Metallic Foams

J. Banhart, J. Baumeister, and M. Weber, Fraunhofer-Institute for Applied Materials Research, Bremen

Introduction

CELLULAR MATERIALS find widespread use in everyday life for cushioning, insulating, damping, constructing, and filtering purposes and in many other applications. Highly porous materials are known to have a high stiffness combined with a very low specific weight. For this reason, cellular materials frequently occur in nature as constructional materials.

Even pure metals and metallic alloys can be produced as cellular solids or metal foams. In the past, metal foams were prepared by adding a foaming agent to a molten metal after properly adjusting the viscosity of the melt (Ref 1, 2). The foaming agent is usually a powdered metal hydride, for example, TiH_2, which releases hydrogen gas when heated to temperatures above approximately 400 °C. As soon as the foaming agent comes into contact with the molten metal, it decomposes such that there is little time to achieve a homogeneous distribution of the gas-releasing powder. Because this process is difficult to control, more widespread application could not be achieved with this technology.

A new P/M process for production of metal foams has been developed at the Fraunhofer-Institute for Applied Materials Research (Bremen, Germany) (Ref 3, 4). This enlarges the application range of cellular materials with the advantageous mechanical and thermal properties of metal foams and fewer ecological problems in comparison to polymer foams. The process has been developed for aluminum foams and is currently being extended to other metals and alloys such as tin- and zinc-base foams (Fig. 1). These nonferrous foams are the subject of this article.

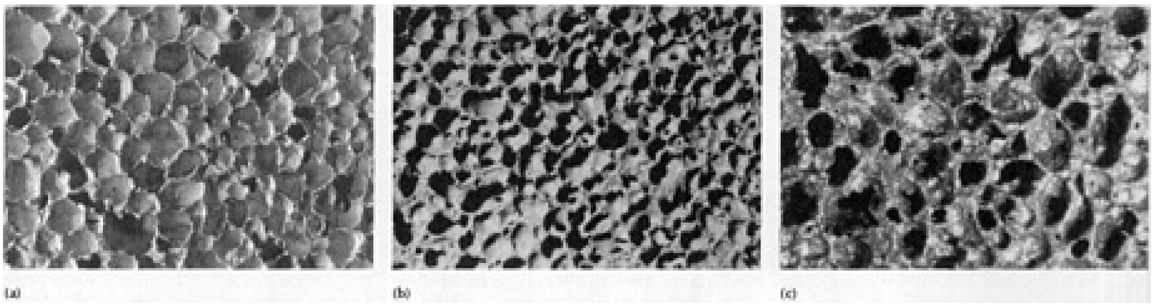

Fig. 1 Optical micrographs of (a) aluminum (4 to 1), zinc (6 to 1), and lead (4 to 1) foams

For the production of steel foams, the type of foaming agent must be changed to prevent excessive oxidation. The foaming process for steel also has to take place in an inert atmosphere or in a vacuum. Using steel foams, the applicable temperature range could be extended. As an example, the exhaust manifold of car engines could be manufactured from this material. Due to the strongly reduced thermal conductivity of the manifold, it would require less time to reach the normal operating temperature of the exhaust catalyst, leading to a reduction in emissions.

References

1. J.A. Ridgeway, "Cellarized Metal and Method of Producing the Same," U.S. Patent 3,297,431, 1967
2. S. Akiyama et al., "Foamed Metal and Method for Producing the Same," European Patent Application EP 0 210 803 Al, 1986
3. J. Baumeister, "Method for Producing Porous Metal Bodies," German Patent DE 40 18 360, 1990
4. J. Baumeister and H. Schrader, "Methods for Manufacturing Formable Metal Bodies," German Patent DE 41 01 630, 1991

Metallic Foams

J. Banhart, J. Baumeister, and M. Weber, Fraunhofer-Institute for Applied Materials Research, Bremen

Production Methods

The P/M process for production of nonferrous foams uses conventional foaming agents with compacted metal powders. Commercially available powders (such as aluminum, zinc, tin, or lead) are mixed with a foaming agent by conventional means, such as a tumbler mixer. In this simple manner, a very homogeneous distribution of the gas-releasing powder is obtained without the necessity of agitating a pool of molten metal. Subsequent to mixing, the powder blend is compacted to give a dense, virtually nonporous, solid semifinished product. Several compaction methods can be employed that range from uniaxial pressing to powder extrusion and even to roll compaction. The result of the densification step is a foamable material that, upon heating to temperatures within the range of the melting point, expands into a highly porous cellular solid with a closed-pore structure. This means that each particle of the foaming agent is embedded in a gas-tight metallic matrix so that, when decomposition of the foaming agent begins, the released gas cannot escape via some interconnected residual porosity.

Numerous shapes can be produced by this method (Ref 3, 5). The semifinished form can be processed by conventional techniques such as rolling, swaging, or extrusion to provide rods, sheets, profiles, and so forth, if desired. Merely heating this material to the melting point initiates the foaming process so that it is also possible to obtain complex-shaped foamed articles. Arbitrarily shaped hollow molds are filled with the foamable material and subsequently heated to effect foaming. It was found that thin-walled molds are particularly advantageous because they allow for a close temperature control of the foaming process.

Using appropriate heating methods, it is possible to selectively expand metallic foams. This means that certain regions of the material can be kept at a high density that facilitates joining to other materials.

Sandwich-type structures also can be produced via several methods. The simplest one is to glue sheets of conventional materials to a sheet of foamed metal. However, due to the low thermal stability of the resins, a metallic bonding of the sheets might be preferred. For example, this can be achieved by using a roll-cladding process.

Foaming agents are chosen to have a decomposition temperature that matches the melting point of the metal or alloy. Various foaming agents have been shown to yield good results for the metals in consideration (aluminum, zinc, lead). Among the foaming agents used are metal hydrides such as titanium, zirconium, and magnesium hydride, which have decomposition temperatures between 280 and 600 °C. Figure 1 shows typical cross sections of aluminum, zinc, and lead foams obtained.

Foaming Kinetics. Metal foam parts are usually produced by heating up a piece of foamable precursor material in a hollow mold and allowing the expanding melt to fill the volume. Foaming times and temperatures can be varied, and their influence on the foam properties studied. This procedure, however, does not yield any direct information about the foaming kinetics, that is, the time dependence of the volume of the expanding metallic melt and the corresponding temperatures. Therefore, an experiment was designed (Ref 6) that allows for measurement of such data. The device consists of a metal tube with a lid on one side and a movable piston on the other side. The position of the piston is measured with a magnetic detector and read out into a computer. Moreover, a thermocouple measures the temperature inside the tube. For an expansion experiment, a piece of foamable material is placed into the tube, which is then closed by the piston. The entire device is heated up at a selected heating rate. The expanding melt causes a displacement of the piston that, together with the temperature reading, generates a pair of functions $V(t)$ (volume) and $T(t)$ (temperature) that characterizes the expansion kinetics.

The expansion behavior of metal foams has been investigated for a variety of metals and alloys. Three examples are shown here: the foaming of an Al-12Si alloy, the expansion of Zn-4Cu, and the expansion of pure lead.

The expansion of Al-12Si is depicted in Fig. 2. As can be seen, the volume expansion takes place in four stages: first, before the melting temperature of the alloy (577 °C) is reached, the expansion is small, resembling the volume increase also found for samples without foaming agent. The actual expansion starts when the metal starts to melt and softens and the released gas can inflate the pores. In this stage II the volume increases to 2.5 times the initial volume. The expansion even accelerates as the liquidus temperature is exceeded, and the now rising temperature releases more and more gas (stage III). After the maximum expansion has been achieved, the foam collapses (stage IV) due to the now-decreasing pressure in the cells as the foaming agent is exhausting.

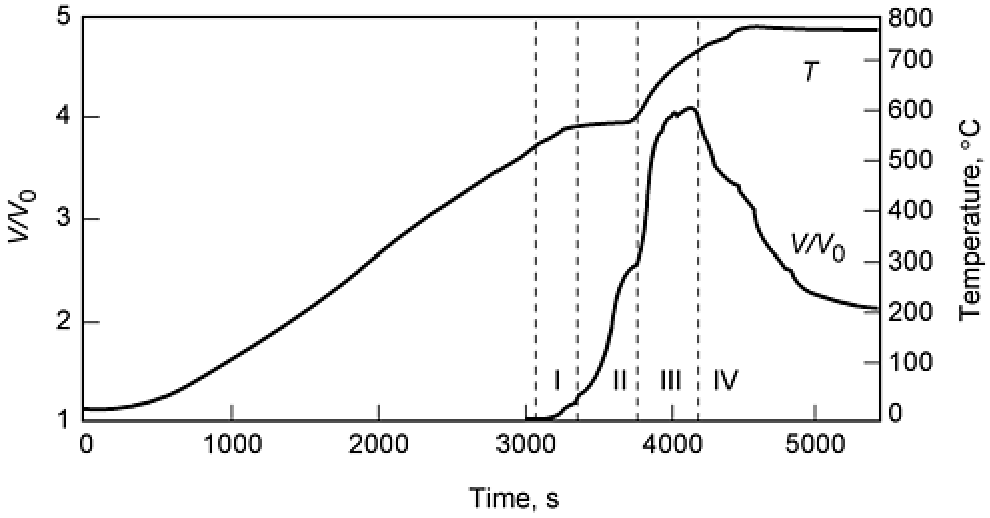

Fig. 2 Expansion characteristics of Al-12Si (heating rate: 10 K/min).

The expansion of the zinc-copper foam is shown in Fig. 3. Here, the expansion takes place in just two stages: expansion (I) and collapse (II). There is hardly any sign of an expansion below the melting temperature, and the main expansion is not separated into two stages. The reason for this can be seen in the much higher heating rate that was applied in this case. One sees that the expansion is time controlled and that foaming is ruled by a complex interplay between melting and decomposition processes. Note that the temperature shows a kink at the melting temperature in Fig. 3. This can be attributed to an alloying process between zinc and copper, which were contained in the powder mixture as elementary powders. For lead foams, the expansion takes place in three stages (Fig. 4): first there is a slight expansion after the melting point has been reached (I), then the expansion accelerates as the temperature increases after all the metal has become molten (II) and, finally, the foam collapses (III). The reason for the slight decrease of volume between stages I and II is not yet clear and is being investigated.

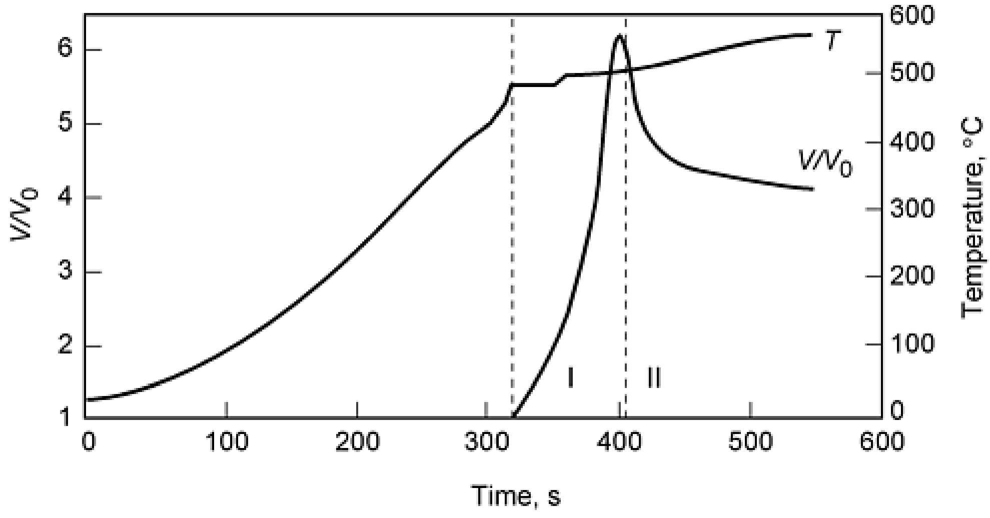

Fig. 3 Expansion characteristics of Zn-4Cu (heating rate: 100 K/min)

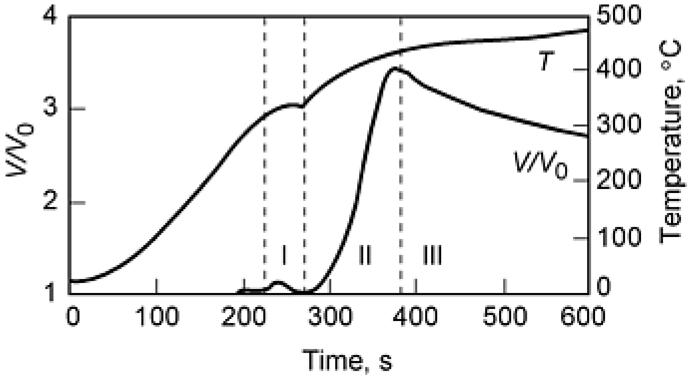

Fig. 4 Expansion characteristics of lead (heating rate: 100 K/min)

Influence of Foaming Agent Content. It is important to know how much of the foaming agent is necessary to obtain the desired density of the foamed metal and how low the achievable densities are. In order to get this information, foamable precursor material was prepared with various contents of foaming agent for two different alloys. The content of the foaming agent was varied between 0 and 3%, the alloys chosen were pure aluminum (99.5% Al) and eutectic (Al-12Si). Each piece of precursor material was expanded to its maximum volume at the same temperature, and each measurement was repeated three times. The averaged results are shown in Fig. 5. The samples without any foaming agent exhibit the lowest expansion rate, which is about 15%. This expansion comes from the P/M preparation of the precursor material, which produces a high content of oxides, hydroxides, and gas in the powder compact that are then released upon heating. Already a small content of 0.1% TiH_2 causes an expansion of more than 50% in volume, producing a structure that justifies the name "foam." The maximum expansion is obtained for foaming agent contents of more than 0.7% and is independent of the foaming agent content up to 3%. Therefore, in practical applications foaming agent contents up to 1% are chosen. The maximum porosities that can be achieved are 80% for aluminum and 85% for Al-12Si. Higher porosities can be produced by changing the alloy composition or by adding reinforcement particles, but not by increasing the content of the foaming agent.

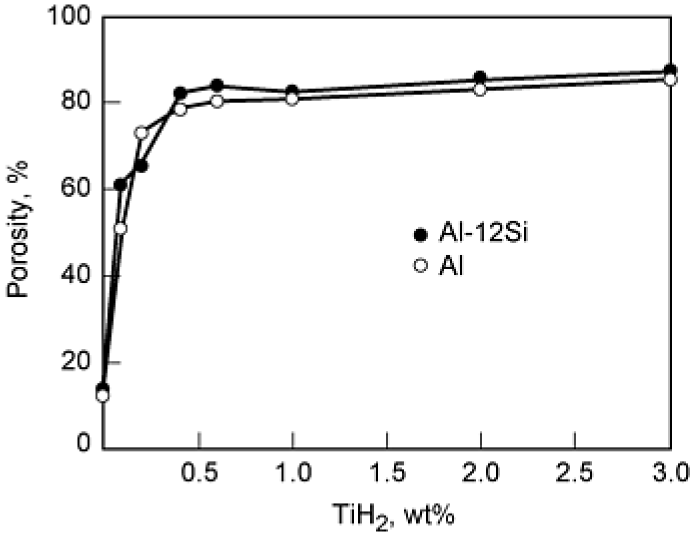

Fig. 5 Maximum porosity achieved when foaming aluminum alloys with various contents of foaming agent. Solid circles, Al-12Si; open circles, aluminum

---

References cited in this section

3. J. Baumeister, "Method for Producing Porous Metal Bodies," German Patent DE 40 18 360, 1990
5. J. Baumeister, J. Banhart, and M. Weber, *Int. Conf. on Materials by Powder Technology,* F. Aldinger, Ed., DGM Informationsgesellschaft Oberursel (Germany), 1993, p 501
6. M. Weber, Ph.D. thesis, Technical University Clausthal, 1995

Metallic Foams

J. Banhart, J. Baumeister, and M. Weber, Fraunhofer-Institute for Applied Materials Research, Bremen

Properties of Metal Foams

Like any other cellular solid, metal foams are characterized by a very low specific weight. Using the P/M technological approach described above, density values ranging between 0.5 and 1 g/cm^3 are usually obtained with aluminum foams, although values down to 0.2 g/cm^3 and up to 2 g/cm^3 can even be achieved. Due to its closed porosity, aluminum foam floats upon water.

Mechanical properties of foams are usually determined by compression testing. To show the superior strength of metal foams, a polyethylene foam (density, 0.12 g/cm^3) is compared to an Al foam (Al-4Cu alloy: density 0.45 g/cm^3) in Fig. 6. In both materials, the initial porosity is about 83 to 87%. For better comparison, the strength scale of the PE foam was enlarged by a factor of 30. The curves show a behavior that is typical for highly porous cellular solids: an initial, approximately linear regime is followed by an extended plastic collapse plateau, truncated by a densification response at high strains during which the stress again increases steeply. Due to this special form of the compressive stress-strain curve, foamed materials have a high capacity to absorb great amounts of energy at a relatively low strength level.

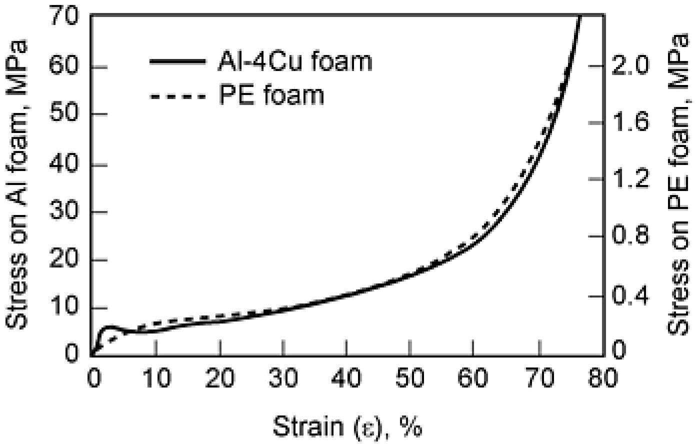

Fig. 6 Stress-strain curve of an Al-4Cu foam (solid line, left scale) and of a polyethylene (PE) foam (broken line, right scale)

To characterize the energy absorption behavior of foamed materials, it is convenient to determine that efficiency η. For a given strain, this parameter is defined as the ratio of the actual absorbed energy to the energy that would be absorbed by an ideal absorber. Because an ideal cushioning material would exhibit a "rectangular" stress-strain curve, a real absorber can only approximate this behavior, giving rise to values below 1, or 100%, for the efficiency.

Compression Strength. Foamed materials show a universal compression behavior that makes them valuable for energy absorption applications: when loaded they first deform elastically until at a certain stress plastic deformation of the cell walls starts. This deformation typically takes place at nearly constant stress until the entire structure is densified. The stress that marks the beginning of the foam collapse is called the compression strength and can be extracted from the stress-strain diagram. Stress-strain curves were measured on specimens of metal foams with various densities (Ref 7).

The compression strength of a series of Al-12Si and Zn-4Cu alloys of various densities are shown as a function of foam density in Fig. 7. Simple theory based on cubic cells predicts a dependence of compression strength from density for an open-pore foam of the form (Ref 8):

$$\sigma_f = 0.3 \cdot \sigma_{ys}\left(\frac{\rho_f}{\rho_s}\right)^n$$

where ρ_f and ρ_s are the densities of the foamed and the massive material, respectively, and σ_{ys} is the yield strength of the matrix material. For closed pores, the formula is more complicated, but experience shows that the mechanical properties are determined by the thick cell edges and not by the thin membranes so that the equation for the open porosity works well. In order to allow for a direct reading of the exponent *n,* the data were plotted logarithmically in Fig. 7; the value of *n* can then be obtained by fitting the experimental data to a straight line, thus yielding:

Alloy	Exponent, *n*	Yield strength (σ_{ys}), MPa
Al-12Si	1.78	660
Zn-4Cu	2.00	990

The value for the exponent is in fairly good agreement with the value derived from the cubic model (1.5), whereas the value for σ_{ys} is much too high in both cases. One should keep in mind that the determination of the parameters *n* and σ_{ys} is not very accurate because of the considerable scatter especially for Al-12Si. As the pore structure of the Zn-4Cu foams is rather homogeneous, the relation between the foam density and its compression strength can be established in a more reliable way for these alloys. The results indicate that the cubic model gives a good description of the relative variation of compression strengths as the density is varied, but is not able to predict the absolute value of such strengths. This finding is compatible with earlier measurements on aluminum-base foams, where exponents between 1.5 and 3 were found, but the parameter σ_{ys} was always too high.

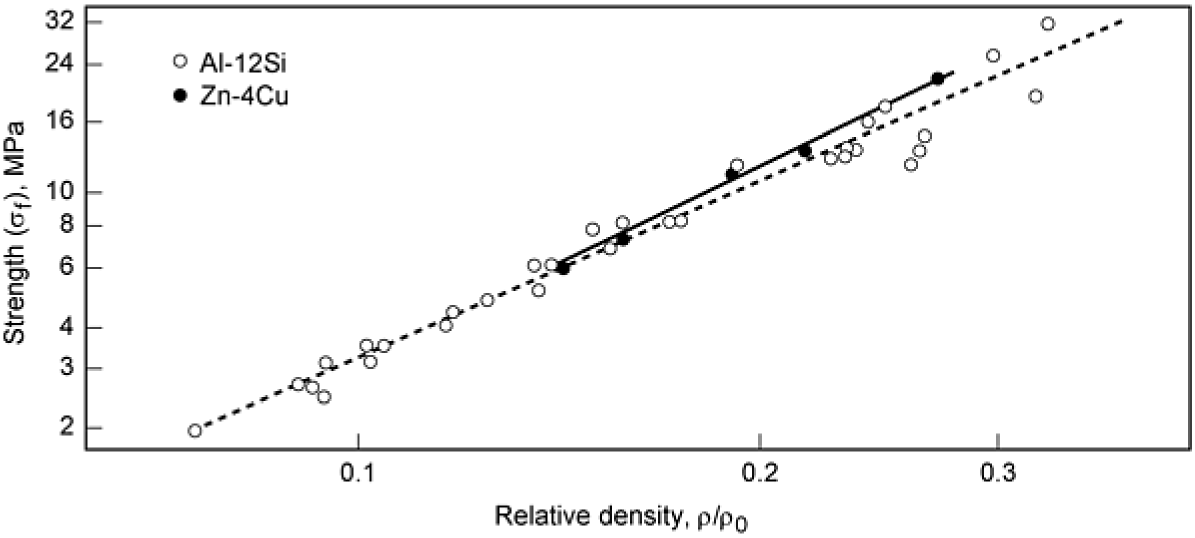

Fig. 7 Compression strength of a series of Al-12Si (open circles) and Zn-4Cu (solid circles) alloys. Test specimens were 30 by 30 by 40 mm. Testing was performed at 5 mm/min. As the transition from the initial linear increase of stress to the plateau regime is not defined unambiguously, the stress at 10% (Zn) or 20% (Al) deformation was taken as the compression strength (σ_f).

Elastic Modulus. The determination of the elastic modulus of foamed metals should not be carried out the convenient way, that is, by evaluation of the slope in the elastic portion of the stress-strain curve. Even in this early stage of loading there are some plastic contributions that result from setting of the specimen, heterogeneities of the pore structure, and other defects. It is therefore preferable to apply elastic loading of the samples, for example, by means of vibrational testing (as described below) or ultrasonic methods.

The elastic modulus of foamed Al-12Si was investigated using vibrational bending tests. The resonance frequency (first order) of rectangular specimen 250 by 10 by 5 mm^3 in size was determined, and the resulting storage modulus calculated. Because the values are independent of frequency, it can be concluded that the results represent the static modulus.

Considering the simplified nature of the cubic model, it is surprising that the predictions from this model describe the elastic modulus to a quite reasonable degree. The equation for the elastic modulus states that (Ref 8):

$$E_f + E_s\left[\left(\varphi\frac{\rho_f}{\rho_s}\right) + (1-\varphi)\left(\frac{\rho_f}{\rho_s}\right)\right]$$

where E_f is the modulus of foamed material, E_s is the modulus of the massive material, and ϕ describes the contribution of material in the cell edges, and where (1 - ϕ) is the contribution from cell faces. A straight line with a slope of 2 would be expected in a double-log plot of the foam modulus versus density. From Fig. 8, it can be seen that this type of correlation has actually been observed (solid line in Fig. 8). An even better approximation of measured values is obtained by taking ϕ= 0.88 (dashed line). This means that most of the material in the aluminum foams investigated is concentrated in the cell edges rather than in the cell faces.

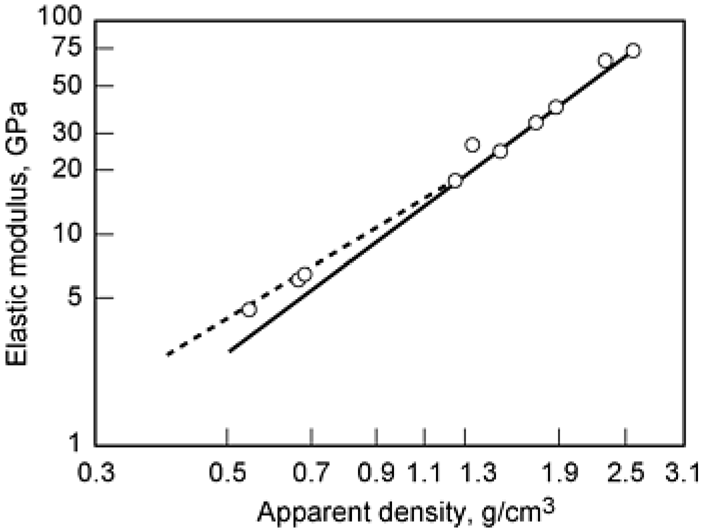

Fig. 8 Elastic modulus of Al-12Si foams as a function of the apparent density

Mechanical Damping. Measuring loss factors of metallic materials is a nontrivial task due to the relatively low level of damping and variables affecting the loss factor. Such variables are the friction between sample and bearings and air friction. Damping also depends on strain amplitude. Reproducible results without these contributions can be obtained by using flat strips of metal foam, which have an attached head. The whole structure is made of one block of foam. The head is used to clamp the sample with a considerable force and to reduce the slip of the sample relative to the mount to a minimum.

The sample was forced into vibrations by magnetic excitation. The resonance amplitude was monitored with a capacitive detector. By sweeping the applied frequency, resonance curves could be recorded. The resonance frequency ν and the width of the resonance $\Delta\nu$ were determined, thus yielding a loss factor:

$$\eta = \Delta\frac{\nu}{\nu}$$

Various samples were made of Al-12Si foam by foaming blocks of this material and cutting out the samples. The density covered a wide range between 0.67 and 2.65 g/cm^3 (unfoamed precursor material). In this density range, η varied from 20 × 10^{-4} (at 0.67 g/cm^3) to 12 × 10^{-4} (at 2.65 g/cm^3).

In order to study the frequency dependence of the damping, the samples were shortened step-by-step, thus making the resonance frequency higher. The loss factor was measured for each length in the second mode of flexural vibration at the frequency determined by the cantilever length. If was found that the loss factor is not a smooth function of frequency for any of the samples, but fluctuates strongly as the frequency changes. The probable explanation is that the loss factor is nearly frequency independent for aluminum foams in reality and that frequency variations are not due to microstructural, frequency-dependent effects but are rather caused by some inhomogeneous material distribution that is characteristic for the particular sample. Therefore, the damping capacity of a highly porous metallic foam is not a simple materials property, but also characteristic of the part itself.

Damping is strongest in the foams with the lowest densities. It is well known that any kind of porosity enhances damping due to the stress concentration and what is called mode conversion around pores. This mechanism applies to microporosity as well as to the large pores found in metal foams. Especially in thin membranes an external force, even if small, can lead to high, multiaxial stresses that induce atomic rearrangements and viscouslike sliding of atoms relative to each other.

Another mechanism is of macroscopic origin: the cell walls of metallic foams sometimes contain cracks and holes that may either originate from the gas released by the foaming agent during the foaming process or from the contraction of the foamed body while cooling to room temperature after foaming. These defects may give rise to an extra frictional contribution caused by the relative movement of the crack or hole walls with respect to each other.

Compact precursor materials that are not foamed have a much higher loss factor than conventional cast aluminum materials. This is due to the P/M production of this material, which yields an aluminum matrix with embedded silicon particles, remnants of the oxide films that covered each aluminum powder particle and also foaming agent particles. This causes extra friction at the interfaces of these particles. It is also well established that P/M materials have higher damping capacities than cast ones.

References cited in this section

7. M. Weber, J. Baumeister, J. Banhart, and H.D. Kunze, *Proc. Powder Metallurgy World Congress PM94* (Paris), Les Editions de Physique, 1994, p 585
8. L.J. Gibson and M. Ashby, *Cellular Solids,* Oxford, 1988

Metallic Foams

J. Banhart, J. Baumeister, and M. Weber, Fraunhofer-Institute for Applied Materials Research, Bremen

Applications

One application of metal foams is for energy absorption. Aluminum foams can also be used for lightweight constructions. The replacement of honeycomb structures with sheets of foamed aluminum may lead to reduced costs and more isotropic properties. For example, the German automotive supplier Karmann is considering replacement of the bulkhead and the rear seat wall of convertible cars by sandwiches containing an aluminum foam core and aluminum face sheets (Fig. 9). The parts are up to ten times stiffer in comparison to the conventional steel parts used in the past and weigh 30 to 50% less.

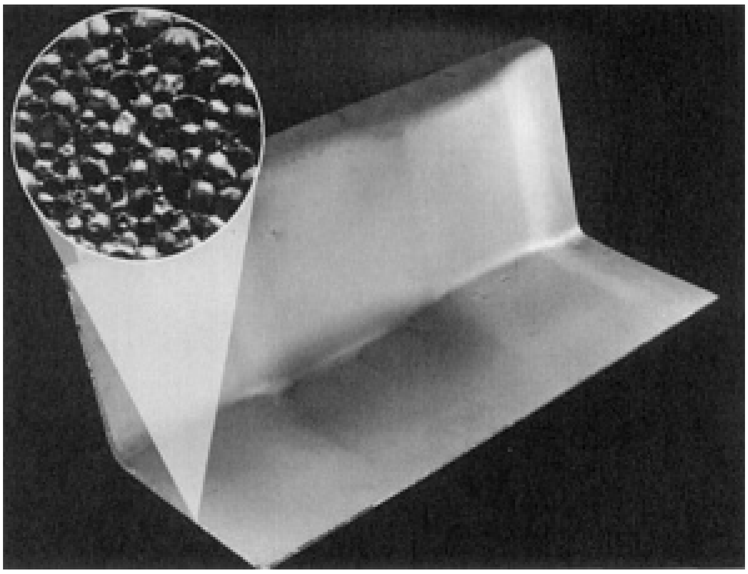

Fig. 9 Sandwich part containing a porous aluminum foam core and two aluminum face sheets (length, 1 m; total width, approximately 60 cm; thickness, 8 to 10 mm). Courtesy of Karmann, Germany

Steel is also used for sandwich face sheets. In Fig. 10, steel sheets were roll cladded to a sheet of foamable aluminum and then deep drawn to yeild a three-dimensional structure. Subsequent foaming created the porous core.

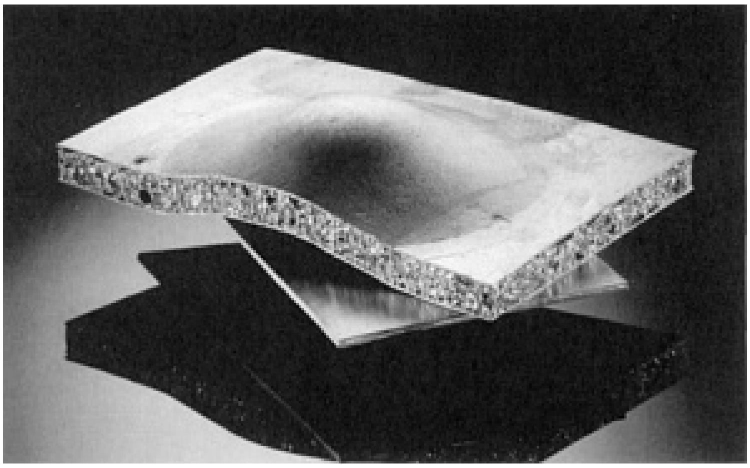

Fig. 10 Sandwich part with steel face sheets and a porous aluminum foam core. Courtesy of Studiengesellschaft Stahlanwendungen, Germany

Because the elastic modulus can be varied within a wide range via the choice of the foam density, it is possible to match the resonance frequency of foamed parts. In this way, detrimental vibrations can be suppressed. Complex-shaped parts of foamed metals can also be used to encapsulate components that are hot or produce noise. In this case, the high thermal stability of foamed metals can be exploited.

Closed-cell foams are especially well suited to use as floating structures because of their high damage tolerance. These structures retain their buoyancy even when locally damaged. In particular, metal foams are able to withstand higher pressures or higher temperature than plastic foams.

Metallic Foams

J. Banhart, J. Baumeister, and M. Weber, Fraunhofer-Institute for Applied Materials Research, Bremen

References

1. J.A. Ridgeway, "Cellarized Metal and Method of Producing the Same," U.S. Patent 3,297,431, 1967
2. S. Akiyama et al., "Foamed Metal and Method for Producing the Same," European Patent Application EP 0 210 803 Al, 1986
3. J. Baumeister, "Method for Producing Porous Metal Bodies," German Patent DE 40 18 360, 1990
4. J. Baumeister and H. Schrader, "Methods for Manufacturing Formable Metal Bodies," German Patent DE 41 01 630, 1991
5. J. Baumeister, J. Banhart, and M. Weber, *Int. Conf. on Materials by Powder Technology,* F. Aldinger, Ed., DGM Informationsgesellschaft Oberursel (Germany), 1993, p 501
6. M. Weber, Ph.D. thesis, Technical University Clausthal, 1995
7. M. Weber, J. Baumeister, J. Banhart, and H.D. Kunze, *Proc. Powder Metallurgy World Congress PM94* (Paris), Les Editions de Physique, 1994, p 585
8. L.J. Gibson and M. Ashby, *Cellular Solids,* Oxford, 1988

Metallic Foams

J. Banhart, J. Baumeister, and M. Weber, Fraunhofer-Institute for Applied Materials Research, Bremen

Selected References

- Baumeister et al., U.S. Patent 5,151,246, 29 Sept 1992

Friction Powder Metallurgy Materials

Introduction

FRICTION MATERIALS are the components of a mechanism that converts mechanical energy into heat upon sliding contact. The conversion product, heat, is absorbed or dissipated by the friction material. The coefficient of friction, an index of shearing force of the contacting parts, determines the degree of performance of the friction material. The required level of the coefficient of friction depends on the operating conditions and the end use of the product.

Sintered metal friction materials have been used as brake disks, especially for heavy-duty application. Because of their good breaking performance and low wear rate under high temperatures and heavy-duty conditions, sintered friction materials have become more important. Sintered friction materials typically comprise:

- Sinterable metal powders (e.g., copper and iron)
- Friction modifiers, such as abrasive particles (e.g., alumina, silica, and mullite) and lubricants (e.g., graphite and molybdenum disulfide)