Aluminium foams: on the road to real applications

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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 available. 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 decompose in-situ, causing the formation of bubbles. A further way is to prepare supersaturated metal-gas systems under high pressure and initiate bubble formation by pressure and temperature control. Yet a further class of techniques starts from solid precursors containing a blowing agent. These can be prepared by mixing metal powders with a blowing agent, compacting the mix and then foaming the compact by melting. Alternatively, casting routes can be used to make such precursors. The unique properties of foams promise a variety of applications ranging from light-weight construction, impact energy absorption to various types of acoustic damping and thermal insulation.

Introduction

Solid metallic foams exhibit many unusual combinations of physical and mechanical properties that make them attractive in a number of engineering applications. For instance, when used as cores of structural sandwich panels they offer high stiffness in conjunction with low weight. Their use in energy absorption devices exploits their capacity to undergo large deformations at almost constant stress.

In the literature and in practical use there is some confusion concerning the term "metallic foam" which is often used for any kind of non-dense metallic material. We define:

- *cellular metals*, which are materials with a high volume fraction of voids - usually more than 70% - made up of an interconnected network of struts and plates,
- *porous metals*, which have isolated, roughly spherical pores. Mechanically, pores do not interact if the porosity is less than about 20%,
- *metal foams*, having polyhedral cells, which may be either *closed* with membranes separating the adjoining cells, or *open*, if there are no membranes across the faces of the cells so that the voids are interconnected. Solid foams originating from a liquid foam are closed. Some prefer to call open-cell metallic structures *metal sponges*.

Examples for such structures are shown in **Figure 1**.

The manufacture of cellular metals in the most general sense is described in review articles and conference proceedings [1-4]. A dedicated web-page offers up-to-date information [5]. The present paper will be restricted to metals closed-cell *foams*. These are low density liquid-gas mixtures at some stage of their evolution which are then solidified to yield solid foams. As surface tension governs morphology in the liquid state – isolated gas bubbles separated from each other by metal films – the corresponding solid metal foams show a similar morphology. We shall first review different manufacturing routes and then discuss applications.

Foaming liquid metals

Metallic melts can be foamed by creating gas bubbles in the liquid provided that the melt has been prepared such that the emerging foam is fairly stable during processing. This can be done by adding fine ceramic powders or alloying elements to the melt which form stabilising particles, or by other means.

Currently three ways for foaming metallic melts are known: firstly, by injecting gas into the liquid metal, second, by causing an in-situ gas release in the liquid by admixing gas-releasing blowing agents to the molten metal, third, by causing the precipitation of gas which was previously dissolved in the liquid.

Foaming melts by gas injection ("Cymat / Metcomb")

The first way for foaming aluminium and aluminium alloys is already being exploited commercially by Cymat Aluminium Corp. in Canada [6]. Silicon carbide, aluminium oxide or magnesium oxide particles are used to enhance the viscosity of the melt, usually one of many aluminium alloys which can be used. The volume fraction of the reinforcing particles typically ranges from 10 to 20%, the mean particle size from 5 to 20 µm. The melt is foamed by injecting gases (air, nitrogen, argon) into it using specially designed rotating impellers or vibrating nozzles which generate 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 and solidify.

The foamed material is either used in the state it comes out of the casting machine, having a closed outer surface, or is cut into the required shape after foaming. Owing to the high content of ceramic particles, machining of these foams can be a problem. Advantages of this direct foaming process include the large volume of foam which can be continuously produced and the low densities which can be achieved.

Quite recently the melt foaming route has been revolutionised by scientists working at the Light-metals Competence Centre (LKR) and the metallurgical plant in Kleinreichenbach, both in Austria [7]. The key point is a new concept of gas injection which leads to foams with an excellent uniformity of cell sizes. Moreover, by casting the foam into moulds, complex-shaped foamed parts with a closed outer skin can be generated. Commercial exploitation of this type of aluminium foam –called "*Metcomb*" – is on the way. Selected data on "Cymat" and "Metcomb" are summarised in Table I.

Foaming melts with blowing agents ("Alporas")

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. 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. The Chinese company Jiangsu Tianbo Light-Weight Materials in Nanjing has also set-up a production plant recently. In a first production 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 oxides, e.g. $CaAl_2O_4$, or intermetallics which thicken the liquid metal. After this, titanium hydride (TiH_2) is added (typically 1.6 wt.%) which acts as a blowing agent as it releases hydrogen gas. The melt soon starts to expand slowly and gradually fills the foaming vessel. The entire foaming process can take 15 minutes for a typical batch of about 0.6 m^3. 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 foams produced in this way - trade name *"Alporas"* – have a very uniform pores structure. Typical data are listed in Table I.

Solid-gas eutectic solidification ("Gasar/Lotus")

A method developed about 15 years ago exploits the difference in gas solubility of liquid and solid metals [10]. A melt is first charged with gas under high pressure (up to 50 atms.), e.g. with hydrogen or nitrogen. If the temperature is then lowered to below the melting point of the metal, the gas will precipitate. Under favourable conditions gas bubbles are entrapped in the metal. The resulting pore morphologies are largely determined by the gas 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 word "*gasar*" was coined for such materials which means "gas-reinforced" in a Russian acronym. Recently the method has been adapted in Japan [11] where the material was named "*lotus*-structured" for its resemblance with lotus roots (see **Figure 1b**).

Foaming metallic precursors

A second class of metal foaming techniques adds an additional step to the process chain. Instead of foaming the melt directly a precursor is prepared which contains a uniformly dispersed blowing agent. The foam is created in a second step by melting the precursor during which the blowing gas evolves and bubbles are created. The advantage of this process is that complex shaped parts can be manufactured by filling moulds with the precursor and foaming. Foamable precursors have been prepared in three ways: by densifying mixtures of powders in the solid state, by shaping such powder blends by thixo-casting and by admixing blowing agent powders to melts.

Foaming of powder compacts ("Foaminal/Alulight")

The production process begins with the mixing of metal powders - elementary metal powders, alloy powders or metal powder blends - with a powdered blowing agent, after which the mix is compacted to yield a dense, semi-finished product [12]. 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 during further processing. The next step is melting the matrix material causing the blowing agent to decompose. 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. Aluminium and its alloys, tin, zinc, brass, lead, gold and some other metals and alloys been foamed by choosing appropriate blowing agents and process parameters.

Sandwich panels consisting of a foamed metal core and two metal face sheets can be obtained by roll-cladding conventional sheets of metal – aluminium, steel or titanium - to a sheet of foamable precursor material. The resulting composite can be shaped in an optional step, e.g. by deep drawing. The final heat treatment, in which only the foamable core expands and the face sheets remain dense, then leads to sandwich structures [13].

The process is now in the stage of a small-scale commercial exploitation by the German companies Schunk (Gießen) and Karmann (Osnabrück) and the Austrian company Alulight (Ranshofen). The names *"Foam-in-Al"* and "*Alulight"* have been coined for these foams.

Foaming thixo-cast precursor material ("Thixofoam")

Instead of consolidating the metal powder mixtures in the solid state by powder pressing one can carry out the densification by thixo-casting in the semi-solid state [14]. For this the powder blend is first pre-densified to billets by cold isostatic pressing, yielding densities of about 80%. These billets are then heated to a temperature at which the respective alloy is semi-solid and are then cast to shapes in a die-casting machine. The resulting precursor can be foamed as described in the previous section by re-melting the precursor. The advantage of this route is that the precursor can have a complex shape and does not have to be worked further. Moreover, compared to the powder densification method, casting leads to a more isotropic precursor material and therefore to foams with a very uniform pore structure.

Foaming of ingots containing blowing agents ("Formgrip")

Foamable precursor material can be prepared without using metal powder at all. For this titanium hydride particles are admixed to liquid metal after which the melt is solidified. The resulting precursor can then be foamed in the same way as described in the previous two sections. To avoid premature hydrogen evolution during mixing, solidification has to be either rapid or the blowing agent has to be passivated to prevent it from releasing too much gas at this stage.

One way is to use a die-casting machine. The powdered hydride is injected into the die simultaneously with the melt **[15]**. Normal casting alloys such as A356 without ceramic additives have been used. However, achieving a homogeneous distribution of TiH_2 powders in the die is challenging. Alternatively, TiH_2 powders can be added to a melt by comparatively slow stirring and subsequent cooling provided that they are subjected to a cycle of heat treatments that form an oxide barrier on each hydride particle to delay their decomposition **[16]**. In order to obtain stable foams, melts containing 10-15 vol.% SiC particles are used. The process has been baptised "*Formgrip*" which is an acronym of "Foaming of reinforced metals by gas release in precursors".

Applications

Metal foams have properties which make them attractive in light-weight construction, for energy absorption devices and for acoustic or thermal control. All applications are of interest to automotive industry, which has been extremely interested in them since they were first developed. Potential applications also exist in ship building, aerospace industry and civil engineering [**1**]. The various applications as shown in **Figure 2** are:

- *Light-weight construction*: foams can be used to optimise the weight-specific bending stiffness of engineering components. The bending stiffness of flat foam panels of a given weight, width and length, e.g., is approximately proportional to their thickness, and therefore inversely related to density. True optimisation, however, calls for more elaborated solutions as will be discussed below. In any case, light-weight construction exploits the quasi-elastic and reversible part of the load-deformation curve (see small graphs in Figure 2)
- *Energy-absorption*: owing to their high porosity foams can absorb a large quantity of mechanical energy when they are deformed, while stresses are limited to the compression strength of the material. Foams can therefore act as impact energy absorbers which limit accelerations in crash situations. This mode exploits the horizontal, irreversible part of the load-deformation diagram. As metal foams can have much higher collapse strengths than polymer-based foams – up to 20 MPa - they can find applications in areas not accessible to foams up to date.
- *Acoustic and thermal control*: Foams can damp vibrations and absorb sound under certain conditions. Moreover, their thermal conductivity is low. These properties are not outstanding – polymer foams are much better sound absorbers – but they could be useful in combination with other features of the foam. This application makes use of the internal configuration of a foam, namely the labyrinth of struts and the associated air-filled voids.

A metal foam is more likely to be competitive if not just one, but two or even more properties are exploited. True multi-functionality would, e.g., imply that a light-weight construction reduces noise and absorbs energy in the case of a crash.

In most cases a bare foam is not the optimum solution for a given engineering problem. Stiffness optimisation calls for sandwich panels with dense face sheets rather than for simple foam panels [17] and foam can act very efficiently if filled into dense metallic sections or hollow cast parts which are reinforced by the foam filling.

The aluminium foam sandwich (AFS) technology of Karmann, a German car builder, is one example [18]: These sandwich panels are 3D-shaped and very stiff at a relatively low weight. **Figure 3** shows a flat panel from which the top face sheet has been torn off to make the pore structure visible and to demonstrate the quality of bonding. By deforming the foamable precursor prior to foaming, quite complex shapes can be manufactured which is a clear advantage to competing technologies such as honeycomb or waffle structures. In combination with new construction principles AFS could replace conventional stamped steel parts in a car and lead to significant weight reductions. At the same time they could also reduce the number of parts in the car frame, facilitate assembly and therefore reduce costs while improving performance because such sandwich panels act as vibration dampers beside being light.

Another example are crash absorbers. As insurance companies are enforcing safety guidelines that protect the passengers in the event of a collision and also minimize damage done to the car and the ensuing repair costs, automakers have been using the idea of a crash box to meet these standards. Such crash boxes are placed between the impact beam and the front rail of the car. They deform to absorb all the energy of a 15 km/hr crash, protecting more expensive front end components in addition to the car frame. One choice for the crash box is an empty tube that plastically collapses and in doing so absorbs energy. The failure mode of the tube is to create plastic folds along the length of the tube at regular intervals. By inserting an aluminium foam core in the centre of the tube there is an increase in energy absorption. The outer tube still folds along its length but the number of folds increases; as a result the energy absorbed by the filled tube is greater than the empty tube. Energy is also absorbed by the foam core and the total energy absorbed by the foam filled tube is greater than the sum of the individual energies of the tube and the foam. **Figure 4** shows a deformed foam-filled tube. Studies done by FIAT and the Norwegian University of Science and Technology show that, along with the improved axial energy absorption, there is also great improvement of energy absorption in off-axis collisions. Cymat is currently in a joint development program with Valeo to design a crash box for implementation in Valeo's front-end module systems.

Yet another application makes use of the beneficial properties of Al foam inside a dense aluminium shell both during manufacture and in use after. One starts from a shaped part of aluminium "metcomb" foam. The part has a dense outer skin and can therefore be used as core in low-pressure die-casting during which a composite consisting of a cast outer surface and a light-weight inner core is formed. Such composites have advantageous service properties such as higher stiffness and improved damping compared to the empty hollow part while its weight is only marginally higher. LKR (Austria) has designed an engine mount for the German car maker BMW based on such composites (see **Figure 5**). It can be loaded with the high weight of a car engine and absorbs mechanical vibration by internal dissipation into thermal energy. As fracture toughness of such composites is high, these parts would also increase safety in crash situations.

Resume

A number of new metal foaming technologies have been developed in the past decade which now offer a wide range of different forms of this exciting material. Compared to early developments in the 1960s and 70s the quality of metal foam has been improved and the possibilities for making composites widened. It seems quite realistic that metal foams will find real applications very soon in cars, ships, aircrafts or even spacecrafts.

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The 3rd International Conference on Cellular Metals and Metal Foaming Technology (MetFoam2003) will be held from 23-25 June 2003 in Berlin (Germany). Contact: www.hmi.de/events/metfoam/

Table

Table I. Some typical properties of three families of aluminium foams.

property	Cymat or Metcomb-type foams	Alporas-type foams	Alulight-type foams
typical products	panels: ≤ 16×1×0.2 m^3 complex shaped parts (Metcomb)	blocks: ≤ 2×0.6×0.5 m^3 slices: 10 mm thick	blocks: ≤ 1×0.5×0.2 m^3 complex shaped parts sandwich panels: ≤ 2×1×0.02 m^3
density range (g/cm^3)	0.069 – 0.54	0.18 – 0.24*	0.3 – 0.7*
pore diameter (mm)	3 – 25	2 – 10	2 – 10
cell wall thickness (μm)	50 – 85	---	50 – 100
alloy range available	Al alloys	Al, AlZnMg	Al-, Zn-, Pb-, Sn-, Au-alloys
literature	[6][7][8][17]	[9][17]	[12][13][14][17][18]
web information of foam manufactures or distributors	www.cymat.com www.lkr.at www.hkb.at	www.tanbor.com www.gleich.de	www.alulight.com www.ifam.fhg.de www.lkr.at www.vasf.de

* w/o skin

Figures

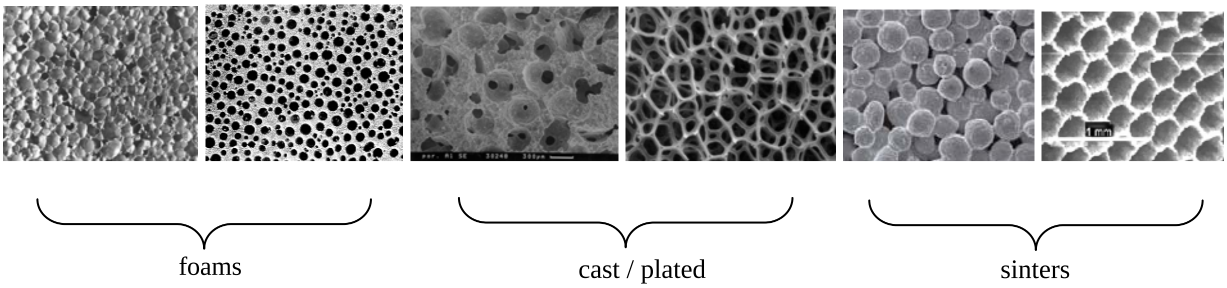

Figure 1. Different types of cellular metal. Only the two leftmost structures were foamed in the liquid state: a) aluminium foam, b) copper lotus structure. These are followed by: c) a cast Al sponge made by infiltration of space holders, d) an open cell nickel structure made by coating a polymer foam e) sintered bronze powders and f) a cellular material with oriented pores made by powder metallurgy.

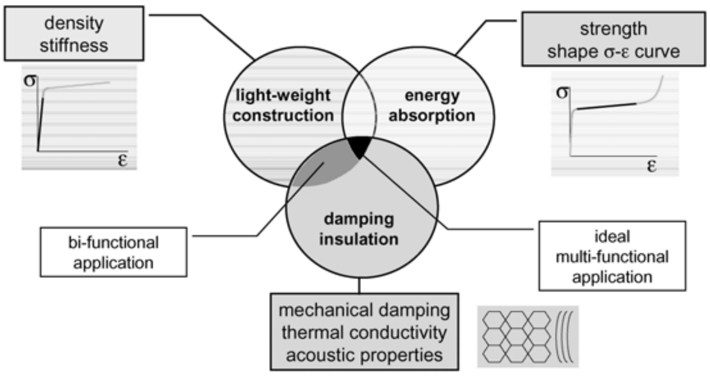

Figure 2. Application ranges of metallic foam in automotive industry. Boxes contain the relevant property of the foam which makes it useful for one of the three application fields given in the circles.

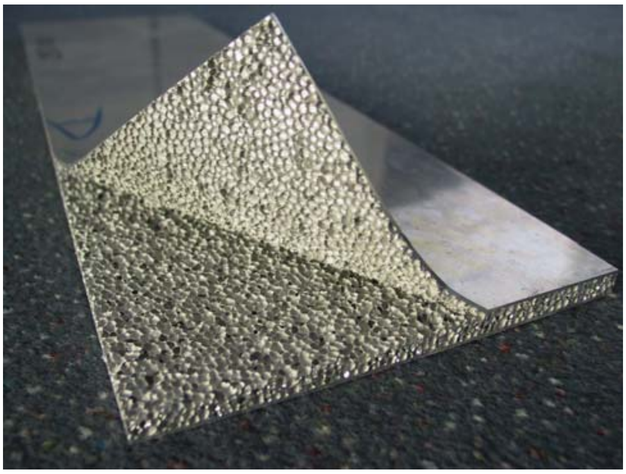

Figure 3. Aluminium foam sandwich (AFS) produced by Karmann, Osnabrück (Germany). Face sheet has been peeled off to make the pore structure visible. Note that the strength of bonding between face sheets and foam core is larger than the inherent strength of the foam (courtesy of Karmann).

Figure 4. Prototypes of crash absorbers based on aluminium extrusions with a filling of Cymat aluminium foam (courtesy of Cymat).

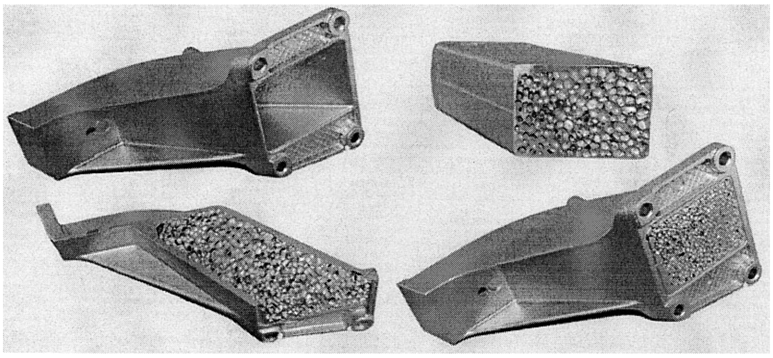

Figure 5. Prototype of a BMW engine mount manufactured by LKR Ranshofen (Austria). From upper left to lower right: empty casting, bare foam core, section through composite part consisting of foam core and cast shell, entire composite part (courtesy of LKR)