P/M Technology for the Production of Metal Foams

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Abstract

A new powder metallurgical method for the production of foamed metals with very low apparent densities is described. The mechanical properties of foamed aluminium are investigated. The compressive strength and elastic modulus of these materials depend strongly on the apparent density. The different types of dependence are discussed and compared to theoretical models. From the properties, several potential applications of foamed metals are derived which make use of the unique mechanical, physical and technological features of this class of cellular solids.

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Introduction

Highly porous materials with a cellular structure are known to have a high stiffness combined with a very low specific weight. For this reason, nature uses cellular materials as a constructional material (for example, wood and bones). Polymeric foams also find widespread applications in solutions to technical problems. Less known is the fact that 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 [1, 2]. The foaming agent is usually a powdered metal hydride, e.g. TiH_2, which releases hydrogen gas when heated to temperatures above approx. 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 obviously difficult to control, a breakthrough could not be achieved with this technology.

Preparation Method

At the *Fraunhofer-Institute for Applied Materials Research* (IFAM) in Bremen (Germany), a new powder metallurgical process for the production of foamed metals (Fig. 1) was developed [3, 4]. According to this method, commercially available powders made of aluminium or aluminium alloys are mixed with a foaming agent by conventional means, e.g. using 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 non-porous, solid aluminium semi-finished product. Several compaction methods can be employed which range from uniaxial pressing to powder extrusion and even to roll compaction. The result of the densification step is a foamable material which, 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.

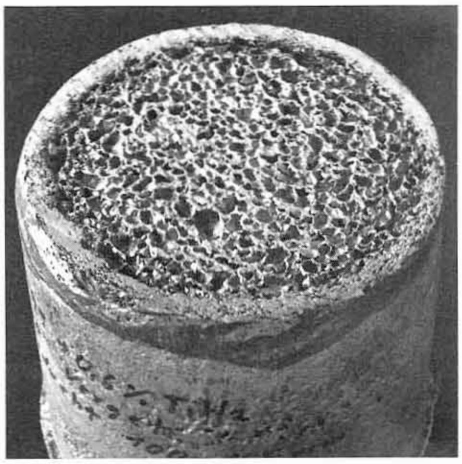

Fig. 1 Structural foam part made of aluminium, consisting of a highly porous core and a dense outer skin. The part was made by adequate temperature control during foaming of semi-finished aluminium in a steel cylinder section.

Properties of the Semi-Finished Product

The properties of the consolidated material are compared to conventional aluminium in Table 1.

It should be pointed out that the resulting aluminium semi-finished product can be processed by means of conventional techniques such as rolling, swaging or extrusion to provide rods, sheets, profiles, etc. 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. For this purpose, arbitrarily shaped hollow moulds are filled with the foamable material and subsequently heated to effect foaming. It was found that thin-walled moulds are particularly advantageous because they allow for a close temperature control of the foaming process.

Table 1 Mechanical properties of the foamable semi-finished product and of conventional aluminium (cold rolled state), according to DIN

Property	Al99.5 + 0.4 wt-% TiH_2	Al99.5 (Lit.)
Tensile strength	176...178 MPa	150 MPa *
Yield strength	138...148 MPa	130 MPa *
Elongation after fracture	6.8...11.2 %	3 % *
Hardness	48 ± 2 HV20	45 HV20
Specific weight	2.70 g/cm³	2.70 g/cm³

* minimum required values

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 which facilitates joining to other materials.

Structural foams - well known in polymer technology - have also been achieved with aluminium, and they are characterised by a highly porous core and an outer skin several mm in thickness having a higher density.

Sandwich-type structures 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.

Properties of Aluminium Foams

Like any other cellular solid, aluminium foams are characterised by a very low specific weight. Using the new P/M technological approach described above, density values ranging between 0.5 and 1 g/cm^3 are usually obtained, 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, aluminium 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 (PE, density 0.12 g/cm^3) is compared to an Al foam (AlCu4 alloy, density 0.45 g/cm^3) in Fig. 2. 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 behaviour which is typical for highly porous cellular solids: an initial, approximately linear elastic 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.

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

In Fig. 3, a stress-strain curve of an aluminium foam is shown which was especially optimised to have a long plateau regime. In contrast to the typical curves given in Fig. 2, it can be seen that the plateau region extends up to strains of 60 %. As a result, the efficiency up to these strain values is as high as 85 %. Further improvements to the efficiency seem possible via a reduction in the peak height at the beginning of the plateau regime.

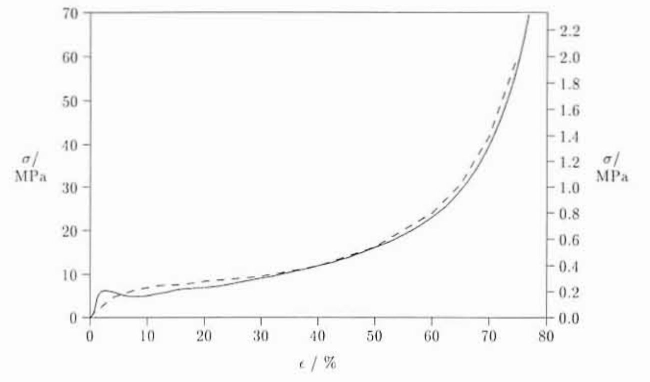

Fig. 2 Stress-strain curve of an AlCu4 foam (solid line, left scale) and of a PE foam (broken line, right scale)

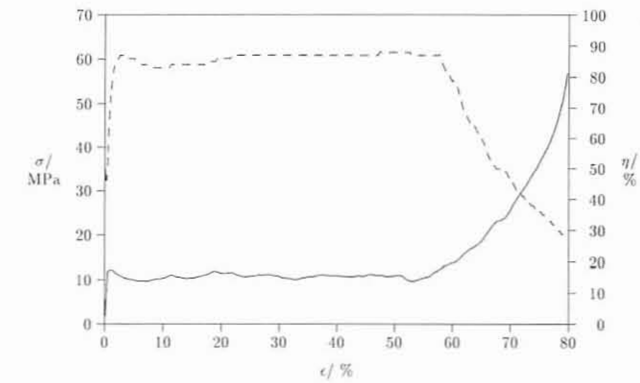

Fig. 3 Stress-strain curve of an aluminium foam with good energy absorption behaviour

The strength of foamed metals depends on several parameters of which the apparent density is the most important. The choice of the matrix alloy, the tempering condition and the morphology of the foam also have a significant influence on mechanical strength properties.

To investigate the relationship between strength and apparent density of aluminium foams, specimen with densities in the range of 0.3 to 1.2 g/cm^3 were prepared. The matrix alloy was AlCu4 and all the specimen were heat-treated in the same manner. The plastic collapse strength was determined in compression tests using a computer-controlled testing machine operated at a constant crosshead speed of 2 mm/min. The height of the first peak, the upper yield strength, was taken as the strength value. If this peak was missing, an extrapolated value using a tangent method was determined.

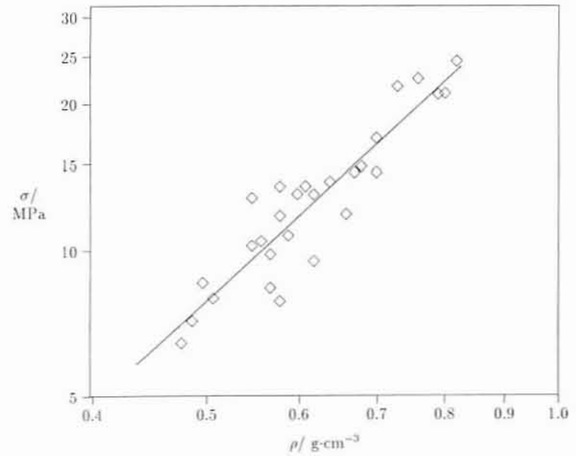

Fig. 4 Plastic collapse strength of AlCu4 foams as a function of the apparent density

The results of the tests are summarised in Fig. 4 for which a log-log-scale was chosen to show the power-law-type dependence of strength versus density. In this plot, the slope of the straight line was found to be close to 2.2, thereby approximately indicating a quadratic dependence of strength vs. density.

A simple model of a foam with a cubic unit cell leads to the following expression for the strength of cellular solids [5]:

$$\sigma_f = \sigma_{ys}\left[0.3\left(\phi\frac{\rho_f}{\rho_s}\right)^{3/2} + (1-\phi)\left(\frac{\rho_f}{\rho_s}\right)\right] \qquad \text{for } \rho_f < 0.3\rho_s \quad (1)$$

where Φ describes the contribution of the material in the cell edges and $(1-\Phi)$ that of the cell faces or membranes. The index "f" denotes properties of the foamed metal, the index "s" those of the solid matrix material. From this relation, in the double-log plot a slope of 1.5 would be expected which is in conflict with the observed value of 2.2 from Fig. 4. However, it should be noted that the cubic model is a very simplified one and that the true cell structure is polygonal rather than cubic so that deviations are to be expected. Moreover, the scatter of the values depicted in Fig. 4 is quite large, so that the uncertainty of the slope is 0.25 in this case.

Additional compression tests have been conducted to investigate the anisotropy of the foamed materials. To this end, several specimen of the same density were prepared and tested parallel to rise, i.e. parallel to foaming direction, others were tested in the two orthogonal directions. It is difficult to analyze the results of these experiments because the testing is destructive and the strength in various directions cannot be measured on one and the same sample. The results, however, indicate a slightly enhanced mechanical strength in the directions perpendicular to the rising direction of the foam.

The elastic modulus of foamed metals was investigated using vibrational bending tests. The resonance frequency (1st order) of rectangular specimen 250 x 10 x 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

$$E_f = E_s\left[\left(\phi\frac{\rho_f}{\rho_s}\right)^2 + (1-\phi)\left(\frac{\rho_f}{\rho_s}\right)\right] \tag{2}$$

from which a straight line with a slope of 2 would be expected in a double-log plot of the foam modulus vs. density. From Fig. 5, it can be seen that this type of correlation has actually been observed (solid line in Fig. 5). An even better approximation of the measured values is obtained by taking Φ=0.88 (dashed line). This means that most of the material in the aluminium foams investigated is concentrated in the cell edges rather than in the cell faces.

Although the first section of the stress strain curve is usually referred to as the linear elastic regime, the determination of the elastic modulus of foamed metals should not be carried out the convenient way, i.e. by evaluation of the slope of this first part of the curve. It was found that, even in this early stage of loading, there are some plastic contributions which 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, e.g. by means of vibrational testing (as described above) or ultrasonic methods.

To illustrate the high stiffness of foamed materials, let us consider the elastic deflection of a beam of square section which is supported at its ends. The task is to minimise the weight of the beam by varying the material, under the condition that a given load F causes a maximum given deflection f. Simple calculation for the mass m of the beam gives the following:

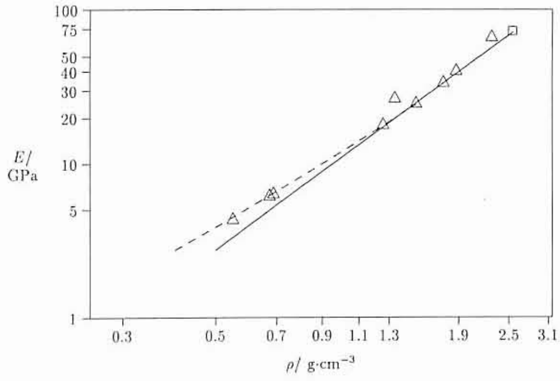

Fig. 5 Elastic modulus of AlSi12 foams as a function of the apparent density (Figs.: FhG IFAM)

Table 2 Material data for a beam of given stiffness

Material	ρ [kg/m³]	E [GPa]	($\rho/\sqrt{E}$)
Steel	7800	200	17.4
Aluminium	2700	69	10.3
Concrete	2500	47	11.5
Glass	2500	69	9.5
GFRP	2000	40	10.0
CFRP	1500	270	2.9
Aluminium foam	500	5	7.1
PU foam	100	0.06	12.9

$$m = \frac{1}{2}\cdot\sqrt{\frac{Fl^5}{f}}\cdot\left(\frac{\rho}{\sqrt{E}}\right) \tag{3}$$

The first term on the right-hand side contains the fixed geometry and boundary conditions, while the second term contains the material properties. The mass of the beam is therefore minimised by choosing a material with a minimum ratio (see heading in the far right column of Table 2). In Table 2, the corresponding values are given for a number of engineering materials. It can be seen that, besides carbon fibre reinforced plastics, foamed aluminium would be the proper choice.

Metallic foams can be described as a two-phase metal-gas composite material. Therefore, the thermal and electrical conductivities of foamed metals are expected to be significantly reduced compared to those of the respective solid [6]. First results on this topic will be presented in further publications.

Applications of Metal Foams

From the properties described above, a number of applications can be derived. Obviously, an important application range will be energy absorption. Using suitable elements made of aluminium foams in the crash zones of automobiles, it will be possible to induce a controlled, programmed deformation with maximum energy consumption. The same is true for side impact protection.

For example, hollow profiles made of steel or aluminium can be filled with aluminium foam, giving rise to a better deformation behaviour of these parts during loading. Other parts of the car body or engine can be made of or reinforced with foamed metals in order to gain a higher stiffness combined with a net weight savings.

Generally, due to the low specific weight, aluminium foams will be used for lightweight constructions. As an example, the replacement of honeycomb structures with sheets of foamed aluminium will lead to reduced costs and more isotropic properties. The noncombustibility of this material is especially of importance for aerospace applications.

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 may be used to encapsulate components which are hot or produce noise. In this case, the high thermal stability of foamed metals can be exploited.

Due to the non-combustibility of metal foams, a further potential is to be seen in fire protection. In this field, even the foamable precursor material may find application as a heat-activated expanding material.

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 temperatures than plastic foams.

Some applications will be based on specific physical properties of foamed metals. In the field of ultrasonic measurements, for example, it is necessary to adapt the impedance of the piezo quartz to the impedance of air. Because the ultrasonic impedance of foamed metals is in the proper range, they might be used as adapters.

A further advantage of foamed aluminium is the fact that it is ecologically harmless. During the foaming process, only hydrogen gas is released which burns to water immediately. The foams are able to be fully recycled and even secondary aluminium powder may be used for the foam production.

One of the future tasks will be to extend the foaming technology, originally developed for aluminium-based materials, to other metals and alloys. As a first step, it was shown that tin- and zinc-based alloys can also be prepared as highly porous cellular solids. The next problem to be solved is the development of a technology for the production of steel foams. In this case, it will be necessary to change the type of foaming agent. Furthermore, to prevent excessive oxidation, the foaming process will have to take place in an inert atmosphere or in a vacuum.

Using steel foams, it will be possible to extend the applicable temperature range. 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 will require less time to reach the normal operating temperature of the exhaust catalyst, leading to a reduction in emissions.

By modifying the preparation technology, it should be possible to obtain open-pore aluminium foams as well. In this context, there are several additional applications in the fields of heat exchangers, filters and catalyst carriers, etc. For this reason, the investigations of foamed metals will also be extended in this direction.

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Kurzfassung

Ein neues pulvermetallurgisches Verfahren zur Herstellung geschäumter Metalle mit sehr geringen Rohdichten wird vorgestellt. Die mechanischen Eigenschaften geschäumten Aluminiums werden untersucht. Die Druckfestigkeit und der Elastizitätsmodul dieser Materialien hängt sehr stark von ihrer Dichte ab. Diese Dichteabhängigkeiten werden diskutiert und mit den Ergebnissen theoretischer Modelle verglichen. Ausgehend von den speziellen mechanischen, physikalischen und technologischen Eigenschaften dieser Klasse poröser Werkstoffe werden mögliche Anwendungen abgeleitet. □