Aluminum Foams: On the Road to Real Applications

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Abstract

Metallic foams have become an attractive research field both from a 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 that decompose *in situ*, causing the formation of bubbles. Another method 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 begins with 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 compacted mix by melting. Alternatively, casting routes can be used to make such precursors. The unique properties of foams offer promise in a variety of applications ranging from lightweight construction and impact-energy absorption to various types of acoustic damping and thermal insulation.

Keywords: *alloys, casting, cellular solids, industrial applications, metals, mechanical properties, powder metallurgy, structural materials.*

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 in structural sandwich panels, they offer high stiffness in conjunction with low weight. Their use in energy-absorption devices exploits their capacity to undergo large deformation under almost constant stresses.

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. In this article, these materials are defined as follows:

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

Examples of these structures are shown in Figure 1.

Manufacturing cellular metals is described, in the most general sense, in review articles and conference proceedings,[1–4] and a dedicated Web page offers up-to-date information.[5] This article limits itself to metallic closed-cell foams. These are low-density, liquid–gas mixtures at some stage of their evolution that 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 first review different manufacturing routes and then discuss applications.

Foaming Liquid Metals

Metallic melts can be foamed by creating gas bubbles in the molten liquid, provided that the melt is prepared in such a manner that the emerging foam is fairly stable during processing. This can be done by adding fine ceramic powders or alloying elements to the melt to form stabilizing particles, for example. The exact stabilization mechanism is still undetermined, but most likely involves the generation of repulsive forces that prevent the film from thinning.

Currently, there are three known ways of foaming metallic melts: first, by injecting gas into the liquid metal; second, by causing an *in situ* gas release in the liquid

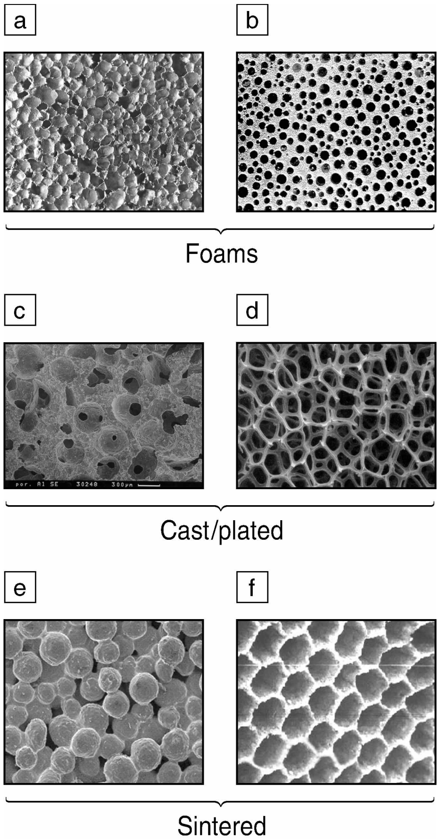

Figure 1. Examples of cellular metals: (a) aluminum foam, (b) copper "lotus" structure, (c) cast aluminum sponge made by the infiltration of space holders, (d) open-cell nickel structure made by coating a polymer foam, (e) sintered bronze powders, and (f) a cellular material with oriented pores made by powder metallurgy. Only (a) and (b) were foamed in the liquid state. Width of each image: (a) 50 mm, (b) 8 mm, (c) 3 mm, (d) 2 mm, (e) 0.8 mm, and (f) 1.8 mm.

by admixing gas-releasing blowing agents to the molten metal; and third, by causing the precipitation of gas that was previously dissolved in the liquid. The precipitated gas nucleates and forms bubbles that contribute to the foam structure.

Foaming Melts by Gas Injection

The first method developed for foaming aluminum and aluminum alloys is already being used commercially by Cymat Aluminum Corp. in Canada.[6] Silicon carbide, aluminum oxide, or magnesium oxide particles are used to enhance the viscosity of the melt, which is chosen from one of many aluminum alloys that can be used. The volume fraction of the reinforcing particles typically ranges from 10% to 20%, with a mean particle size of 5–20 μm.[7] The melt is foamed by injecting gases (air, nitrogen, argon) into the melt using specially designed rotating impellers or vibrating nozzles that generate gas bubbles in the melt and distribute them uniformly. The resultant viscous mixture of bubbles and metal floats to the surface, 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 the 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 in which 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, these foams can be difficult to machine. Advantages of this direct foaming process include the large volumes of foam that can be continuously produced and the low densities that can be achieved.

Quite recently, scientists working at the Light Metals Competence Center (LKR) and the metallurgical plant in Kleinreichenbach, Austria,[8] developed a new concept of gas injection that leads to foams with excellent cell size uniformity; this involves the relatively gentle generation (compared with the violent dispersion of gases using rotating impellers) of a multitude of uniform bubbles in the melt. Moreover, by casting the foam into molds, complex–shaped foamed parts with a closed outer skin can be produced. Commercial development of this aluminum foam, called Metcomb, is planned. Selected data on gas-injection foams are summarized in Table I.

Foaming Melts with Blowing Agents

A second way to foam melts directly is to add a blowing agent to the melt. The blowing agent decomposes under the influence of heat and releases gas, which then propels the foaming process. Shinko Wire Co. in Amagasaki, Japan, has been producing foams by this method since 1986 with production volumes of reportedly up to 1000 kg of foam per day. Jiangsu Tianbo Lightweight Materials in Nanjing, China, also set up a production plant recently.

In the first production step, ~1.5 wt% calcium metal is added to an aluminum 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 that thicken the liquid metal. Titanium hydride (TiH_2) is then added (typically 1.6 wt%), which acts as a blowing agent, as it releases hydrogen gas. The melt soon starts to expand and gradually fills the foaming vessel. The entire foaming process can take 15 min for a typical batch of about 0.6 m^3. After the vessel is cooled to a temperature below the melting point of the alloy, the liquid foam turns into solid aluminum foam containing some additional titanium and can be taken out of the mold for further processing. The foams produced in this way have a very uniform pore structure. Typical data for blowing-agent foams are listed in Table I.

Solid–Gas Eutectic Solidification

A method developed about 15 years ago exploits the difference in the gas solubility of liquid and solid metals.[10] A melt is first charged with gas (e.g., hydrogen or nitrogen) under high pressure (up to 50 atm). The temperature is then lowered below the melting point of the metal, precipitating the gas. Under favorable conditions, gas bubbles are trapped in the metal. The resulting pore morphologies are largely determined by the gas content, the pressure over the melt, the direction and rate of heat removal, and 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 (total pore volume/total volume of foam) from 5% to 75%. The term *GASAR*, a Russian acronym for gas-reinforced, was coined for such materials. Recently, the method was adapted in Japan,[11] where the material was called "lotus-structured" for its resemblance to lotus roots (see Figure 1b).

Foaming Metallic Precursors

A second class of foaming techniques for metals adds an additional step to the process chain. Instead of foaming the melt directly, a precursor containing a uniformly

Table I: Typical Properties of Three Families of Aluminum Foams.

	Gas-Injection Foams	Blowing-Agent Foams	Powder-Compaction Foams
Typical End Products	Panels: ≤16 m × 1 m × 0.2 m Complex-shaped parts	Blocks: ≤2 m × 0.6 m × 0.5 m Slices: 10 mm thick	Blocks: ≤1 m × 0.5 m × 0.2 m Complex-shaped parts Sandwich panels: ≤2 m × 1 m × 0.03 m
Density Range (g/cm³)	0.069–0.54	0.18–0.24[a]	0.3–0.7[a]
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
References	6–8,17	9, 17	12–14, 17, 18
URLs for Manufacturers 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.iwu.fhg.de/english/index.htm www.lkr.at www.vasf.de, www.alm-gmbh.de

[a] Not including skin.

dispersed blowing agent is prepared. The foam is created in a second step by melting the precursor, at which time the blowing gas evolves and bubbles are created. The advantage of this process is that complex-shaped parts can be manufactured by filling molds with the precursor, then performing the foaming step. Foamable precursors are prepared in three ways: densifying mixtures of powders in the solid state; shaping such powder blends by thixocasting (heating to a temperature between the solidification and liquefaction temperatures to form a semisolid that can be cast); and admixing blowing-agent powders with melts.

Foaming 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, semifinished 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 must be carried out very carefully because residual porosity or other defects will lead to poor results during further processing.

Next, the matrix material is melted, 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. Aluminum and its alloys, tin, zinc, brass, lead, gold, and some other metals and alloys are 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 (aluminum, steel, or titanium) onto 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 commercially available on a small scale by Schunk (Giessen, Germany) and Karmann (Osnabrück, Germany) and Alulight (Ranshofen, Austria) under the names Foam-in-Al and Alulight.

Applications for Open-Cell Metallic Foams

B. Leyda

Metallic foams have been used for many years in selected niche applications, frequently in the military and aerospace industries. With the Cold War now far behind us, these foams are being introduced more heavily into civilian industry. Satellite heat exchangers, explosion-energy absorbers, silencers, and porous rocket-engine fuel injectors made with metallic foams are finding new uses, often in technology-intensive industries such as the manufacture of semiconductors, electronics, and alternative-energy vehicles. Ironically, metallic-foam military components that often relied upon biological analogies in their design processes are now being adapted to biological uses (e.g., medical implants). As industrial applications expand, metallic foams are being produced using a wider variety of raw materials, in both closed-cell and open-cell structures, by an increasing number of manufacturers.

Metallic foams offer a combination of properties that are being exploited in increasingly diverse applications. They can be designed to crush at a roughly constant stress to large deformations, absorbing substantial kinetic energy without generating high peak stresses. The automobile industry is considering metallic foams for auto-body components to absorb the kinetic energy of a crash impact, reducing the deceleration of the vehicle and minimizing the risk of passenger injury. Honeycomb materials have been used for many years as energy-absorbing structures in the telescoping columns that support front and rear car bumpers. While these structures have provided major improvements in safety, the separate bumper and its support columns are complex, expensive, heavy, and only function at greatest efficiency if impacted directly from the front or rear. Metallic foams are mechanically isotropic and absorb the same amount of energy regardless of the impact direction. Consequently, they do not require the separate column structures that honeycombs do; rather, they can be incorporated directly into the body-part structure. This enables the entire vehicle body to absorb impact energy regardless of the impact direction. Low-cost, continuously producible closed-cell aluminum foams have the greatest potential in this application.

Open-cell metallic foams are attractive as heat exchangers due to their combination of high thermal conductivity and interconnected porosity that enables fluid flow. Heat exchangers generally heat or cool gases or liquids using extended surface-area structures such as fins and tubes. If heat-exchanger performance is measured in terms of initial cost, current mass-produced technologies perform very well. If, however, performance is measured in terms of size or design flexibility, the current technologies are often found wanting. As an example, modern electronic devices are becoming so small and powerful that they cannot be thermally controlled using conventional air-cooled heat exchangers. Liquid cooling can be substituted, but this creates a variety of new problems that are technically difficult to overcome, and whose solutions face an acceptance barrier in the industry. Metallic foams, which provide better heat-transfer coefficients and higher specific surface areas than traditional fins, are being used more and more frequently to break through the classical heat-exchanger performance barrier. This often requires more powerful air fans, but this is generally considered acceptable in order to maintain the basic simplicity and reliability of air-cooled systems.

Metallic foams are also being introduced into liquid-cooled systems. It is common, particularly in the semiconductor manufacturing industry, for a customer to demand greater heat removal from an existing system while requiring that the size and interconnections of the heat

Typical data for powder-compaction foams are listed in Table I.

Foaming Thixocast Precursor Material

In addition to consolidating the metal powder mixtures in the solid state by powder pressing, densification can be carried out by thixocasting in the semisolid state.[14] The powder blend is first predensified into billets by cold isostatic pressing, yielding densities of about 80%. These billets are heated to a temperature at which the respective alloy is semisolid and then are cast to shape in a die-casting machine. The resulting precursor can be foamed as described in the previous section by remelting 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 with the powder-densification method, casting leads to a more isotropic precursor material and, hence, to foams with a very uniform pore structure.

Foaming Ingots Containing Blowing Agents

Foamable precursor material can be prepared without using metal powder at all. For this, titanium hydride particles are admixed with 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 must be rapid, or the blowing agent must be passivated, to prevent the release of too much gas at this stage. One way to achieve this is with 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. This process is known as FORMGRIP, which is an acronym for foaming of reinforced metals by gas release in precursors.

Applications

Metal foams have properties that are attractive in lightweight construction, for energy-absorption devices, and for acoustic

exchanger remain constant in order to minimize other design changes. This upgrade may also be combined with a coolant change from distilled water to one of the low-conductivity hydrocarbon coolants in order to reduce the risk of damage if a leak occurs. Such demands are often beyond the capability of fin technology, but are routinely fulfilled by metallic foams. This is accomplished by using the foam to increase the heat-transfer surface area and thus compensate for both the increased heat load and low conductivity of the coolant.

In living systems, it is common for structures to perform multiple functions. In a tree trunk, for example, the wood cells both provide the structural strength to support the tree and circulate fluids from the roots to the leaves. Metallic foams often perform multiple functions, in mimicry of their natural counterparts.

One promising power source for future vehicles is the hydrogen–oxygen fuel cell. Within these devices, metallic foams frequently perform multiple functions: they provide structural support for thin interface films while simultaneously collecting electrical current. In addition, they often are used as *in situ* heat exchangers to ensure that delicate chemical processes operate within the optimum temperature range regardless of internal power output or external environmental conditions.

The storage vessels that supply hydrogen to the fuel cells also use metallic foams. In order to eliminate the need for heavy and potentially dangerous high-pressure gas bottles in fuel-cell-powered vehicles, hydrogen is occasionally stored by absorption in hydride powders. The hydride powders are generally contained within lightweight low-pressure canisters or tubes. There are often two problems with this approach. First, the absorption and release of hydrogen from these powders generate or demand heat. The required heat must pass from the canister walls through the hydride powder. Since the thermal conductivity of these powders is very low, the hydrogen flow rate in a simple canister is also very low, thus increasing the refueling time and reducing the potential power output of the fuel cell. Hydride powders also swell when they absorb hydrogen and shrink when they release it. While very entertaining to watch on a time-lapse video, this phenomenon creates an additional headache for hydride-storage designers. Second, hydride powders or granules pack very closely in the storage vessels, thus limiting the space between granules for the hydrogen to flow. The shrinkage and swelling of repeated operating cycles in a normal gravity field tend to pack the powders increasingly tighter in the bottom of the canister. After some time, hydrogen cannot flow into or out of the storage bed fast enough to be effective.

By performing multifunctional roles, metallic foams solve both of these problems. Metallic-foam inserts are tightly installed in the canisters, and the hydride granules are then loaded into the foam. As a heat exchanger, the foam significantly increases heat flow within the entire hydride bed and enables rapid hydrogen loading and release. By introducing a secondary internal structure, the initial packing efficiency of the hydride granules is disrupted, and abnormally large hydrogen-gas paths are provided. In addition, by nesting only a limited number of granules within each individual foam cell structure, the hydride can shrink and swell with minimal stress from adjacent granules. This minimizes the cyclic packing tendency and ensures that the gas paths remain open with the passage of time.

In many of the previous examples, exotic Cold War applications have led to equally exotic, multifunctional civilian uses. However, some metallic-foam components have undergone a simpler metamorphosis. Metallic-foam pistol silencers easily evolved to perform the same function in pneumatic nailing and stapling guns for the construction industry in order to meet noise safety standards. Similarly, small metallic-foam inserts that once uniformly catalyzed or ionized rocket propellants are now used to electrically charge spray paint. By providing the opposite charge to the item being painted, a more uniform paint coverage is ensured, thus minimizing waste overspray and air pollution. Metallic foams are also being introduced into electrical and electromagnetic applications. Metallic foams developed to shield electrical conductors in missiles from electromagnetic interference are being adapted to isolate sensitive semiconductor plasma processes from mutual interference. The numerous sharp ligament tips at the surface of foams are also being examined to increase emission efficiency within electron guns and other particle-generating devices.

or thermal control. Applications of these materials are of particular importance to the automotive industry, which has been extremely interested in metal foams since they were first developed. Potential applications also exist in shipbuilding, the aerospace industry, and civil engineering.[1] Key categories of applications for metallic foams in the automotive industry are (see Figure 2):

- *Lightweight construction:* Foams can be used to optimize the weight-specific bending stiffness of engineering components. 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 optimization, however, calls for more elaborate solutions (as will be discussed later). In any case, lightweight construction exploits the quasi-elastic and reversible part of the load-deformation curve.
- *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 used, for example, to limit acceleration in vehicle 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 currently accessible to polymer, ceramic, or glass foams.
- *Damping and insulation:* 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 the foam, namely, the labyrinth of struts and associated air-filled voids.

A metal foam is more likely to be competitive with alternative engineering solutions if two or more properties are exploited. True multifunctionality would, for example, imply that a lightweight construction reduces noise and absorbs energy in the case of an automobile crash.

In most cases, a bare foam is not the optimum solution for a given engineering problem. Stiffness optimization calls for sandwich panels with dense face sheets rather than simple foam panels,[17] and foam can perform very efficiently if enclosed in dense metallic skin sections or used as a reinforcing filling for hollow cast parts. The aluminum foam sandwich (AFS) technology of the German car builder Karmann is one example;[18] these sandwich panels are three-dimensional, very stiff, and relatively lightweight. Figure 3 shows a panel from which the top face sheet has been removed to make the pore structure visible and demonstrate the quality of bonding. By deforming the foamable precursor using deep drawing or simple bending prior to foaming, complex shapes can be manufactured. This is a clear advantage over competing technologies such as honeycomb or waffle structures. In combination with new construction principles, the AFS could replace conventional stamped-steel parts in a car and lead to significant weight reductions. At the same time, because such sandwich panels act as

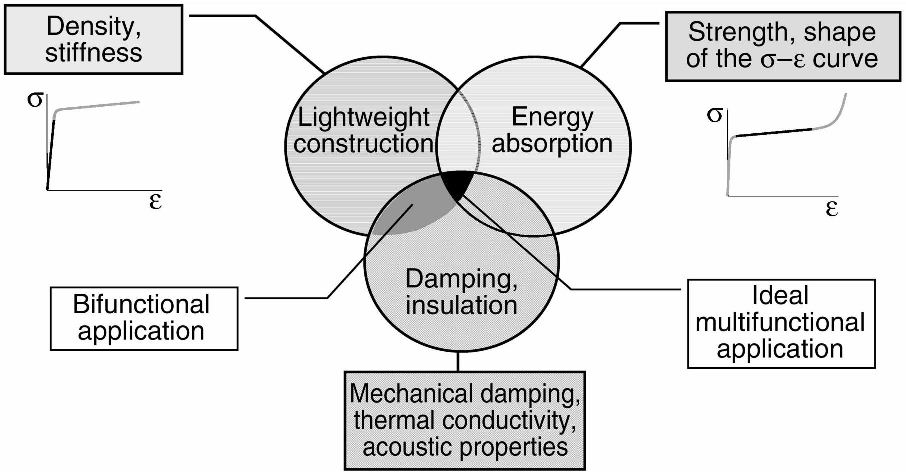

Figure 2. Application categories for metallic foams in the automotive industry. Boxes contain the relevant properties that make the foams useful for one of the three application fields given in the circles.

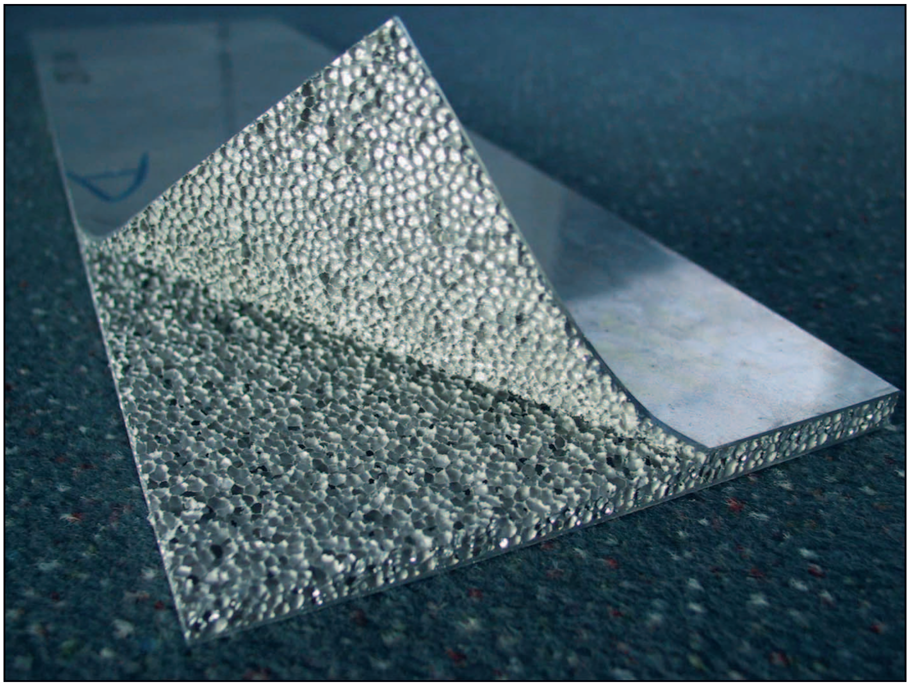

Figure 3. Aluminum foam sandwich (AFS) produced by German automaker Karmann (Osnabrück, Germany). The face sheet has peeled back to make the pore structure visible. The bonding strength between the face sheets and the foam core is greater than the inherent strength of the foam. Width of panel = 30 cm. (Photo courtesy of Karmann.)

vibration dampers in addition being lightweight, they could be used to reduce the number of parts in the car frame, thereby facilitating assembly and reducing costs while improving performance.

Another example is crash absorbers. As insurance companies are enforcing safety guidelines that protect passengers in the event of a collision and also minimize vehicle damage, automakers are 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. The front rail runs down the side of the car perpendicular to the bumper beam. They deform to absorb all the energy of a 15 km/h (9.3 mph) crash, protecting expensive front-end components and the car frame as well as the passengers within. 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 aluminum foam core in the center 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 in energy absorption in off-axis collisions because isotropic foams can absorb energy from all directions. Cymat is currently in a joint development program with Valeo to design a crash box for implementation in Valeo's front-end module systems.

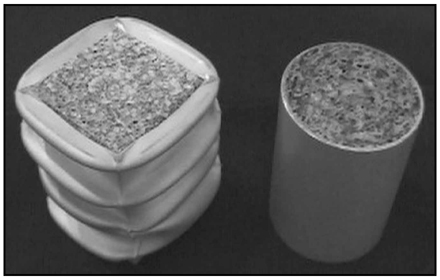

Figure 4. Prototypes of foam-filled tubes developed as crash absorbers. The tubes are aluminum extrusions filled with an aluminum foam. Tube diameter = 65 mm. (Photo courtesy of Cymat.)

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

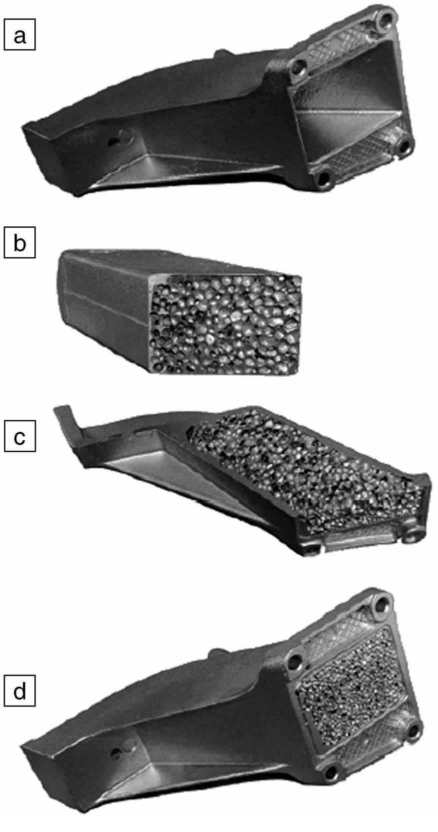

Figure 5. Prototype of an automobile engine mount manufactured by LKR Ranshofen (Austria). (a) Empty casting, (b) bare foam core, (c) section through composite part consisting of foam core and cast shell, and (d) complete composite part (25 cm long). (Photo courtesy of LKR.)

Summary

A number of new metal foaming technologies have been developed in the past decade that enable a wide range of forms for this exciting material. Compared with early developments in the 1960s and 1970s, the quality of metal foams has improved, and the possibilities for making composites using it have widened. It seems quite realistic that metal foams will find real applications very soon in cars, ships, aircrafts, and even spacecraft.

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