Aluminium foams for lighter vehicles

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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 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 start 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 in vehicle design ranging from light-weight construction, impact energy absorption to various types of acoustic damping and thermal insulation. Four applications are discussed, including a lifting arm on a lorry, an automobile and a train crash box, and a motor bracket.

Keywords: light metal foam; light-weight construction; energy obsorption; crash protection.

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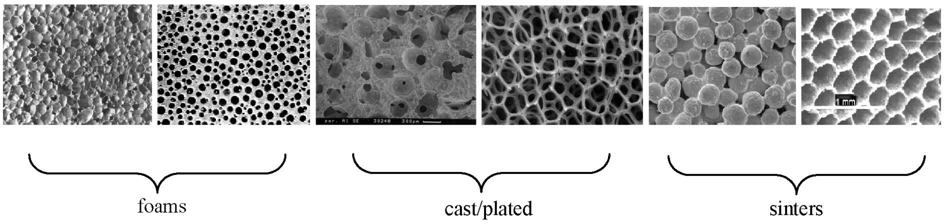
1 Introduction

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.

Examples for what is nowadays getting popular as ‘metallic foams’ are shown in Figure 1 including a variety of different metals, alloys and also a wide range of morphological features. In this paper, we restrict ourselves to aluminium as a base metal and to actual foams, i.e. materials which were generated by gas injection into a specially prepared melt and subsequent solidification to a durable foam. These materials have closed cells in contrast to many other ‘foams’. The literature on such foams is quite ample now with the best information available from review papers, books and conference proceedings (Banhart, 2001; Ashby et al., 2000; Banhart et al., 1999, 2001, 2002a; Degischer and Kriszt, 2002) and a dedicated web page offering up-to-date information (www.metalfoam.net).

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



2 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: first, 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. The former two have technological relevance at the moment.

2.1 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 (Harte and Nichol, 2001). Silicon carbide, aluminium oxide or magnesium oxide particles are used to stabilise 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 μm 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 (Leitlmeier et al., 2002). 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* foams are summarised in Table 1.

Table 1 Some typical properties of three families of aluminium foams

Property	*Cymat or Metcomb-type foams*	*Alporas-type foams*	*Alulight-type foams*
Typical products	panels: ≤$16 \times 1 \times 0.2$ m^3 complex-shaped parts (Metcomb)	blocks: ≤$2 \times 0.6 \times 0.5$ m^3 slices: 10 mm thick	blocks: ≤$1 \times 0.5 \times 0.2$ m^3 complex-shaped parts AFS-sandwich panels: ≤$2 \times 1 \times 0.02$ 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	Ashby et al. (2000), Harte and Nichol (2001), Leitlmeier et al. (2002) and Kenny (1996)	Ashby et al. (2000) and Miyoshi (1999)	Ashby et al. (2000) Baumgärtner et al. (2000), Baumeister, (2000), Stanzick et al. (2002) Seeliger (1999, 2001)
Web information of foam manufactures or distributors	www.cymat.com www.lkr.at www.hkb.at	www.metalfoam.co.kr www.gleich.de	www.alulight.com www.alm-gmbh.de (AFS) www.ifam.fhg.de, www.ifam.iwu.de www.lkr.at

*w/o skin.

2.2 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 (Miyoshi, 1999). The Korean company Foam Tech has also set-up a production plant recently. In the 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 five owing to the formation of oxides, e.g. $CaAl_2O_4$, or intermetallics which stabilise the liquid foam. 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 pore structure. Typical data are listed in Table 1.

3 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 the 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.

3.1 Foaming of powder compacts

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 (Baumgärtner et al., 2000). 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 which causes 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 (Baumeister, 2000).

The process is now in the stage of a small-scale commercial exploitation by the German companies Schunk (Gießen) and ALM (Saarbrücken) and the Austrian company Alulight (Ranshofen). The names '*Foam-in-Al*' and '*Alulight'* have been coined for these foams; aluminium foam sandwich panels are called *AFS*.

3.2 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 (Stanzick et al., 2002). 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.

3.3 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 (Melzer et al., 1998). 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 have been subjected to a cycle of heat treatments before that form an oxide barrier on each hydride particle to delay their decomposition (Gergely and Clyne, 2000). 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'.

4 Properties of aluminium foams

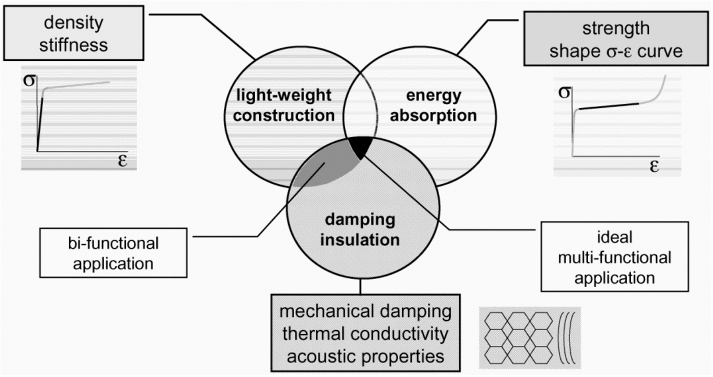
Metal foams are quite complex systems with respect to both their macro- and microstructure. Microstructure and local mechanical properties are governed by alloy composition, conditions of foaming and cooling and an optional post-foaming heat treatment of the material. By varying the conditions of heat treatment alone, the compression strength of 6XXX alloy foams could be varied by a factor of three (Lehmhus and Banhart, 2003). Macroscopic morphological features, such as pore size or curvature of cell walls, have a pronounced influence on mechanical response. As such features are inherently statistical and also depend on processing conditions very much, it is quite difficult to set up a reliable database for aluminium foams describing their properties in a simple way. Nevertheless, some general design rules for aluminium foams have been derived (Ashby et al., 2000) and progress has also been seen on the field of modelling of mechanical properties. Such modelling efforts include simple uniaxial compression properties, fracture and fatigue phenomena (Banhart et al., 2002, pp.325, 369, 393, 409, 413, 431). Even multi-axial loading can be understood with the now well-established Deshpande-Fleck model (Deshpande and Fleck, 1999; Ashby et al., 2000).

5 Applications: general concepts

Metal foams have properties which make them attractive in light-weight construction, for energy absorption devices and for acoustic or thermal control. All these fields are relevant for 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 (Banhart, 2001). 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. For example, the bending stiffness of flat foam panels of a given weight, width and length is approximately proportional to their thickness, and therefore inversely related to density. True optimisation, however, calls for more elaborate 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.

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



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

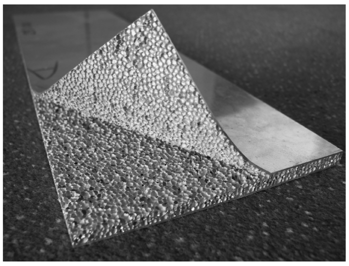
In most cases, a bare foam is not the optimum solution for a given engineering problem. Stiffness optimisation calls for sandwich panels with dense face sheets rather than for simple foam panels (Ashby et al., 2000) and foam can act very efficiently if filled into dense metallic sections or hollow cast parts which are reinforced by the foam filling.

5.1 Applications: examples

5.1.1 Aluminium foam sandwich technology

The AFS technology developed in 1994 by Fraunhofer-IFAM in Bremen and Karmann GmbH, a German car builder, is one example of the use of foams in conjunction with dense material (Seeliger, 1999, 2001). These sandwich panels can be 3D-shaped and are 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 constructional 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 besides being light. AFS sandwich parts can be joined with aluminium sections by various welding techniques which facilitate their integration into the car body (Banhart et al., 2002).

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)



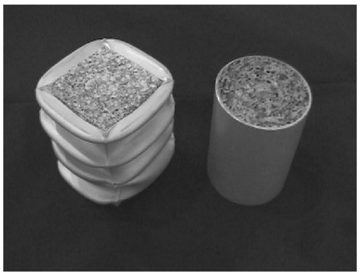
Recently advanced light-weight materials (ALM) – a spin-off company of Karmann's metal foam activities – has constructed a novel lifting arm supporting a repair platform mounted on a small lorry (see Figure 4, r.h.s.). The objective was to increase the vertical range of the platform from 20 m to 25 m while keeping the total weight of the vehicle below 3.5 tonnes because otherwise the lorry would fall into a different category. This would imply that the staff would have to use a special driver's licence thus creating higher operational costs. Finite-element calculations showed that a welded structure based on aluminium sections would not be able to support the weight of the platform while a steel-based structure would be at least 80 kg to heavy. AFS panels could be successfully used to solve the problem. The solution consists of flat AFS panels which were MIG-welded together (see Figure 4, l.h.s.). The total weight is 105 kg which is acceptable. The vertical force at the turning point of the arm is 65 kN, the torque at the bottom part of the arm 85 kNm. The components were tested quasi-statically and in cyclic tests to up to 80000 cycles and showed no signs of damage. There is now a small-scale production of parts for the manufacturer of the lifting system, Teupen GmbH Gronau (Germany) (www.teupen.de). AFS is successful in this case because it allows one to increase the lifting height of the system while keeping the weight below a certain threshold given by legislation.

Figure 4 Base of a lifting arm made from AFS sandwich panels. Manufacturer is Advanced Light-weight Materials GmbH in Saarbrücken, Germany (courtesy of ALM)

5.1.2 Foam-filled tubes and sections

Another example for aluminium foam applications is crash absorbers. As insurance companies are enforcing safety guidelines that protect the passengers in the event of a collision and also minimise 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 5 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 programme with Valeo to design a crash box for implementation in Valeo's front-end module systems.

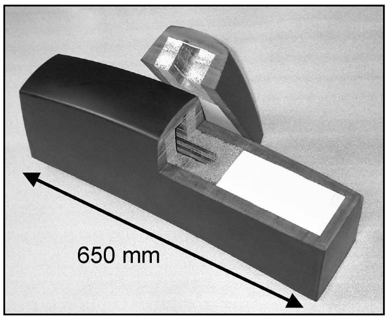
Figure 5 Prototypes of crash absorbers based on aluminium extrusions with a filling of Cymat aluminium foam (courtesy of Cymat)



5.1.3 Metal foams as reinforcement of polymer structures

Crash absorbers are also required for rail-based vehicles. One example is railcars (Geyer, 2003). Again, the driver for technological innovation is safety issues. Trams must have an underride protection which prevents pedestrians hit by the tram to be dragged under the vehicle. This and other consideration sets certain design rules which have to be obeyed. At the same time, effective crash protection for collisions with heavier objects such as, e.g., cars is required. As mounting space is very limited, the use of aluminium foam can be useful. A collaboration of three companies (the tram manufacturer Siemens, the manufacturer of the crash absorber Hübner, and the metal foam producer Schunk Sintermetalltechnik, all Germany) developed the crash system shown in Figure 6 for the modular tram concept COMBINO® which allows to realise customer-given design requirements with components based on the same chassis. The crash absorbers are now being produced in quantities of hundreds and are also sold to other tram manufacturers and tram operators for refurbishment.

Figure 6 Crash energy absorber for a tram built for the COMBINO vehicle system (courtesy of Hübner, Schunk, Siemens)



5.1.4 Aluminium foams as cores for castings

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* or *Alulight* 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 (Leitlmeier et al., 2002; Körner et al., 2002). 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) and the German car maker BMW have jointly designed an engine mounting bracket based on such composites (see Figure 7). The produced parts show no noticeable infiltration of the core itself by the melt during casting. It can be loaded with the high weight of a car engine and absorbs mechanical vibrations by internal dissipation into thermal energy. Stiffness is enhanced and, as fracture toughness of such composites is high, these parts also increase safety in crash situations.

Figure 7 Prototype of a BMW engine mounting bracket manufactured by LKR Ranshofen (Austria). From left to right: empty casting, entire composite part consisting of foam core and cast shell, section through composite part (courtesy of LKR)

5.2 Economics of aluminium foams

Aluminium foam is not a cheap material. The number of processing steps is high despite efforts to facilitate manufacture, and raw materials such as powders and MMCs are also expensive. Therefore, simple direct replacement of existing materials by aluminium foam is not viable. As already mentioned, multi-functionality is one key point for bringing aluminium foams into application. Multi-functionality means that different typical properties of aluminium foam are exploited, including mechanical, thermal, acoustic and other properties, and also advantages such as easy net-shaping ability or advantages in secondary processing such as cutting, joining or recycling.

The cost situation of various aluminium foam production routes has been analysed by various groups (see e.g. Maine and Ashby, 2000). Not surprisingly, one of the main problems in the present stage of market exploration is the low volume of production. Higher production volumes would help lowering fixed costs and therefore the total price. Alulight – the Austrian aluminium manufacturer – is building a new plant for producing large quantities of aluminium foam precursor material (pressed powder mixture $Al + TiH_2$). As a result, the price for this precursor is expected to drop from 20 €/kg in 1995 to 5 €/kg in 2005, the present price being 12 €/kg (Schäffler, 2003).

Other strategies for making aluminium foams cheaper include the use of secondary aluminium, MMC scrap or less expensive blowing agents such as calcium carbonate instead of titanium hydride for foaming (Cambronero, 2003). However, as process stability is often negatively influenced by impurities, care has been taken not to deteriorate foam properties by using inferior raw materials. Quite some research is still required here.

6 Conclusion

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 1970s, the quality of metal foam has been improved and the possibilities for making composites widened. Production output is at a comparatively small scale at the moment but producers are learning how to improve their processes and how to reduce costs, thus making these materials more interesting for the mass market. It seems quite realistic that metal foams will find wider use in transport industry very soon.

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