

- [⇐ Title page](#)
- [⇐ Previous](#)
- [⇒ References](#)

1. Introduction

Cellular materials are widespread in everyday life and are used for cushioning, insulating, damping, construction, filtration, and many other applications. Highly porous materials combine high stiffness with very low density. Cellular materials frequently occur in nature as construction materials (e.g., wood, bone). The fact that even metals and metal alloys can be produced as cellular solids or metal foams is not as well known as the possibility to foam more traditional engineering materials such as plastics, ceramics, and glass. Metallic foams offer interesting properties due to the combination of metallic character with a porous structure.

Since ca.1960, many attempts have been made to foam metals or to produce porous metallic structures. Here some of the more important and successful procedures are described.

There is no clear-cut and generally accepted definition for the term "foam". First, one has to distinguish between liquid and solid foams. A liquid foam is a fine dispersion of gas bubbles in a liquid. Cooling a liquid foam to below the melting point of the respective material yields a frozen liquid foam which is then clearly a solid foam. What is generally meant in the context of metallic foams are in general solid metallic foams. The use of the word "solid foam" could be restricted to materials which originally were in the liquid state. However, customarily other porous structures such as sintered metal powders are often also called foams, although they never were in a liquid state. Hence, the use of the word "foam" is often extended to porous metal structures which are not actually foams, but resemble foams with respect to their high porosity, the interconnectivity of the solid material, and their irregular structure.

[⇒ Continued ...](#)

- [⇐ Title page](#)
- [⇐ Previous](#)
- [⇒ References](#)

2. Production

2.1. Production from Metallic Melts

One group of foam-making processes starts from the molten metal, which is processed into a porous material by foaming it directly, by using an indirect method via a polymer foam, or by casting the liquid metal around solid filler materials, which reserve space for the pores or which remain in the foam.

Direct Foaming of Melts. Metallic melts can be foamed directly under certain circumstances by injecting gases into the liquid. Normally, the gas bubbles which are then formed in the metallic melt will tend to rise to its surface quickly due to the high buoyancy forces in the high-density liquid, but this can be impeded by increasing the viscosity of the molten metal. This can be done by adding fine

ceramic powders or alloying elements that form particles in the melt.

Numerous attempts to foam liquid metals were undertaken in the 1960s and 1970s [1], but apparently the processes then invented could not be sufficiently optimized to yield foams of a satisfactory quality and cost. In the 1990s, however, a number of new developments have taken place, and better production routes are now available.

Currently, there are two methods for directly foaming metallic melts. One of these is exploited by Cymat (originally by Alcan) in Canada and Hydro Aluminum in Norway [2][3][4][5][6][7][8][9] for foaming aluminum and aluminum alloys. Silicon carbide, aluminum oxide, or magnesium oxide particles are used to enhance the viscosity of the melt. The first step involves making an aluminum melt and adding 5–15 % of one of these particulate substances. The main problems here resemble those encountered in the production of conventional metal-matrix composites (MMCs), namely, the wetting of the particles by the melt and achieving a homogeneous distribution of the reinforcing particles [10]. The liquid MMC melt is then foamed by injection of gases (air, nitrogen, argon) with specially designed rotating impellers that produce very fine gas bubbles and distribute them homogeneously in the melt. The resulting foam floats to the surface of the melt where it can be pulled off, for example, by means of a conveyor belt. Care must be taken not to damage the foam structure by excessive shearing of the semisolid foam. The resulting material can, in principle, be as long as desired, as wide as the vessel containing the melt, and typically 10 cm thick.

The foamed material is used in the as-cast state with a closed outer surface or is cut into the required shape after foaming. Due to the high content of ceramic particles, machining of MMC foams could be problematic. The advantage of the process is the ability to produce large volumes at relatively low cost, and the low density that can be achieved. Porosities range from 80 to 97 %. A possible disadvantage is the eventual necessity for cutting the foam, thereby opening the cells, and brittleness due to reinforcing particles in the cell walls. Attempts to make shaped parts by casting the semiliquid foam into molds or by shaping the emerging foam with rolls have been undertaken [11], [12]. Some properties of such metal foams have been investigated [13], [14]. MMC foams are probably the least expensive metallic foams.

The second method of foaming melts directly is to add a foaming agent to the melt instead [15], [16], [17]. The foaming agent decomposes under the influence of heat and releases the foaming gas. In the small-scale commercial process operated at Shinko Wire in Japan, calcium is used to increase the viscosity of the melt, presumably by forming an Al_4Ca intermetallic phase, and titanium hydride TiH_2 , added by using a rotating impeller, serves as the foaming agent, releasing hydrogen gas on heating. The foamed aluminum is produced in batches of approximately $2000 \times 1000 \times 600$ mm by foaming and solidification in a closed mold. Typical densities are $0.25\text{--}0.33$ g/cm³. The blocks are cut into sheets of the required thickness [18] (e.g., 5–250 mm, standard thickness 10 mm). The pore structure of the material, known as ALPORAS, is rather uniform [19]. Mechanical [19] and sound absorption properties [20] have been measured. The material is reportedly more expensive than the MMC foams.

Solid–Gas Eutectic Solidification (Gasars). A method developed in the Ukraine [21], [22] exploits the fact that some liquid metals form a eutectic system with hydrogen gas. Dissolving hydrogen in these metals under high pressure (typically 50 bar) gives a pore-free melt in which the hydrogen is completely dissolved. Reducing the temperature and pressure causes the melt to go through the two-phase region. Below the eutectic temperature, a two-phase field corresponding to solid plus gas is reached. If the process parameters (cooling rate and pressure profile) are chosen appropriately, the gas accumulates as fine gas bubbles in the solid, thus forming a foam. The possibility of solidifying the liquid directionally offers the advantage of making foams with elongated pores. If the casting vessel is cylindrical, radial and axial pores can be made [23]. The maximum porosities that can be achieved by this process are not very high (5–75 %), but metals with moderate to high melting points such as copper and nickel can be foamed. The pore structure of such foams, known as gasars, is somewhat problematic [24], [25], so that further improvements have to be awaited. The mechanical properties

(compression and tension) of gasars have been determined [26], [27], [28].

Investment Casting. Metal foams can also be fabricated without directly foaming the metal [29][30][31] by starting from a polymer foam. The polymer foam is turned into a structure with open pores by manipulating the foaming process or by a reticulation (thermophysical shock treatment to remove residual membranes). The foam is then filled with a slurry of heat-resistant material, for example, a mixture of mullite, phenolic resin, and calcium carbonate [30]. After drying, the polymer is removed (e.g., by heating) and molten metal is cast into the resulting open voids which exactly reproduce the original foam structure. After removal of the mold material (e.g., by high-pressure water), a metallic foam is obtained that is an exact image of the original polymer foam. Figure (1) shows a micrograph of such a foam, which is being sold by ERG in California under the trade name DUOCEL. Various grades are available ranging from 2.5 to 16 pores per centimeter. Complex shaped parts can be fabricated by preforming the polymer foam. Prices are reportedly high. Aluminum alloys are usually used, but other metals can also be processed. The densities and foam morphologies are determined by the polymer foam. Porosities typically range from 80 to 97 %.

Syntactic Foams with Filler Materials. Lightweight porous metals can be produced by casting around inorganic granules or hollow spheres of low density or by infiltrating such materials with a liquid melt. A loose bulk of expanded clay granules, foamed glass spheres, or hollow aluminum oxide spheres can be used [32], [33]. The granules are then introduced into the melt, or the melt is poured over the bulk filler material. The heat capacity and conductivity of the granules is very low and therefore does not disturb the flow of the metal too much. Due to the high surface tension of the liquid metal, wetting of the granules is a problem, and in general the interstices between the granules will not be filled completely. Applying a slight vacuum or external pressure facilitates infiltration significantly. After solidification of the melt, the filler can optionally be removed, for example, by heating. A wide range of metals can be processed in this way, including aluminum, magnesium, zinc, lead, and tin. Parts of a predefined shape can be fabricated by designing a mold of the appropriate geometry. Sandwich panels have also been made [34].

⇒ Continued ...

⇐ Title page

⇐ Previous

⇒ References

2.2. Production from Metal Powders

Instead of molten metal, metal powders can be used to make porous metallic structures. Several methods can be applied. In some of these processes the powders are processed into a compact precursor material prior to the actual foaming step, in others powders (or fibers, hollow spheres, etc., which are regarded as powders here) are used for direct processing.

Fraunhofer Process. Foamed metals can be produced by a powder metallurgical method invented and patented [35][36][37][38][39] by the Fraunhofer-Institute IFAM in Bremen, Germany. The process begins with the mixing of metal powders (elemental metals, alloys, or powder blends) with a foaming agent, after which the blend is compacted to yield a dense, semifinished product. In principle, compaction can be performed by any technique that ensures that the foaming agent is embedded in the metal matrix without any residual open porosity, for example, uniaxial compression, extrusion, and

powder rolling [34]. The choice of compaction method depends on the required shape of the precursor material. However, extrusion seems to be the most economical method at the moment and is therefore the preferred technique. Rectangular profiles with various cross sections are usually made. Thin sheets are then obtained by rolling.

Heat treatment at temperatures near the melting point of the matrix material is the next step. During this process the foaming agent, which is homogeneously distributed within the dense metallic matrix, decomposes. The released gas forces the compacted material to expand, forming a highly porous structure. Prior to foaming, the precursor material can be processed into sheets, rods, profiles, and other shapes by conventional techniques like rolling, swaging, or extrusion in order to improve the flow conditions during foaming in molds. The density of the metal foams can be controlled by adjusting the content of foaming agent and several other foaming parameters such as temperature and heating rate. If metal hydrides are used as foaming agents, a content of less than 1 % is sufficient in most cases.

Although most applications are based on aluminum foams, the Fraunhofer method is not restricted to this metal: tin, zinc, brass, lead, and some other metals and alloys can also be foamed by choosing appropriate foaming agents and process parameters. The most common alloys for foaming, however, are pure aluminum, 2xxx alloys and 6xxx alloys. Casting alloys such as AlSi7 and AlSi12 are also frequently used because of their low melting point and good foaming properties. In principle virtually any aluminum alloy can be foamed by properly adjusting the process parameters. Figure (2) shows a typical cross section of a powder metallurgical foam. The random distribution of cell sizes and shapes is typical for a foaming process.

Foaming a piece of precursor material in a furnace results in a lump of metal foam with an undefined shape unless expansion is restricted in certain directions. This is done by inserting the precursor material into a hollow mold and expanding it by heating. In this way near-net-shape parts can be prepared. Quite complicated parts can be manufactured by injecting the expanding foam into suitable molds and allowing the final expansion to occur there [40].

Sandwich panels consisting of a foamed metal core and face sheets can be obtained by gluing the face sheets to a sheet of foam. Alternatively, if a pure metallic bonding is required, conventional metal sheets (aluminum or steel) are roll-cladded onto a sheet of foamable precursor material [39]. The resulting composite can be deformed in an optional step, for example, by deep drawing. The final heat treatment then leads to sandwich structures such as those shown in Figures (3) and (4). The large aluminum/aluminum foam part shown in Figure (4) was a joint development of the car component supplier Karmann and the Fraunhofer-Institute for a concept car in which structural aluminum foam applications were demonstrated. The part is intended to replace the rear seat wall and has higher stiffness and lower weight than the conventional steel part.

Tubes can be filled with aluminum foam in various ways (Fig. (5)). The easiest way is to insert a rod of foamable precursor material into the tube that is to be filled and to place the tube into a furnace. The precursor material foams and eventually fills the tube completely. The disadvantage of this method is that only tubes with a significantly higher melting temperature than the material to be foamed can be used. If aluminum tubes are filled with foam in this way, the top of the tube melts during foaming because it is not supported mechanically and the heat from the furnace is not conducted into the precursor material. An alternative method is to insert a foamable tube into the tube that is to be filled. Then the foam expands towards the center of the tube. The foamable material is always in contact with the outer tube and therefore supports it. The expansion of the foam can be limited to a certain wall thickness by using a core in the center of the tube. The third possibility involves a co-extruded structure consisting of an outer tube of conventional aluminum and an inner tube of foamable precursor material. The two layers have a metallic bond, in contrast to the situation in which the inner tube is merely inserted into the outer one. This bond ensures better heat flow between the two tubes and therefore minimizes the risk of melting the outer tube. Moreover, the metallic bond between the foam and the outer tube is also better, because oxide layers between the inserted and outer tubes partially prevent a

metallic bonding during foaming. Examples of foam-filled tubes are shown in Fig (6).

More details of the Fraunhofer process are given elsewhere [41][42][43]. Many mechanical and other physical properties have been determined [44][45][46]. The process is now being extended to metals with higher melting points such as iron and steel [47][48][49]. Due to their excellent biocompatibility, titanium foams could be used in prosthetic applications. However, these are still in the developmental stage.

Gas Entrapment. Metals can be foamed without a propellant by compressing powders into a precursor material and allowing gas to be entrapped in the metal structure during compaction [50], [51]. Heating the precursor material then leads to an expansion of the metal due to the internal pressure created by the entrapped gas. The process has mainly been used for making porous titanium structures. Titanium powder is filled into a can that is then evacuated and refilled with argon gas. The filled can is densified by hot isostatic pressing, subsequently worked, and finally foamed by heating. Refinements and extensions of this process have been developed, and properties of materials and components have been determined [52], [53].

Foaming of Slurries. Metallic foams can be produced by preparing a slurry of metal powder mixed with a foaming agent. The slurry is poured into a mold after mixing and dried at elevated temperature. The slurry becomes more viscous and starts to foam as gas begins to evolve. If sufficient stabilizing measures are taken, the expanded slurry can be dried completely to give a metal foam. Such foams have been produced from aluminum powders with orthophosphoric acid/aluminum hydroxide or hydrochloric acid as foaming agents [54]. Relative densities as low as 7% have been achieved, but there are problems with low strength [55] and cracks in the foamed material.

Other Techniques. There are many ways to make porous metallic products from metal powders, fibers, or hollow spheres. The easiest method is to sinter loose powder fillings in a canister to give a porous material with open porosity. Mixtures of metal powders and polymer binders can be extruded and then heat treated to produce porous parts [56]. In this way porous materials with cylindrical pores can be produced. Reaction sintering of metal powder mixtures can also yield porous products. Hollow spheres made of titanium or steel can be used to form highly porous structures by sintering [57]. Ordered and disordered arrangements can be realized. The density of such structures is extremely low with strengths that are still sufficient for many applications. By infiltrating the interstices between the hollow spheres, the strength can be increased.

⇒ Continued ...

⇐ Title page

⇐ Previous

⇒ References

2.3. Production by Deposition Techniques

Deposition techniques use metal ions as starting materials. The metal is galvanically deposited on a polymer foam with open cells [58][59][60]. Galvanic deposition on a polymer foam requires a certain electrical conductivity of the initial polymer foam. This is achieved by dipping the polymer foam into graphite solutions or by coating it with a thin conductive layer by metal vaporization. After electroplating, the polymer can be removed from the metal–polymer composite by thermal treatment.

Foams of various grades can be fabricated, ranging from 2 to 30 cells per centimeter. The preferred metal is nickel or an NiCr alloy, but copper foams can also be fabricated. Foams have been offered on a commercial basis under the name RETIMET (Dunlop, Great Britain) and CELMET (Sumitomo, Japan [56]). There is also a source in Belorussia [60]. Sheets with thicknesses between 2 and 10 mm are available with densities ranging from 0.2 to 0.5 g/cm³.

⇒ Continued ...

⇐ Title page

⇐ Previous

⇒ References

3. Toxicology and Occupational Health

Typically, metal foams have the same toxicological properties as the corresponding dense, base metal alloy. No specific precautions for the processing and handling of metallic foams are known.

⇒ Continued ...

⇐ Title page

⇐ Previous

⇒ References

4. Applications and Outlook

The development of aluminum-based foams has been especially promoted by the requirement for certain structural lightweight applications so that the widest range of foams is available for this metal and its alloys. Various small-scale production facilities for aluminum foams are now existent in Japan, Canada, Slovakia, Austria and Germany. Some prototypes of aluminum foam parts have been developed and tested. However, it is not yet entirely clear in all cases whether the aluminum foam part can compete with the conventional part that it is intended to replace both with respect to its physical and mechanical properties and to its economical performance.

An interesting application for three-dimensional shaped sandwich foam structures was recently presented by the car outfitter Karmann. These complex shaped panels will be used as fire walls or luggage-compartment walls and will simultaneously stiffen the entire automotive body structures [61]. A comparison of a luggage compartment wall made of conventional stamped steel with an equivalent aluminum foam sandwich panel reveals a ten times higher stiffness of the latter. A combination of this high-stiffness material with the aluminum space frame concept opens the opportunity to build different variations of vehicles—even cabriolets with their high stiffness requirements—based on one common body structure.

The cost effectiveness of the various process is difficult to evaluate and should be regarded on a part by part basis. Only few methods are suitable for high-volume mass production, and many will remain restricted to specialized applications where cost is not the most important parameter. However, some of the processes for the production of aluminum foams, especially the melt and the powder metallurgical processes, have the potential for mass production at reasonable costs. There seems to be a market for these materials in applications where the unique properties of the metallic foam are fully exploited. This is the case when the foam has multiple functions, for example, when its low weight in combination with its high-temperature resistance is desired.

⇒ Continued ...

⇐ Title page

⇐ Previous

5. References

- ⇐ [1] US 3 794 481, 1974 (L. M. Niebylski, C. P. Jarema, P. A. Immethun).
- ⇐ [2] US 4 973 358, 1990 (I. Jin, L. D. Kenny, H. Sang).
- ⇐ [3] WO-A 91/03578, 1991 (I. Jin, L. D. Kenny, H. Sang).
- ⇐ [4] WO-A 92/03582, 1992 (I. Jin, L. D. Kenny, H. Sang).
- ⇐ [5] US 5 112 696, 1992 (I. Jin, L. D. Kenny, H. Sang).
- ⇐ [6] WO-A 94/172218, 1994 (M. Thomas, L. D. Kenny).
- ⇐ [7] J. T. Wood, *Proc. Fraunhofer USA Metal Foam Symposium, Oct. 7.–8. 1997, Stanton, Del.*, 31.
- ⇐ [8] WO-A 90/00115, 1990 (W. Ruch, B. Kirkevag).
- ⇐ [9] WO 91/01387, 1991 (W. Ruch, B. Kirkevag).
- ⇐ [10] WO-A 91/19823, 1991 (D. J. Lloyd, A. D. McLeod, P. L. Morris, I. Jin).
- ⇐ [11] WO-A 94/09931, 1994 (L. D. Kenny, M. Thomas).
- ⇐ [12] WO-A 92/21457, 1992 (H. Sang, L. D. Kenny, I. Jin).
- ⇐ [13] O. Prakash, H. Sang, J. D. Embury, *Mat. Sci. Eng. A* **199** (1995) 195.
- ⇐ [14] Product data sheets of Hydro Aluminium, Sunndalsøra 1994.
- ⇐ [15] EP-A 0 210 803 A 1, 1986 (S. Akiyama et al.).
- ⇐ [16] US 4 713 277, 1987 (S. Akiyama et al.).
- ⇐ [17] M. Itoh, T. Miyoshi, *Mat. Res. Soc. Symp. Proc.* **521** (1998) R3.2.
- ⇐ [18] ALPORAS product information, Shinko Wire Co. Ltd., Izumisano 1998.
- ⇐ [19] M. Otsuka, A. Kojima, M. Itoh, E. Ishii, in "Science and Engineering of Light Metals", *Proc. Conf. RASELM '91, Tokyo, Oct. 1991* (1991) 999.
- ⇐ [20] E. Ishii, M. Itoh, Y. Morisawa, *Kobe Steel Engineering Reports* **41** (1991) 59.
- ⇐ [21] US 5 181 549, 1991 (V. I. Shapovalov).
- ⇐ [22] MRS-Bulletin, April 1994, p. 24–28.
- ⇐ [23] Y. Zheng, S. Sridhar, K. C. Russel, in S. Komareni et al. (eds.): "Advances in Porous

Materials", *MRS Society Bull.* **371** (1995) 365.

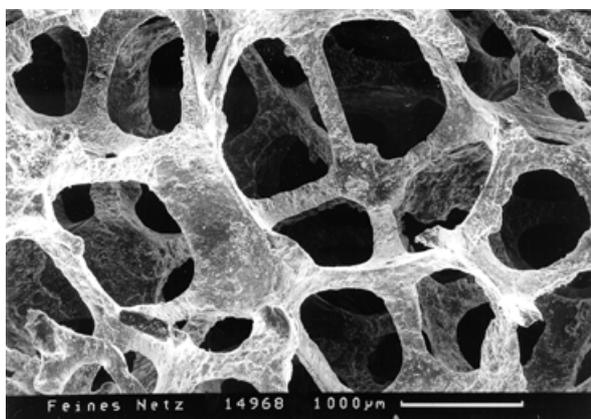
- ↪ [24] A. Pattnaik, S. C. Sanday, C. L. Vold, H. I. Aaronson, in "Advances in Porous Materials", *MRS Society Bull.* **371** (1995) 371.
- ↪ [25] J. M. Wolla, V. Provenzano, in S. Komareni et al. (eds.): "Advances in Porous Materials", *MRS Society Bull.* **371** (1995) 377.
- ↪ [26] V. Provenzano, J. Wolla, P. Matic, A. Geltmacher, A. Kee, in S. Komareni et al. (eds.): "Advances in Porous Materials", *MRS Society Bull.* **371** (1995) 383.
- ↪ [27] A. E. Simone, L. J. Gibson, *Acta. Met.* **44** (1996) 1437.
- ↪ [28] *J. Mat. Sci.* **32** (1997) 451.
- ↪ [29] DUOCELL product information, ERG Inc., Oakland Ca., 1996.
- ↪ [30] Y. Yosida, C. Hayashi, *Proc. Conf. Casting Sci. Technol.* 1990, Sept., 103.
- ↪ [31] I. Wagner et al., DGM Hauptversammlung 20.–23.5.1997, Braunschweig, Germany, (abstract).
- ↪ [32] DE 1 933 321, 1971 (W. Thiele).
- ↪ [33] W. Thiele, *Metals Mat.* 1972, Aug., 349.
- ↪ [34] M. Hartmann, R. F. Singer, in *Proc. Symp. Metal. Foams, Bremen March 6.–7. 1997*, 39.
- ↪ [35] DE 4 018 360, 1990 (J. Baumeister).
- ↪ [36] US 5 151 246, 1992 (J. Baumeister).
- ↪ [37] EP 0 460 392 A 1, 1996 (J. Baumeister).
- ↪ [38] DE 4 101 630, 1991 (J. Baumeister, H. Schrader).
- ↪ [39] DE 4 426 627, 1997 (J. Baumeister, J. Banhart, M. Weber).
- ↪ [40] F. Simancik, F. Schörghuber, *Mar. Res. Soc. Symp. Proc.* **521** (1998) R3.7.
- ↪ [41] M. Weber, J. Baumeister, J. Banhart: "Metals and Composites," *5th Eur. Conf. Adv. Mat.* (1997) 467.
- ↪ [42] J. Banhart, J. Baumeister, M. Weber, *Proc. Euro. Conf. Adv. PM Mat. (PM '95), Birmingham Oct. 23.–25., 1995*, 201.
- ↪ [43] F. Simancik, J. Kováčik, F. Schörghuber, Proc. cited in [34], p. 171.
- ↪ [44] J. Banhart, J. Baumeister, *J. Mat. Sci.* **33** (1998) 1431.
- ↪ [45] H. P. Degischer, U. Galovski, R. Gradinger, R. Kretz, F. Simancik, Proc. cited in [34], p. 79.
- ↪ [46] M. Weber, Phd thesis 1995, TU Clausthal ISBN 3-9805748-3-0.
- ↪ [47] B. Kriszt, A. Falahati, H. P. Degischer, Proc. cited in [34], p. 59.
- ↪ [48] M. Weber, M. Knüwer, Proc. cited in [34], p. 73.
- ↪ [49] C. J. Yu, H. Eifert, M. Knüwer, M. Weber, *Mat. Res. Soc. Symp. Proc.* **521** (1998) R3.4.
- ↪ [50] R. L. Martin, R. J. Lederich, *Metal Powder Report* 1992, Oct., 30.
- ↪ [51] M. W. Kearns, P. A. Blenkinshop, A. C. Barber, T. W. Fathing, *Int. J. Powder Met.* **24** (1988) 59.
- ↪ [52] D. S. Shih et al., *Mat. Res. Soc. Symp. Proc.* **521** (1998) R7.3.
- ↪ [53] D. S. Shih et al., *Mat. Res. Soc. Symp. Proc.* **521** (1998).
- ↪ [54] J. P. Drolet, *Int. J. Powder Met.* **13** (1977) 223.
- ↪ [55] S. B. Kulkarni, P. Ramakrishnan, *Int. J. Powder Met.* **9** (1973) 41.
- ↪ [56] L. Tuchinskiy, R. Loutfy, Proc. cited in [7], p. 23.
- ↪ [57] K. M. Hurysz et al., *Mat. Res. Soc. Symp. Proc.* **521** (1998) R5.3.
- ↪ [58] Product data sheet of SEAC International B.V., Krimpen aan den IJssel, The Netherlands

1986.

- ↔ [59] Product data sheet of Sumitomo Electric, 1986.
- ↔ [60] Product data sheet of Ecosot, Belorussia 1996.
- ↔ [61] H.-J. Emmelmann, W. Bunsmann, W. Seeliger, J. Baumeister, Proc. IBEC'97, Stuttgart Sept. 30.–Oct. 02 1997.

↔ first occurrence in article

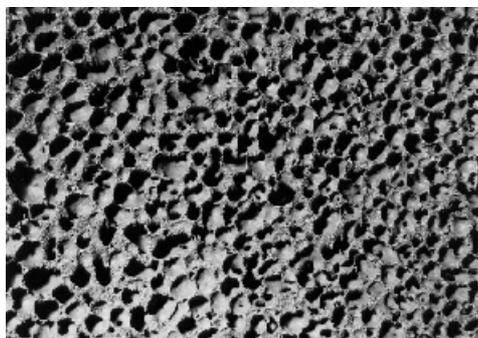
Metallic Foams - Figure 1



SEM image of a metal foam made by investment casting (DUOCEL)

↔ first occurrence in article

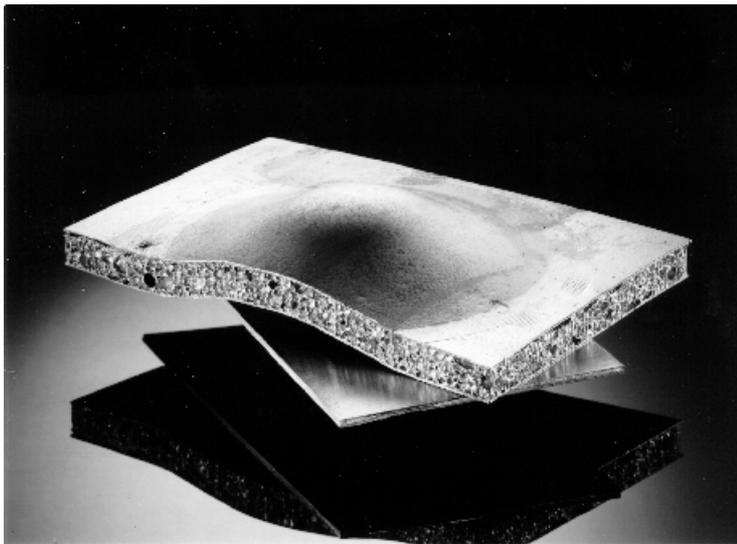
Metallic Foams - Figure 2



Lead foam made from metal powder

↔ first occurrence in article

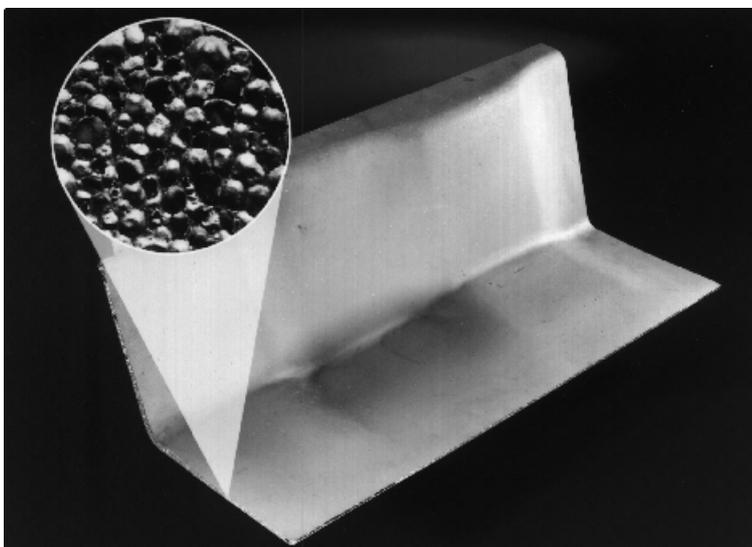
Metallic Foams - Figure 3



Composite structure made of an aluminum foam core and steel face sheets (dimensions $250 \times 250 \times 20$ mm)

↔ first occurrence in article

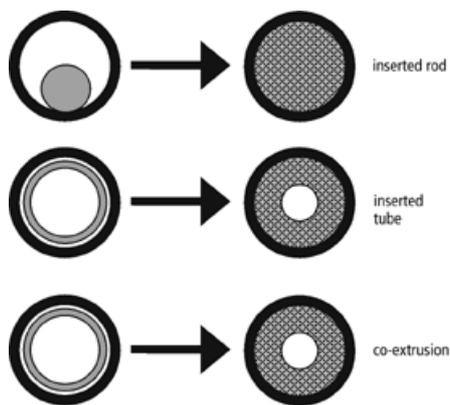
Metallic Foams - Figure 4



Shaped sandwich of aluminum foam with aluminum face sheets (width 1000 mm, thickness 8 mm)

↔ first occurrence in article

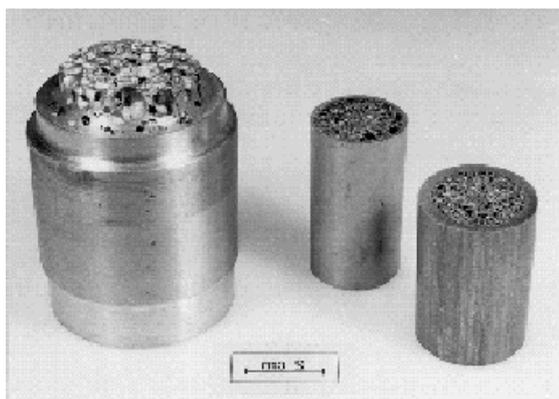
Metallic Foams - Figure 5



Methods for filling metal tubes with metal foam [39]

↩ first occurrence in article

Metallic Foams - Figure 6



Foam-filled aluminum tubes (Foam: AlSi12 alloy, tube: 6061 alloy)