Selected mechanical and physical properties of metal foams

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Abstract: Due to a new powder metallurgical method it is possible to obtain highly porous metallic parts with a relative density of 20 % and lower. This cellular structure gives rise to unique properties which could in former times only be exploited for cellular plastics. The mechanical properties for foamed metals are presented in form of compression strength and Young's modulus data. The dependencies of the properties on the apparent density are discussed and compared with theoretical models.
The electrical conductivity of metal foams exhibit a power-law dependence on the apparent density with exponents of about 1.5 and is shown for different material compositions.

1. Introduction

Cellular materials are widespread in everyday life and are used for cushioning, insulating, damping, constructing, filtering purposes and a lot of other applications. Highly porous materials are known to have a high stiffness combined with very low specific weight. For this reason cellular materials frequently occur in nature as constructional materials (e.g. woods and bones).
Using a new powder metallurgical production method which was developed at the Fraunhofer-Institute for Applied Materials Research (IFAM) in Bremen it has now become possible to obtain metallic foams of various metals and alloys. They enlarge the application range of cellular materials because of advantageous mechanical and thermal properties and fewer ecological problems in comparison to polymeric foams.
For the production of such foams commercial metal powders are mixed with a foaming agent and subsequently compacted. During an ensuing heat treatment at temperatures near the melting point of the matrix material the compacted P/M material expands and develops its highly porous structure. Even parts of an arbitrary shape can be produced near-net-shape by filling hollow moulds with foamable material and merely heating. This and other feasible processes are specified more precisely in [1].

2. Mechanical properties of aluminium foams

The properties of cellular materials can vary widely, depending on three sets of parameters: the properties of the matrix material of which the cells are made of, the apparent density and the geometry of the cells.
Like any other cellular solid, aluminium foams are characterised by a very low specific weight. Using the new P/M-technological approach, density values in the range between 0.5 and 1 g/cm^3 are usually obtained although even values down to 0.2 g/cm^3 and up to 2 g/cm^3 can be achieved. Due to its closed porosity aluminium foam floats upon water.
Mechanical properties of foams are usually determined by compressive testing. To show the superior strength of metal foams in Fig. 1 a polyethylene foam (PE, density 0.12 g/cm^3) is compared to an alu-

minium foam (AlCu4 alloy, density 0.45 g/cm³). In both materials, the initial porosity is about 83% to 87%. For better comparison, the strength scale of the PE-foam is 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 which itself is finally followed by a densification response at high strains in which the stress again increases steeply. Due to this special form of the compression stress-strain curve foamed materials have a high capacity of absorbing great amounts of impact energy at a relatively low strength level.

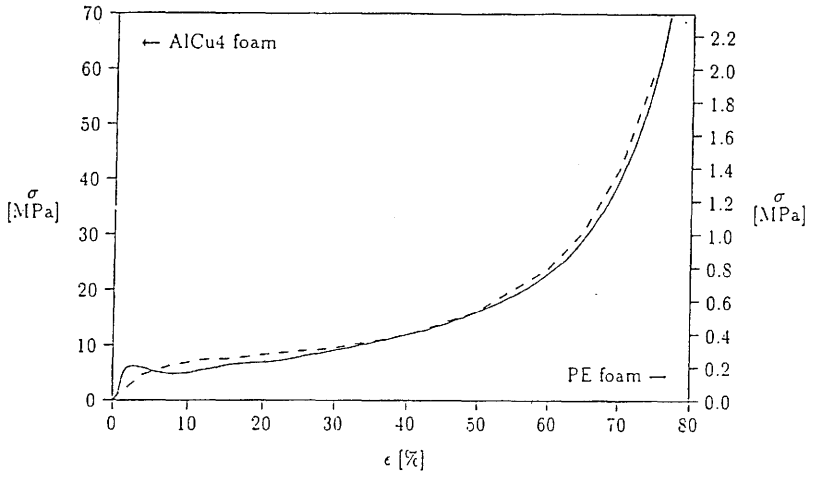

Fig. 1: Compression stress-strain curves of an AlCu4-foam (solid line, left scale) and of a PE-foam (broken line, right scale)

In order to investigate the relationship between strength and apparent density of aluminium foams, specimens with densities in the range from 0.2 to 1.2 g/cm³ were prepared. The matrix alloy was AlSi12 and all the specimens were in the same temper condition. The plastic collapse strength was determined in compression tests using a computer controlled testing machine. Because no sharp transition from linear elastic to the plateau regime is to be found for the foams, the stress level at a compressive strain of 20 % was taken as strength value. Here the compressive stress has reached the plateau regime and the measured strength is relatively insensitive to inaccuracies of the sample preparation and the setting of samples at the beginning of the tests. The results of the tests are summarised in Fig. 2 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 1.75.
A simple model of a foam with a cubic unit cell, proposed by Ashby [2], leads to the following expression for the strength of cellular solids:

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

where ϕ describes the fraction of the solid which is contained in the cell edges and $(1-\phi)$ that in the cell faces. The index "f" denotes properties of the foam, the index "s" those of the solid material of which the cell walls are made. From this relation in the double-log plot a slope of 1.5 would be expected where the results by the authors show a value of 1.75 in Fig. 2. It should be noted that, of course, 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. On the other hand the scatter of the values depicted in Fig. 2 is quite large, so that the uncertainty of the slope is ±0.2 in this case. Moreover, it is not to be expected that the strength of a foam can be described by one simple equation for the whole density range in an exact manner.

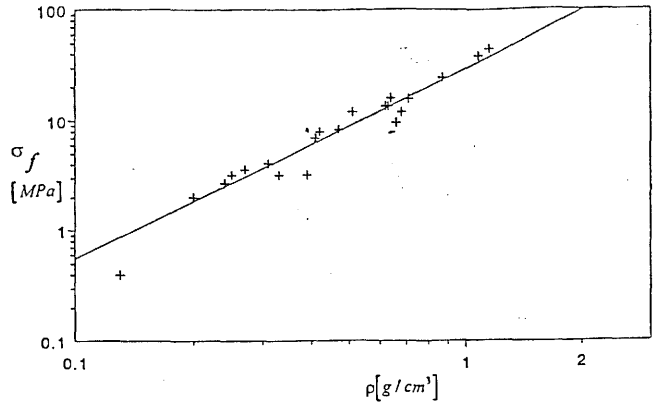

Fig. 2: Compression strength of AlSi12 foams at 20 % deformation as a function of the apparent density

The Young's modulus of foamed metals was investigated by flexural vibration tests. The resonance frequency (1st order) of rectangular specimens of 250x10x5 mm³ size was determined and the resulting storage modulus calculated. Because the values are independent of frequency it is concluded that the results represent the static modulus.

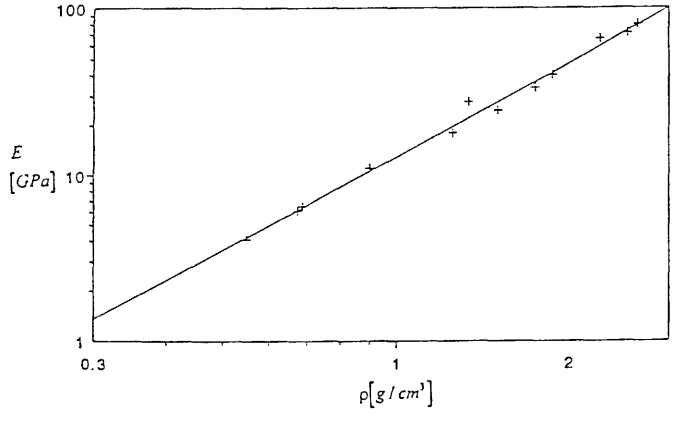

Fig. 3: Young's modulus of AlSi12 foams as a function of the apparent density

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 [2] states that

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

from which in a double-log plot of the foam's modulus vs. its density a straight line with a slope of 2 would be expected. From Fig. 3 it can be seen that this type of correlation is nearly observed. The experimental values show a good fitting to a line with a slope of 1.85, thereby approximately indicating a quadratic dependence of Young's modulus vs. density. An even better approximation could be obtained by taking into account the factor ϕ, describing the material distribution in the cells.

Although the first portion of the stress strain curve usually is referred to as linear elastic regime the determination of the elastic modulus of foamed metals should not be done in the convenient way by evaluation of the slope in 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 of the specimen. It is therefore preferable to apply elastic loading of the samples, e.g. by vibrational testing (as described above) or ultrasonic methods.

3. Field properties of metallic foams

Metallic foams can be treated as a two phase metal-gas composite material. As an example for the field properties the electrical conductivity of foamed materials was measured over a wide range of densities. Two different cell materials, pure Al and AlSi12Mg, were examined in order to investigate the influence of the alloying elements. For this purpose Si and Mg powders were admixed to the aluminium/ TiH_2-blend, compacted and subsequently foamed thus forming a homogenous foamed alloy.

As it is expected and shown in Fig. 4 the conductivity increases with increasing density. The solid lines are calculated from considerations of the continuum theory and its application to two-phase materials [3]. In our calculation pores are described as the second, dispersed phase with a neglectable conductivity. The calculated curves for spherical and isotropically distributed pores correspond well with the measured data. With these suppositions the general field property equation [3] simplifies to the following expression

$$\varphi_f = \varphi_s \left(\frac{\rho_f}{\rho_s} \right)^{3/2} \qquad (3)$$

with φ_f as the conductivity of the foam, φ_s as the conductivity of the dense matrix material. It should be mentioned that the calculated lines also represent the third order upper bound equation, describing the maximum possible field properties of porous materials.

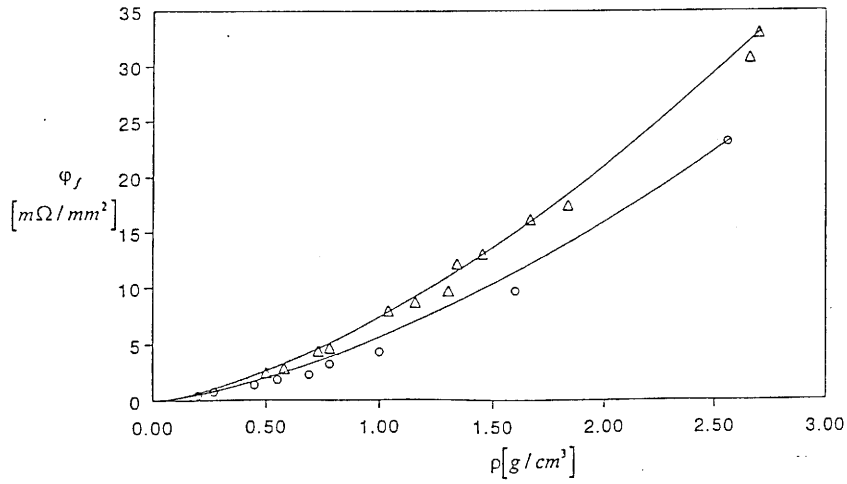

Fig. 4: Electrical conductivity of Al-foams (Δ) and AlSi12Mg-foams (o) as a function of apparent density

These results make it possible to tailor precisely a metallic foam with respect to a desired conductivity. According to the Wiedemann-Franz law an analogous dependency is expected for the thermal conductivity vs. the density and material relationships.

References

[1] Baumeister J. et al. "Methods for the Production of Metallic Foams" Conf. Proceedings PM '94, Paris
[2] Gibson L. J. and Ashby M. F., Cellular Solids (Pergamon Press, 1988) pp. 137-147
[3] Ondracek G., *Metall* 36 (1982) pp. 523-531