31
- [4] O. Prakash, H. Sang, J.D. Embury, Mat. Sci. Eng. **A199**, 195 (1995)
- [5] T. Miyoshi, in "Metal Foams and Porous Metal Structures", Editors.: J. Banhart, M.F. Ashby, N.A Fleck, MIT-Verlag, Bremen (1999), p. 125
- [6] L. Ma, Z. Song, Scripta Mater. **39**, 1523 (1998)
- [7] V. Shapovalov, in "Porous and cellular Materials for Structural Applications", Ed's: D.S. Schwartz, D.S. Shih, A.G. Evans, H.N.G. Wadley, MRS. Symp. Proc. **521**, 281 (1998)
- [8] F. Baumgärtner, I. Duarte, J. Banhart, Adv. Eng. Mater. **2**, 168 (2000)
- [9] V. Gergely, T.W. Clyne, Adv. Eng. Mater. **2**, 175 (2000)
- [10] S.W. Ip, Y. Wang, J.M. Toguri, Canadian Metallurgical Quarterly, **38**, 81 (1999)
- [11] G. Kaptay, in "Metal Foams and Porous Metal Structures", Editors.: J. Banhart, M.F. Ashby, N.A Fleck, MIT-Verlag, Bremen (1999), p. 141
- [12] P. Weigand, Thesis, MIT-Verlag Bremen (1999) [in German]
- [13] A. Irretier, P. Weferling, J. Banhart, Scripta Mater., (submitted 2000)
- [14] D. Weaire, S. Hutzler, *The Physics of Foams*, Oxford University Press (2000)
- [15] M.F. Ashby et al, *Metal Foams: a Design Guide*, Butterworth-Heinemann (2000)